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Atmospheric Measurement Techniques Discussions

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7, C4754–C4781, 2015

Interactive Comment

Interactive comment on "Atomic oxygen retrievals in the MLT region from SCIAMACHY nightglow limb measurements" *by* O. Lednyts'kyy et al.

O. Lednyts'kyy et al.

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Received and published: 30 January 2015

Anonymous Referee #1 (received and published: 27 November 2014):
This paper describes how upper mesospheric-lower thermospheric atomic oxygen densities have been derived from nighttime SCIAMACHY observations of atomic oxygen green line emissions. The retrieval methodology, error analysis, and retrieval results are described and assessed via comparisons with MSIS and SD-WACCM model results as well as with TIMED/SABER retrievals. The paper is well written, has a clear and logical flow, uses sound methodologies, and is relevant to AMT. There are only a few relatively minor concerns (detailed below) that need to be addressed before the paper could be published.
Dear Referee, first of all thank you for very interesting and helpful comments. Our final

responses and changes to the manuscript (in normal font) follow each comment (in bold font).

General comments
It is mentioned in the introduction that there are WINDII, OSIRIS, and ISUAL derived [O] data sets. Has there been any attempt to obtain the [O] research products from these missions? Direct comparisons with OSIRIS and ISUAL would be highly beneficial, and perhaps comparisons of SCIAMACHY and WINDII [O] for periods of similar geomagnetic conditions could be useful as well. SCIAMACHY and WINDII [O] probability density functions could also potentially be compared.
Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2. We are indebted to the OSIRIS team and particularly to Patrick Sheese, University of Toronto, Canada, for making OSIRIS data available to us. We are going to analyze the retrieved SCIAMACHY [O] in comparison with the 22:00 LT data of OSIRIS [O], ISUAL [O], and the WINDII [O] in a future publication.

The results section at times lacks specificity, and at times explanations of differences between different methodologies/data sets are not offered. Instead of quantifying results, vague terms such as "close" or "bigger than" are used in qualification. Results need to be explicitly stated in quantifiable terms, and then possible explanations for these results need to be considered. Specific instances are given below.
Response: Done. The corresponding parts of the manuscript were substantially changed, and differences to other datasets quantified.

Specific comments
Abstract: **Should highlight more results, i.e. error analysis results, quenching model works best, etc.**

AMTD
7, C4754–C4781, 2015

Interactive Comment

New "Abstract" in manuscript: "Vertical distributions of atomic oxygen concentration in the mesosphere and lower thermosphere (MLT) region were retrieved from sun-synchronous SCIAMACHY/Envisat limb measurements of the oxygen 557.7 nm green line emission in the terrestrial nightglow. A band pass filter was applied to eliminate contributions from other emissions, the impact of measurement noise and auroral activity. Vertical volume emission rate profiles were retrieved from integrated limb emission rate profiles under the assumption that each atmospheric layer is horizontally homogeneous and absorption and scattering can be neglected. The radiative transfer problem was solved using regularized total least squares minimization in the inversion procedure. Atomic oxygen concentration ([O]) profiles were retrieved from data collected for altitudes in the range 85–105 km with approximately 4 km vertical resolution during the time period from August 2002 to April 2012 at approximately 22:00 local time. The retrieval of [O] profiles was based on the generally accepted 2-step Barth transfer scheme including consideration of quenching processes and the use of different available sources of temperature and atmospheric density profiles. A sensitivity analysis was performed for the retrieved [O] profiles to estimate maximum uncertainties assuming independent contributions of uncertainty components. Errors in photochemical model parameters depending on temperature uncertainties and random errors of model parameters contribute less than 50% to the overall [O] retrieval error. The retrieved [O] profiles were compared with reference [O] profiles provided by SABER/TIMED or by the NRLMSISE-00 and SD-WACCM4 models. A comparison of the retrieved [O] profiles with the reference [O] profiles led to the conclusion that the photochemical model taking into account quenching of $O(^1S)$ by O_2, $O(^3P)$ and N_2 and SABER/TIMED as a source of temperature and density profiles are the most appropriate choices for our case. The retrieved [O] profile time series exhibits characteristic seasonal variations in agreement with satellite observations based on analysis of OH Meinel band emissions and atmospheric models. A pronounced 11-year solar cycle variation can also be identified in the retrieved atomic oxygen concentration time series."

AMTD

7, C4754–C4781, 2015

Interactive Comment

Page 10833

Line 1: "if the data were available" is misleading. Granted, [O] is not a standard level 2 or 3 product for these instruments, but undoubtedly the research products are readily available from the missions' science teams.

Changes in manuscript: "(e.g., WINDII, OSIRIS, ISUAL) if the measurement data were available." has been changed to "(e.g., WINDII, OSIRIS, ISUAL)."

Line 19: should maybe be "the Earth's radiation..."

Response: SCIAMACHY measured the radiation field of the Earth's atmosphere.
Changes in manuscript: "the radiation field" has been changed to "the atmospheric radiation field"

Page 10834

Line 6: "in the vertical"

Changes in manuscript: "in vertical direction at" has been changed to "in the vertical direction at"

Line 16: what issues do the calibration flags identify?

Response: The flags correspond to all relevant corrections of instrumental artifacts and calibration steps that are required to obtain fully calibrated SCIAMACHY limb radiances. These corrections include, e.g., memory effect correction, wavelength calibration, dark signal correction, polarization correction, and absolute calibration. For more information see Gottwald et al. (2006).
Changes in manuscript: "calibrated using all calibration flags." has been changed to "calibrated using all calibration flags (Gottwald et al., 2006) required to obtain fully calibrated SCIAMACHY limb radiances."

Line 20: should add reference for the SABER instrument, I believe that it's Mlynczak et al. 1997.

Response: Our response considers the interactive comments of the Anonymous

Referee #1 and the Anonymous Referee #2.
Changes in manuscript: “radiometer on board” has been changed to “radiometer (Mlynczak, 1997, Russell et al., 1999) on board”
Mlynczak, 1997:
Mlynczak, M. G., Energetics of the mesosphere and lower thermosphere and the SABER experiment, Adv. in Space Res., 20, 6, 1177–1183, doi:10.1016/S0273-1177(97)00769-2, 1997.

Line 22: **“provides the data”**
Line 22: **“the Internet” is somewhat vague. Consider “their website.”**
Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.
Changes in manuscript: “provides data via the Internet” has been changed to “provides the data online via their website”

Page 10835
Line 4: **is a constant mixing ratio valid at 105 km? Do the MSIS and WACCM data suggest that this is the case? What errors are introduced by this assumption (a point aimed more at the error analysis section).**
Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.
The SD-WACCM4 data that we had in our disposition did not let us determine if the mixing ratios at 105 km are constant or not. NRLMSISE-00 data show a steadily falling $[O_2]/[N_2]$ ratio by 9% in the altitude range 100–105 km that (presumably) is exaggerated. Picone et al. (2002) suggest that entirely empirical MSIS-class models await the addition of credible mesospheric $[O_2]$ data to the NRLMSISE-00 database.
In the presented O retrieval we supposed that a constant mixing ratio is valid at 105 km, which is also assumed in the SABER O retrieval (Smith et al., 2010). Smith et al. (2010) suggest a small decrease in O_2 mixing ratio that causes slight underestimation of O. We also expect slight underestimation of O.

To estimate errors introduced by the constant mixing ratio assumption we used the a priori information of varying mixing ratio obtained from NRLMSISE-00 in our O retrieval with SABER density/temperature profiles. The relative differences of [O] without the mixing ratio correction vs. [O] with such a correction is less than 4% in the altitude range 100–105 km.
Smith et al. (2010):
Smith, A. K., Marsh, D. R., Mlynczak, M. G., Mast, J. C.: Temporal variations of atomic oxygen in the upper mesosphere from SABER, J. Geophys. Res., 115, D18309, doi: 10.1029/2009JD013434, 2010.
Changes in manuscript: "The concentrations of [O_2] and [N_2] were calculated from atmospheric density profiles assuming constant mixing ratios. The atomic oxygen mixing ratio" has been changed to "The concentrations of molecular oxygen ([O_2]) and molecular nitrogen ([N_2]) were calculated from atmospheric density profiles assuming constant mixing ratios. The decrease of the [O_2]/[N_2] ratio with altitude according to NRLMSISE-00 data is not reliable as pointed out by Picone et al. (2002), because credible mesospheric [O_2] data are absent in the NRLMSISE-00 database. If the mixing ratio correction based on NRLMSISE-00 [O_2] and [N_2] profiles were applied in the O retrieval, [O] values would fall by 4% in the altitude range 100–105 km. In the presented O retrieval we supposed that a constant mixing ratio is valid at altitudes up to 105 km, which is also assumed in the SABER O retrieval (Smith et al., 2010). The atomic oxygen mixing ratio"

Line 10: **"incorporates" would probably be more accurate than "includes".**
Changes in manuscript: "includes" has been changed to "incorporates"

Line 12: **"to complete them" isn't necessary.**
Changes in manuscript: "extrapolate the data to complete them." has been changed to "extrapolate the data."

Line 16: **"the National..."**

AMTD
7, C4754–C4781, 2015

Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.
Changes in manuscript: “by National” has been changed to “by the National”

Line 17: **consider “online” instead of “via the Internet”.**
Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.
Changes in manuscript: “provided via the Internet” has been changed to “provided online”

Line 24: **What benefits does a nudged GCM have over a standard GCM?**
Response: To make the standard GCM (General Circulation Model, here WACCM) nudged, meteorological fields simulated by GEOS-5 (Goddard Earth Observing System 5) at altitudes lower than 50 km were applied at each WACCM time step. The nudged SD-WACCM4 will much better be able to couple chemistry, radiation, and atmospheric dynamics to reproduce specific events, e.g., sudden stratospheric warmings.

Page 10836
Line 5: **It is not clear what is meant by “we exploited the longitudinal variation”. Does this mean that you sampled the model output at the longitude where the local time is 22:00?**
Response: Yes, we sampled the model output at the longitude corresponding to 22:00 local time.
Changes in manuscript: “As described by Kowalewski et al. (2014), we exploited the longitudinal variation of the SD-WACCM4 fields - provided with daily resolution at 00:00 UTC - to extract the required atmospheric parameters at 22:00 LT.” has been changed to “To extract the required atmospheric parameters at 22:00 LT we sampled the corresponding longitude of the SD-WACCM4 output provided with daily resolution at 00:00 UTC, as in Kowalewski et al. (2014).”

Line 18: **The SAA data is not the only data in Fig. 2 that is in green (as per the caption). Please make the main text and the caption consistent.**
Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.
Changes in manuscript: "The measurements within the South Atlantic Anomaly (SAA) are shown in green in Fig. 2." has been changed to "For the retrieval we used the limb measurements marked in blue in Fig. 2, but not the measurements that are affected by Aurora Borealis, highly energetic particles or by contaminating emissions (shown in green)."

Lines 21-22: **I assume the subtraction of the 110-126 km average is because any airglow signal is below the detector threshold, hence giving the detector noise signal. Please explicitly state the reason for this step.**
Response: The subtraction of the 110-126 km average is because of contributions from other emissions, the impact of noise and auroral activity.
Changes in manuscript: "For each individual spectrum the emission spectra averaged over the 110–126 km tangent height range were subtracted from the spectrum at each tangent height." has been changed to "For each individual spectrum the emission spectra averaged over the 110–126 km tangent height range were subtracted from the spectrum at each tangent height. The subtraction of the 110–126 km average is because of contributions from other emissions, the impact of noise and auroral activity."

Line 37 (line 10 on page 10837): **delete "like".**
Changes in manuscript: "(CMEs), like, e.g.," has been changed to "(CMEs), e.g.,"

Line 11: **"see section 2.1" is unnecessary.**
Changes in manuscript: "anomaly reports, see Sect. 2.1)" has been changed to "anomaly reports)"

AMTD
7, C4754–C4781, 2015

Interactive Comment

Line 29: **"and so they should be considered" is unnecessary.**
Changes in manuscript: "561 nm and so they should be considered." has been changed to "561 nm."

Page 10838
Lines 9-10 (and afterwards): **LER has already been defined as limb emission rate. There is no need to continue defining the acronym.**
Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.
Done. LER is now only defined once.

Line 16 (and afterwards): **VER has already been defined as volume emission rate. There is no need to continue defining the acronym.**
Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.
Done. VER is now only defined once.

Line 23: **since the forward model has not yet been introduced, "A linear... was used to map volume..." may be more appropriate.**
Changes in manuscript: "The linear forward model (Rodgers, 2000) maps volume emission rate profiles" has been changed to "A linear model was used to map (Rodgers, 2000) VER profiles"

Page 10839
Line 5: **the vector term b should be more generally defined as the random error of model parameters (even if the only parameter considered is the tangent height registration).**
Changes in manuscript: "***b*** representing errors in tangent height registration," has been changed to "the vector term ***b*** representing the random error of model parameters (one of the model parameters relevant for this retrieval step is an offset in

AMTD
7, C4754–C4781, 2015

Interactive Comment

Full Screen / Esc
Printer-friendly Version
Interactive Discussion
Discussion Paper

tangent height registration),"

Page 10840

Line 15: **Why is it assumed that S_e informs S_a? Shouldn't a priori data be obtained independently from the measurements? Either way, it is unclear what you are using as S_a, please explicitly state how S_a is obtained/derived.**

Response: S_a was derived according to the following algorithm:
1) The trace of the S_e matrix was squared. 2) The resulting array was scaled to the range from 0 to 1 and then added to a much bigger constant value. 3) This array was assigned to the trace of the S_a matrix. The Eq. (4) holds valid, which makes the S_a matrix non-informative to the retrieval.
The VER profiles retrieved according to Eq. (2) and Eq. (3) are evidently equivalent. This equivalence was achieved due to application of the S_a matrix calculated with help of S_e. Please note that we didn't inform the retrieval by the a priori state vector.

Line 26: **Please specify what is meant by "similar".**

Response: The curve representing the synthetic vector $\boldsymbol{s} = \mathbf{K}\boldsymbol{x}$ fits the curve representing the measurement vector $\boldsymbol{y}$. The relative difference error between the smoothed fit of $\boldsymbol{y}$ by $\boldsymbol{s}$ is less than 0.1 (or 10%) for data sets on a daily timescale and less than 0.05 (or 5%) on a monthly timescale in the altitude range 82–100 km.
Changes in manuscript: "the measurement vector $\boldsymbol{y}$ is similar to the synthetic vector $\boldsymbol{s} = \mathbf{K}\boldsymbol{x}$. Figure 5 presents the results for LER profiles ($\boldsymbol{y}$) and synthetic profiles based on the retrieved VER profiles averaged for a sample day (Fig. 5a) and a sample month (Fig. 5d)." has been changed to "the measurement vector $\boldsymbol{y}$ is similar to the synthetic vector $\boldsymbol{s} = \mathbf{K}\boldsymbol{x}$. In fact, the curve representing the synthetic vector $\boldsymbol{s}$ fits the curve representing the measurement vector $\boldsymbol{y}$. The relative difference between $\boldsymbol{s}$ and $\boldsymbol{y}$ is less than 0.1 (or 10%) for data sets on a daily timescale and less than 0.05 (or 5%) on a monthly timescale in the altitude range 82–100 km. Figure 5 presents the results for LER profiles ($\boldsymbol{y}$) and synthetic profiles based on the retrieved VER profiles averaged for a sample day (Fig. 5a) and a sample month (Fig. 5d)."

AMTD
7, C4754–C4781, 2015

Page 10841

Lines 4-5: The averaging kernel isn't necessarily expected to be "a simple peak". In an ideal observing system it would be a delta function, but different observation systems will yield different averaging kernel shapes. This should be rephrased.

Changes in manuscript: "The shape of the averaging kernel represented by a row of the matrix $\mathbf{A} = \mathbf{GK}$ is expected to be a simple peak (Rodgers, 1990)." has been changed to "The shape of the averaging kernel represented by a row of the matrix $\mathbf{A} = \mathbf{GK}$ is, in our case, a simple peak."

Line 25: "coarser" would be more accurate than "bigger".

Changes in manuscript: "bigger" has been changed to "coarser"

Page 10843

Line 5: "parameters means the retrieval is over-regularized and..."

Changes in manuscript: "parameters mean overregularization and cause flatness" has been changed to "parameters mean that the retrieval is over-regularized leading to flatness"

Lines 18-19: The first part of this sentence is a bit confusing. Are you trying to say that only the systematic forward model parameter error is represented by $\mathrm{S_f}$? Please rephrase.

Changes in manuscript: "with the measurement error covariance matrix $\mathbf{S}_\mathrm{m}$ related to random and systematic errors and the smoothing error covariance matrix $\mathbf{S}_\mathrm{s}$. The forward model parameter error is represented by covariance matrix $\mathbf{S}_\mathrm{f}$ related to systematic errors and the error covariance matrix $\mathbf{S}_\mathrm{b}$ represents random errors of model parameters that are not retrieved (see Sects. 4 and 6)." has been changed to "with the measurement error covariance matrix $\mathbf{S}_\mathrm{m}$ related to random and systematic errors, the smoothing error covariance matrix $\mathbf{S}_\mathrm{s}$, the error covariance matrix $\mathbf{S}_\mathrm{b}$ related to random errors of model parameters that are not retrieved (see Sects. 4

AMTD

7, C4754–C4781, 2015

and 6), and the covariance matrix $\mathrm{S_f}$ corresponding to the systematic forward model parameter error."

Line 20: **the vector term b was previously defined as tangent height registration error, and is now being defined more generally. It might make more sense to define in general terms earlier in the text.**
Response: Changes in manuscript were performed to the text on the page 10839, line 5.

Line 5: **the way the smoothing error is defined here (as it is defined in Rodgers) assumes that the true state is known. Can you please explain further exactly how you are determining the smoothing error?**
Response: According to Rodgers (1990), page 70, we don't need to know the true state vector in the frames of the maximum a posteriori solution of the forward linear model upon generalisation that the state vector is composed of several independent components. So, we calculate the covariance matrix $\mathrm{S_s}$ of the smoothing error according to the Eq. (13) which doesn't include any a priori information. The state vector $\boldsymbol{x}$ appearing in $\mathrm{S_n}$ in the Eq. (13) represents a retrieved VER profile that is used to calculate the mean value of the retrieved VER profile $\bar{\boldsymbol{x}}$.

Page 10845
Line 19: **"^{1}S-^{1}D" should be "$\mathrm{O}(^1\mathrm{S}-^1\mathrm{D})$".**
Changes in manuscript: "^{1}S–^{1}D" has been changed to "$\mathrm{O}(^1\mathrm{S}-^1\mathrm{D})$"

Page 10846
Line 8: **"approaches of retrieve" should maybe be "approach to retrieving".**
Changes in manuscript: "model approaches to retrieve" has been changed to "model approach to retrieving"

Lines 24-25: **Why were the quench/SABER profiles chosen? Could the**

AMTD
7, C4754–C4781, 2015

Interactive Comment

other profiles be shown as well?

Changes in manuscript: "Figure 8 shows sample daily and monthly averaged [O^{quench}_{SABER}] profiles within the latitude range" has been changed to "Figures 10 and 11 show different possible sample daily and monthly averaged [O] profiles within the latitude range"

Page 10847

Line 17: "(denoted by subscript..."

Changes in manuscript: "(denoted by ±1)" has been changed to "(denoted by subscript ±1)"

Line 18: The phrasing is a bit confusing. Consider, "avoid assumptions about the parameter distributions, e.g. that they are Gaussian."

Changes in manuscript: "to avoid assumptions about certain, e.g., normal, type of the parameter distributions." has been changed to "to avoid assumptions about the parameter distributions, e.g., that they are Gaussian."

Line 20: "unperturbed" would be more accurate than "error-free".

Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.

Changes in manuscript: "error-free" has been changed to "unperturbed"

Page 10850

Line 14: "assessment" is more suitable than "validation", as the profiles aren't actually being validated.

Changes in manuscript: "In this section we first present in Sect. 7.1 results of the error analysis introduced in the previous section, followed by a verification and first validation of the retrieved [O] profiles." has been changed to "In this section we first present results of the error analysis introduced in Sect. 6. Then the derived [O] densities are assessed via comparisons with NRLMSISE-00 and SD-WACCM4 model

AMTD

7, C4754–C4781, 2015

results as well as with TIMED/SABER retrievals."

Lines 22 and 24: It's not exactly clear what is meant by "fields". Perhaps climatologies?
Changes in manuscript: "fields" has been changed to "climatologies"

Page 10851
Section 7.1: Please explicitly state the magnitude of the errors shown in Figs. 6 and 8. Are these results typical of the entire data set? What are the average errors? How do the errors compare with the overall errors of other satellite derivations of [O]?
Response: Magnitudes of the errors were calculated according to the maximum uncertainty approach discussed in Sects. 3, 6.1 for LER profiles, Sects. 4, 4.3, 6.1, 7.1 for VER profiles and Sects. 4, 4.3, 6.1, 7.1 for [O] profiles. Figure 4 presents error components of LER profiles, Fig. 6 those of VER profiles and Fig. 8 those of [O] profiles. Values of the errors are listed in Tables 3–8 in the supplementary material on the 1 km altitude grid used in the [O] retrieval. The last two columns of Tables 3–8 include the total magnitude of the errors, i.e. the uncertainty in all error components as in the worst case discussed in Sect. 6 and Table 1. The magnitude of the presented errors is typical of the entire data set.
The magnitude of the maximum error was estimated to be up to 60% on the daily timescale and up to 47% on the monthly timescale in the altitude range 90–100 km. We averaged the errors in the same altitude range and calculated the relative errors of each error component to the total error in percent, so that added partial errors result in 100% of the error (see the last two columns of Tables 3–8) for:
1. partial LER error components (see Sects. 3, 6.1 and Fig. 4) on daily and monthly timescale in the latitude bin 20–25° N compared to the partial errors typical of the entire data set averaged over 11 years:
- percent contribution of errors in tangent height registration to the total error is 6.4% (daily), 21.6% (monthly), and 16.5% (11 years) respectively,

AMTD
7, C4754–C4781, 2015

- percent contribution of limited radiometric accuracy values to the total error is 10.2%, 31.7%, and 23.9% respectively,
- percent contribution of spectrum integrating uncertainty values to the total error is 83.4%, 46.7%, and 59.6% respectively.

2. partial VER error components (see Sects. 4, 4.3, 6.1, 7.1 and Fig. 6) on daily and monthly timescale in the latitude bin 20–25° N compared to the partial errors typical of the entire data set averaged over 11 years:
- percent contribution of smoothing error to the total error is 9.8%, 8.7%, and 5.8% respectively,
- percent contribution of retrieval noise to the total error is 54.1%, 20.6%, and 28.4% respectively,
- percent contribution of parameter error to the total error is 24.3%, 46.4%, and 43.5% respectively,
- percent contribution of modelling error to the total error is 11.8%, 24.3%, and 22.3% respectively.

3. partial [O] error components (see Sects. 4, 4.3, 6.1, 7.1 and Fig. 8) on daily and monthly timescale in the latitude bin 20–25° N compared to the partial errors typical of the entire data set averaged over 11 years:
- percent contribution of VER smoothing error to the total error is 7.3%, 4.3%, and 3.4% respectively,
- percent contribution of VER retrieval noise to the total error is 37.1%, 12.1%, and 18.8% respectively,
- percent contribution of VER parameter error to the total error is 18.9%, 31.4%, and 31.9% respectively,
- percent contribution of VER modelling error to the total error is 9.1%, 15.8%, and 16.5% respectively,
- percent contribution of temperature uncertainty to the total error is 23.1%, 29.8%, and 24.2% respectively,
- percent contribution of density uncertainty to the total error is 4.5%, 6.6%, and 5.2% respectively.

The estimated magnitude of the maximum error (see the last two columns of Tables 3–8 in supplementary) is bigger than the magnitude of the root-sum-square (RSS) error for other satellite derivations of [O] (less than 25% for SABER (Mlynczak et al., 2013), and less than 44% for OSIRIS (Sheese at al., 2011)). Note that the maximum error could be equal to the RSS error if all absolute error components were equal, otherwise the estimation of maximum uncertainty results in a bigger error than an RSS error.

New Sect. "7.1 Results of error analysis" in manuscript: "The calculated uncertainty components in the retrieved VER profiles are represented by $\boldsymbol{LER}_{+1}$ and $\boldsymbol{LER}_{-1}$ in Fig. 6 with daily (Fig. 6a) and monthly (Fig. 6b) averaging within the latitude range 20–25° N. The distribution of uncertainty components in the retrieved [O] profiles is presented in Fig. 8 with daily (Fig. 8a) and monthly (Fig. 8b) averaging within the same latitude range. The magnitudes of the errors, which are typical of the entire data set, are listed in Tables 3–8 in the supplementary material. The estimated magnitude of the maximum error (up to 60% on the daily timescale and up to 47% on the monthly timescale in the altitude range 90–100 km, see the last two columns of Tables 3–8) is bigger than the magnitude of the root-sum-square (RSS) error for other satellite derivations of [O] (less than 25% for SABER (Mlynczak et al., 2013), and less than 44% for OSIRIS (Sheese at al., 2011)). Note that the maximum error can be equal to the RSS error if all absolute error components are equal, otherwise the estimation of maximum uncertainty results in a bigger error than an RSS error.

The averaged errors in the altitude range 90–100 km were used to calculate the relative errors of each error component to the total error, so that added partial errors result in 100% of the error (see the last two columns of Tables 3–8). The retrieval noise $\vec{\sigma}_{\mathbf{S}_\mathrm{m}}$ component is represented by relatively large coloured zones in Fig. 6 and in Fig. 8 and corresponds to 54% and 37% partial error, respectively. The corresponding coloured zone is smaller in the monthly averaged profiles (21% and 12%) because of a larger number of averaged profiles. The modelling error $\vec{\sigma}_{\mathbf{S}_\mathrm{f}}$ in VER and [O] profiles is relatively small (12% and 9% on the daily timescale as well as 24% and 16% on the monthly timescale, respectively) compared to the total uncertainty $\vec{\sigma}_{\mathbf{S}_{tot}}$ (100%)

AMTD

7, C4754–C4781, 2015

Interactive Comment

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Interactive Discussion

Discussion Paper

associated with the inversion procedure.
The [O] profile error associated with temperature errors assumes the highest values within the altitude range where the [O] peak occurs. Similar behaviour, but to a lesser extent, is characteristic for the [O] profile uncertainty caused by errors in atmospheric density (the sum of [O_2] and [N_2])."

Line 24: **what specifically is meant by "certain deviations"? And "shows" should be "exhibits". The figure starts at 85 km, but the range being discussed is 82–87 km (or is 82 a typo?).**
Response: We provide a cumulative response to the text on pages 10851–10853 below.

Page 10852
Lines 1-3: **Please specify what is meant by "much higher", "a bit higher ones", and "quite similar".**
Response: We provide a cumulative response to the text on pages 10851–10853 below.

Line 9: **Please specify what is meant by "quite similar".**
Response: We provide a cumulative response to the text on pages 10851–10853 below.

Lines 9-13: **This discussion seems to imply that the SABER measurements are considered to be of better quality than the model results. Please explain why the SABER measurements are preferred.**
Response: We did not imply that the SABER measurements are considered to be of better quality than the model results. The matter is that the retrieval of [O] profiles (based on them as different reliable sources of temperature and atmospheric density profiles) provides us with different results. For example, SABER temperature and density profiles cause the retrieved [O^{quench}_{SABER}] profiles to exhibit seasonal changes (see

AMTD
7, C4754–C4781, 2015

Sect. 7.5), but such seasonal changes are not so evident for the model results. Does that mean that SABER measurements are better than WACCM simulations? We are not in a position to make this claim, but the fact is that SABER measurements (affected by noise) differ from NRLMSISE-00 and SD-WACCM4 simulations (affected by their incompleteness as any formal model system). Which way is better depends on the case.

Lines 16-17: **How much SABER data is there for this time period? Is it biased to any season/region?**
Response: We used SABER measurements at 21:00–23:00 LT affected by yaw-cycles. This led to gaps in daily time series with active periods that are interrupted by breaks. Besides, active periods were dispersed in latitude in time intervals from one day to three weeks resulting typically in one week of continuous data. When daily averaged data were not available in the particular latitude bins we used in the [O] retrieval monthly averaged SABER data as stated in Sect. 7.5. SABER data shown in Fig. 14 suppose such substitution of daily data by monthly data provided, that in the same region SCIAMACHY VER data are available at this time as well.

Line 21: **Please specify what is meant by “even bigger”.**
Response: We provide a cumulative response to the text on pages 10851–10853 below.

Page 10853
Line 1: **“has to be” should maybe be “is”.**
Response: Our cumulative response to the text on pages 10851–10853 considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.
Changes in manuscript for Sections 7.2 and 7.3 on pages 10851–10852 and first line on the page 10853:
“7.2 Verification step 1
Figure 9 shows atomic oxygen concentration ($[O^{quench}_{SABER}]$) profiles and reference [O] profiles provided by SABER, NRLMSISE-00 and SD-WACCM4 in the altitude range

AMTD
7, C4754–C4781, 2015

85–105 km in the latitude bin 20–25° N for a sample day (9th September 2010) and month (September 2010). The altitude dependence of $[O^{quench}_{SABER}]$ in comparison with $[O^{SABER}]$, $[O^{MSIS00}]$ and $[O^{WACCM4}]$ exhibits some deviations in the altitude range 85–87 km. These deviations correspond to low values of the measurement response (see Fig. 5) in the altitude range 82–87 km. The comparisons shown in Fig. 9 allow to make the preliminary conclusion that SABER as the source of temperature and density profiles (which we need to retrieve [O] profiles from SCIAMACHY VER profiles) seems to be preferable.
Figure 9 allows the conclusion to be drawn that the reference $[O^{MSIS00}]$ profiles are characterized by lower concentrations in comparison with the retrieved $[O^{quench}_{SABER}]$ profiles. We use the absolute of the mean relative difference ($<|\epsilon|>$) determined according to the equation $<|\epsilon|>=<|([O^{current}]-[O^{reference}])/[O^{reference}]|>$ averaged over the altitude range 90–100 km to quantify differences between different [O] profiles. For $[O^{MSIS00}]$ ($[O^{current}]$) in comparison with $[O^{quench}_{SABER}]$ ($[O^{reference}]$) we obtain $<|\epsilon|>\approx$ 0.6 on the daily timescale and $\approx$ 0.54 on the monthly timescale. For $[O^{WACCM4}]$ in comparison with $[O^{quench}_{SABER}]$ we obtain $<|\epsilon|>\approx 0.27$ on the daily timescale and ≈ 0.24 on the monthly timescale. For $[O^{SABER}]$ in comparison with $[O^{quench}_{SABER}]$ we obtain $<|\epsilon|>$ ≈ 0.13 on the daily timescale and ≈ 0.14 on the monthly timescale.
Figures 10 and 11 (with data corresponding to the same altitude, latitude and time ranges as in Fig. 9) present [O] profiles retrieved from SCIAMACHY VER profiles according to the cubic ($[O^{cubic}]$) and extended cubic ($[O^{quench}]$) approaches (see Eq. 15), and show that $[O^{quench}]$ concentrations are higher than the $[O^{cubic}]$ concentrations. $<|\epsilon|>$ for $[O^{cubic}_{WACCM4}]$ in comparison with $[O^{cubic}_{SABER}]$ is about 0.02 on the daily and monthly timescale. $<|\epsilon|>$ for $[O^{cubic}_{MSIS00}]$ in comparison with $[O^{cubic}_{SABER}]$ is about 0.05 on the daily timescale and 0.06 on the monthly timescale. $<|\epsilon|>$ for $[O^{quench}_{WACCM4}]$ in comparison with $[O^{quench}_{SABER}]$ is about 0.05 on the daily timescale and 0.02 on the monthly timescale. $<|\epsilon|>$ for $[O^{quench}_{MSIS00}]$ in comparison with $[O^{quench}_{SABER}]$ is about 0.13 on the daily timescale and 0.11 on the monthly timescale. This leads to the preliminary conclusion that NRLMSISE-00 does not seem to be a reliable source of temperature and density

AMTD
7, C4754–C4781, 2015

profiles. A comparison between Figs. 9, 10 and 11 indicates that $[O^{quench}_{SABER}]$ profiles are (by sight) in better agreement with $[O^{SABER}]$ profiles than $[O^{cubic}]$ profiles are. This implies that the extended cubic equation seems to be preferable for the retrieval of [O] profiles.
7.3 Verification step 2
Relative differences (ϵ) between different [O] profiles were calculated according to the equation $\epsilon = ([O^{current}]-[O^{reference}])/[O^{reference}]$. Figure 12 presents sample distributions of relative [O] differences as a function of latitude and altitude in the time period from April 2010 to March 2011 which corresponds to SD-WACCM4 data that we had in our disposition.
Provided that $< |\epsilon| >$ in the following text is averaged over altitude range 86–100 km, over the latitude range 50° S–70° N and over the time period from April 2010 to March 2011, we find that $< |\epsilon| >$ for $[O^{cubic}_{MSIS00}]$ ($[O^{current}]$) in comparison with $[O^{MSIS00}]$ ($[O^{reference}]$) is about 0.81 on the monthly timescale. The mean absolute relative difference between $[O^{quench}_{MSIS00}]$ and $[O^{MSIS00}]$ (not shown in Fig. 12) of $< |\epsilon| > \approx 1.74$ is at least twice as big as the value for $[O^{cubic}_{MSIS00}]$ vs. $[O^{MSIS00}]$. The mean absolute relative difference between $[O^{quench}_{WACCM4}]$ and $[O^{WACCM4}]$ (not shown in Fig. 12) is ≈ 0.65. $< |\epsilon| >$ for $[O^{cubic}_{WACCM4}]$ in comparison with $[O^{WACCM4}]$ is about 0.24 and exhibits the same anomaly cluster with high negative $< |\epsilon| >$ of unknown origin in the subtropical region as for $[O^{quench}_{WACCM4}]$ vs. $[O^{WACCM4}]$. For $[O^{quench}_{SABER}]$ in comparison with $[O^{SABER}]$ we obtain $< |\epsilon| > \approx 0.19$, which is smaller than $< |\epsilon| >$ for $[O^{cubic}_{SABER}]$ vs. $[O^{SABER}]$ of about 0.28."

Lines 1-4: Can you justify that SABER is the better source for reference profiles? What is the reason for doubting MSIS density/temperature profiles in this region? SDWACCM profiles should also be reliable. Can you please comment on this?

Response: SABER [O]/density/temperature profiles in our case seem to be at least more preferable than those from SD-WACCM4 or NRLMSISE-00:
1. $[O^{MSIS00}]$ profiles exhibit a 180 degree phase shift compared to OSIRIS [O] (Sheese

AMTD
7, C4754–C4781, 2015

et al., 2011) measurements and somewhat similar to 180 degree phase shift of the seasonal variation compared to [O^{quench}_{MSIS00}] retrievals (see Sects. 7.4).
2. SD-WACCM model results are known for low-bias in O_3 in the MLT region, therefore also low-bias in O.
3. The presented retrieval of [O] profiles supposed that temperature and atmospheric density profiles were to be taken from different available sources such as direct on board SABER measurements, or NRLMSISE-00 and SD-WACCM4 simulations. Sample distributions of relative (retrieved vs. reference) [O] differences were estimated as a function of latitude and altitude in Sect. 7.3 and shown in Fig. 12. The verification enables a conclusion that the relative differences of [O^{quench}_{SABER}] vs. [O^{SABER}] (-0.1 to 0.1) are smaller than those of [O^{quench}_{MSIS00}] vs. [O^{MSIS00}] (0.4 to 3.4), [O^{cubic}_{MSIS00}] vs. [O^{MSIS00}] (-0.1 to 2.1) and [O^{cubic}_{SABER}] vs. [O^{SABER}] (-0.4 to -0.1) as well as [O^{cubic}_{WACCM4}] vs. [O^{WACCM4}] (-0.3 to 0.3) in the ranges 50°S–50°N and 88–98 km except of the small region near the equator.
Changes in manuscript: "If we assume the SABER [O] retrievals to be the most reliable reference profile source - compared to NRLMSISE-00 and SD-WACCM4 - then our comparison results favor the extended cubic equation over the cubic equation." has been changed to "This enables the preliminary conclusion that NRLMSISE-00 is not an adequate source of [O] profiles. We use SABER temperature and density profiles for future analysis and the extended cubic approach to retrieve [O] profiles."

Line 13: **Please quantify what is meant by "very good".**
Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.
Changes in manuscript: "Since the photochemical model employed by Kaufmann et al. (2014) is essentially the one by McDade et al. (1986) - corresponding to our [O^{cubic}_{SABER}] data set (see lower left panel of Fig. 12) - the agreement between the Kaufmann et al. (2014) retrievals and the our retrievals is very good." has been changed to "Since the photochemical model employed by Kaufmann et al. (2014) is essentially the one

AMTD
7, C4754–C4781, 2015

by McDade et al. (1986) - corresponding to our [O^{cubic}_{SABER}] data set (see lower left panel of Fig. 12) - we come to a conclusion as Kaufmann et al. (2014): our SCIAMACHY [O^{cubic}_{SABER}] retrievals are at least 30% lower in comparison with [O^{SABER}]."

Section 7.4: are you simply multiplying the correlation coefficient by 100 in order to express it as a percent? If so, why is this being done instead of using values between -1 and 1?
Response: Yes, the correlation coefficients (Section 7.4, Figure 13) were multiplied by 100 in order to express them in percentage, which was meant more convenient. We multiplied the relative differences by 100 in order to express them as a percent because of the same reason.
Changes in manuscript: Figures 12-13 (enclosed) on pages 10878–10879 are changed in accordance with the referee's proposition in order to express the correlation coefficient using values between -1 and 1.

Line 24: even though the correlation coefficient values are significant, a value of -0.3 is not at all a strong anti-correlation. Can you really deduce a 180 degree phase shift from such a weak correlation?
Response: The correlation coefficient value of -0.3 obtained for a large number (≈ 365) of data points is significant. The correlation coefficients in their dependence on altitude and longitude are presented in Fig. 13 with help of colour spectrum in such a way that negative values correspond to shades of blue colour and positive values - to shades of colours from green to brown. As a result, Fig. 13 looks like a map representing the land relief with "lakes" (negative zones) and "mountains" or "plains" (positive zones). With such a map you can see that the marked -0.3 value of anti-correlation (top left panel in Fig. 13) is not the total minimum of the anti-correlation. In fact, correlation coefficients are in the range from moderate correlation (-0.46 value of anti-correlation at 10°N) to strong correlation (0.93 value of correlation at 20°S). The presence of somewhat similar to 180 degree phase shift can be deduced from the fact that there is a meridional gradient from a strong correlation in the southern

AMTD
7, C4754–C4781, 2015

Interactive Comment

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Interactive Discussion
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hemisphere to a moderate anti-correlation in the northern hemisphere.

Page 10854

Lines 3-6: Are there any physical reasons that could explain why this is the case?

Response: We currently have no explanation for this effect.

Lines 13-14: The daily SABER correlation values aren't much higher than 30% (again, I assume this means a correlation coefficient of 0.3). These are quite weak values that would indicate essentially no correlation. Does this not indicate that either one or both data sets (SCIA, SABER) are too noisy on a daily timescale to make these types of comparisons?

Response: Our comparisons on a daily timescale are reasonable:
1. Considering the number of days within the time period from April 2010 to March 2011 even the correlation coefficients of 0.3 are highly significant.
2. The patterns of daily and monthly SABER correlation values are quite similar by sight (see bottom left and bottom right panels in Fig. 13 on page 10879). This means that data sets ($[O^{quench}_{SABER}]$, $[O^{SABER}]$) are not so noisy on a daily timescale not to make the comparisons.
However, we agree that SCIAMACHY [O] profiles on a daily timescale are noisier than those on a monthly timescale. In any case, a single spectrum of an orbital measurement is too noisy to be used for the retrieval.
Changes in manuscript: "We note that both for the monthly and daily averaged data there appears an altitude range with relatively high correlation coefficients - between about 88 and 95 km." has been changed to "We notice the presence of relatively high correlation coefficient values in the altitude range 88–95 km for monthly averaged $[O^{quench}_{SABER}]$ vs. $[O^{SABER}]$. The distribution of correlation coefficient values for monthly and daily averaged data are quite similar by sight (see bottom left and bottom right panels in Fig. 13)."

AMTD
7, C4754–C4781, 2015

Page 10855
Line 26: **Which earlier studies are you referring to?**
Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.
Changes in manuscript: "earlier studies, and" has been changed to "earlier studies (e.g., Liu and Shepherd, 2008; von Savigny and Lednyts'kyy, 2013), and"
Liu and Shepherd (2008):
Liu, G. and Shepherd G. G.: An investigation of the solar cycle impact on the lower thermosphere $O(^1S)$ nightglow emission as observed by WINDII/UARS, Adv. Space Res., 42, 933–938, doi:10.1016/j.asr.2007.10.008, 2008.

Page 10856
Lines 10-17: **Please briefly summarize your error analysis results.**
Changes in manuscript: "A comprehensive sensitivity analysis was carried out to determine the effect of various error contributions occurring at the different steps of the [O] profile retrieval including the effect of errors in tangent height registration, limited radiometric accuracy, the impact of measurement errors, parameter errors and smoothing errors. Using the sensitivity analysis results an error budget for the [O] profile retrievals from SCIAMACHY green line nightglow observations was established based on successive linear addition of the estimated uncertainty components in order to avoid any assumptions concerning distributions of model parameters and other error components." has been changed to "A comprehensive sensitivity analysis was carried out to determine the effect of various error contributions occurring at the different steps of the [O] profile retrieval. Using the sensitivity analysis results an error budget for the [O] profile retrievals from SCIAMACHY green line nightglow observations was established based on successive linear addition of the estimated uncertainty components in order to avoid any assumptions concerning distributions of model parameters and other error components. The errors were averaged in the altitude range 90–100 km and partial contributions of each error component relative to the total error were calculated in percent (added partial errors result in

100% of the error shown in the last two columns of Tables 3–8 in the supplementary material). At the retrieval step resulting in LER profiles (see Sects. 3 and 6.1) the maximum uncertainty calculation includes the effect of errors in tangent height registration (partial contribution of 21.6% for September 2010 to the total error in percent), limited radiometric accuracy (partial contribution of 31.7%), and spectrum integrating uncertainties (partial contribution of 46.7%). At the retrieval step resulting in VER profiles (see Sects. 4, 4.3, 6.1 and 7.1) the maximum uncertainty calculation includes the impact of modelling errors (partial contribution of 24.3% for September 2010), parameter errors (partial contribution of 46.4%) measurement errors (partial contribution of 20.6%), and smoothing errors (partial contribution of 8.7%). At the retrieval step leading to [O] profiles (see Sects. 5, 6.2, 7.1) the maximum uncertainty calculation includes the impact of modelling errors (partial contribution of 15.8% for September 2010), parameter errors (partial contribution of 31.4%), measurement errors (partial contribution of 12.1%), smoothing errors (partial contribution of 4.3%), temperature uncertainty values (partial contribution of 29.8%), and density uncertainty values (partial contribution of 6.6%)."

Lines 18-25: **There is no mention of comparison results with WACCM.**
Changes in manuscript: "The retrieved [O] profiles were compared to simulations with NRLMSISE-00 and SDWACCM and observations with SABER. The comparisons showed that NRLMSISE-00 [O] concentrations are systematically lower than data from the three other sources. Moreover, the SCIAMACHY [O] profiles are in good agreement with co-located SABER observations, if the extended photochemical model - considering quenching of $O(^1S)$ by $O(^3P)$ or N_2 - is used. This is an indication, that the extended photochemical model is more appropriate for retrieving [O] profiles from the O green line emission than the standard photochemical model." has been changed to "The retrieved [O] profiles were compared to simulations with NRLMSISE-00 and SD-WACCM4, and to observations with SABER. The comparisons showed that NRLMSISE-00 [O] concentrations are significantly lower than the other ones.
Seasonal variations found in atomic oxygen anomalies in SABER and SCIAMACHY

data sets are not so evident in SD-WACCM4 model simulations. The SCIAMACHY [O] profiles are in better agreement with co-located SABER observations when the extended photochemical model - considering quenching of $O(^1S)$ by $O(^3P)$ or N_2 - is used. This is an indication that the extended photochemical model is more appropriate to retrieve [O] profiles from the O green line emission than the standard photochemical model."

Table 1, last line of caption: delete "in".
Changes in manuscript: "further in details." has been changed to "further details."

Figures: Units should be in parentheses to avoid confusion (especially when plotting scaled densities).
Changes in manuscript: Figures 3-15 (enclosed) on pages 10869–10881 are changed in accordance with the referee's proposition: units are in parentheses now to avoid confusion (especially when plotting scaled densities).
Changes in manuscript on page 10872: "and calculated for the $\boldsymbol{LER}_{-1}$ retrieval." has been changed to "and calculated for the $\boldsymbol{LER}_{-1}$ retrieval. See Sects. 4, 4.3, 6.1 and 7.1 for further details."

Figure 2: "related to contaminating".
Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.
Changes in manuscript: "related contaminating" has been changed to "related to contaminating"

Figure 3: How many scans are included in the averaging? This should also be mentioned in the main text.
Changes in manuscript: "Sample daily (a) and monthly (b) averaged green line emission spectra at 95 km altitude for" has been changed to "Sample daily (a) and monthly (b) green line emission spectra (calculated upon averaging of 12 (a) and 480

AMTD
7, C4754–C4781, 2015

(b) orbital spectral measurements) at the altitude of 95 km for"
Changes in manuscript on page 10838, lines 6-8: "Figure 3 presents sample daily and monthly averaged spectra at 95 km altitude within the latitude range 20–25° N." has been changed to "Figure 3 presents sample daily (a) and monthly (b) spectra that are calculated upon averaging of 12 (a) and 480 (b) orbital spectral measurements at the altitude of 95 km in the latitude range 20–25° N."

Figure 7: Caption should explain the meaning of the shaded/non-shaded regions.
Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.
Changes in manuscript: "the identification of the optimal regularization parameter γ_r. The cross-validation (CV) function" has been changed to "the identification of the optimal regularization parameter γ_r. Shading (with vertical blue lines) of the regions in the range of possible regularization parameters means their rejection from the retrieval, absence of shading means their acceptance. The cross-validation (CV) function"

Figure 9: To avoid confusion, could label the SCIAMACHY data as "SCIA [O] (VER+SABER)".
Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.
Changes in manuscript: Figures 9-11 (enclosed) on pages 10875–10877 are changed in accordance with the referee's propositions.

Figures 9-11: The x-axis is expanded far beyond the maximum [O] values, presumably to fit the legend in the top right corner. The plots would be much easier to read if the x-axis was limited to 12×10^{11} atoms/cm and the legend was more strategically placed. Also, to avoid confusion, could label the SCIAMACHY data as "SCIA [O] ...".

Response: Our response considers the interactive comments of the Anonymous Referee #1 and the Anonymous Referee #2.

Changes in manuscript: Figures 9-11 (enclosed) on pages 10875–10877 are changed in accordance with the referee's propositions.

AMTD

7, C4754–C4781, 2015

Interactive Comment