SCIAMACHY SOLAR AND LUNAR OCCULTATION: VALIDATION OF OZONE, NO_2 AND NO_3 PROFILES

L. K. Amekudzi, K. Bramstedt, A. Bracher, A. Rozanov, H. Bovensmann, and J. P. Burrows

Institute of Environmental Physics and Remote sensing (IUP/Ife),
University of Bremen, Otto-Hahn-Allee 1, 28334 Bremen, Germany

ABSTRACT

Using a global spectra fitting method by the differential optical depth within the radiative transfer and retrieval code SCIATRAN 2.1, vertical profiles of stratospheric traces gases are derived from SCIAMACHY solar and lunar occultation transmission spectra. From solar occultation observations ozone and NO_2 profiles have been retrieved, from lunar occultation measurements ozone, NO_2, and NO_3 profiles have been derived. To access the quality of the SCIAMACHY occultation retrieved products a validation study was carried out, by comparing the retrieved ozone and NO_2 profiles to correlative observations of other satellite instruments. These instruments are the Halogen Occultation Experiment (HALOE), the second Stratospheric Aerosol and Gas Experiment (SAGE II), and The third Polar Ozone and Aerosol Measurement (POAM III) . The NO_3 profiles are compared with results from a photochemical model scheme. The validation show good results for SCIAMACHY occultation products. In solar occultion, the deviation of ozone is mostly within 0 % to +10 % for ozone and within 20 % for NO_2 over a wide altitude range. In lunar occultation, the agreement is +10% to +20 % for ozone and within 20 % for NO_2 in the main part of the profiles. The NO_3 results show good agreement with the model outputs within the accuracy of 35 %.

Key words: Stratospheric ozone; NO_2; NO_3; validation; SCIAMACHY; occultation.

1. INTRODUCTION

SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) is a passive remote sensing moderate-resolution imaging UV-Vis-NIR spectrometer on board the European Space Agency's (ESA) Environmental Satellite (ENVISAT), launched in March 2002 from Kourou, French Guiana. The instrument observes the Earth atmosphere in Nadir, limb and solar/lunar occultation geometries and provide column and profile information of atmospheric trace gases of relevance to ozone chemistry, air pollution, and climate monitoring issues (Bovensmann et al., 1999).

Since 2002 SCIAMACHY has been making observations of sunrise event in every orbit over the northern hemisphere (49^o N–70^o N depending on season, see Figure 1) using the well-established and proven solar occultation technique, with a total of approximately 14 events per day. The SCIAMACHY solar occultation measurements are performed in sun scanning mode. Usually the sun disk is scanned permanently, while spectral measurements are performed every 62.5 msec. Only directly transmitted light contributes significantly in occultation geometry. Transmissions are calculated dividing atmospheric measurements by an appropriate measurement from above the atmosphere. Due to the sun fixed orbit and the position of SCIAMACHY on ENVISAT, the instrument is not able to measure the sunset events in the southern hemisphere. However, during local nighttime in the southern latitudes (30^o S–90^o S) SCIAMACHY performs lunar occultation measurements. The lunar occultation observations begin when the phase of the Moon is 0.6–0.7 and end shortly after full moon. The measurements are performed 6–8 days per month and 4–8 months in a year (see Figure 1). These measurements are performed in moon pointing mode, usually starting around 17 km the moon is followed up to 100 km tangent height with a vertical resolution of approximately 2.5 km. The integration time for the lunar occultation measurements is 1.0 s and the horizontal resolution is 30 km across track and extending approximately 400 km along track. Detailed information on SCIAMACHY occultation measurements are provided in Meyer (2004); Meyer et al. (2005) (solar occultation) and Amekudzi et al. (2005b); Amekudzi (2005) (lunar occultation).

The SCIAMACHY occultation measurements are expected to provide vertical profiles information of trace gases (O_3, NO_2, BrO, ClO, OClO, OBrO and NO_3) that contribute significantly to stratospheric ozone chemistry. In solar occultation ozone and NO_2 has been measured (Meyer, 2004) and from the lunar occultation spectroscopic observations ozone, NO_2 and NO_3 have been inferred (Amekudzi, 2005). In this paper we are reporting on the validation preformed to access the quality of the retrieved scientific products from both solar and lunar occultation measurements. We will provide information on the improved SCIAMACHY occultation retrieval scheme

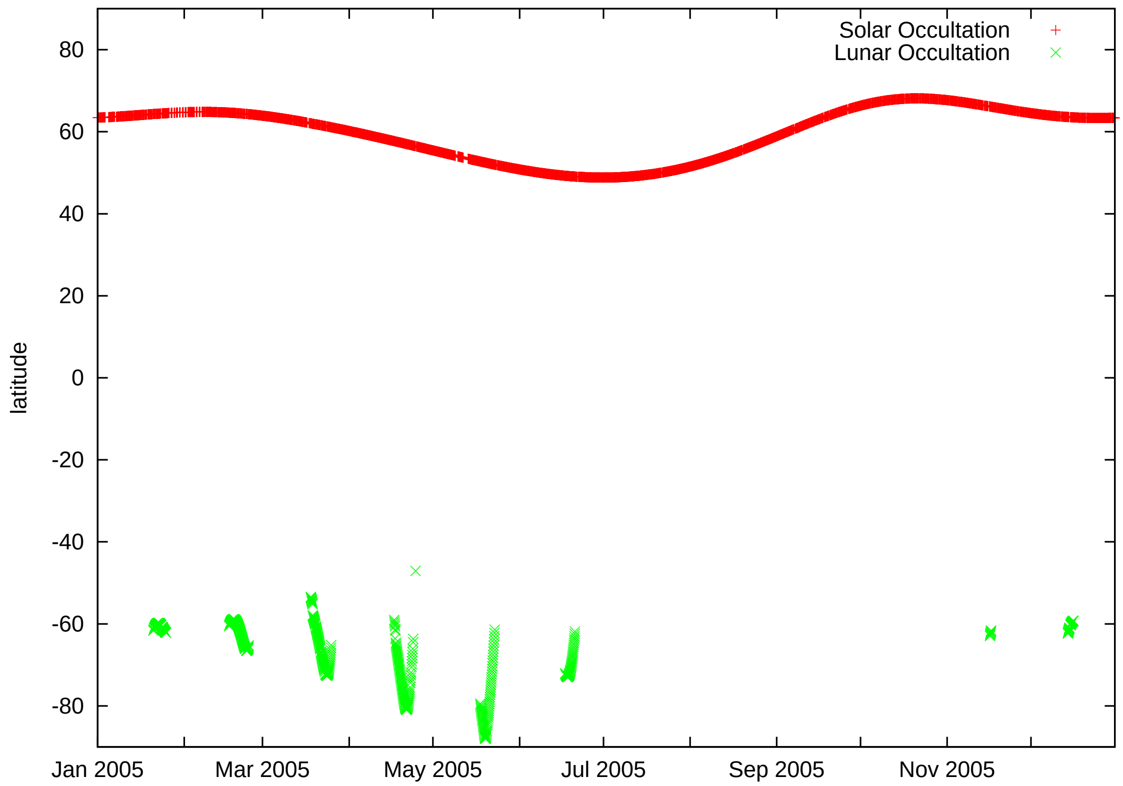

Figure 1. Latitudinal distribution of SCIAMACHY solar and lunar occultation measurements in 2005. Solar occultation measurements marked in red, lunar measurements in green.

and the validation data set. We will then present the available occultation validation results at the time of writing this paper.

2. DATA ANALYSIS PROCEDURE

2.1. Tangent height determination

Uncertainties in the viewing direction are a prominent error source in the retrieval of trace gas profiles from SCIAMACHY limb and occultation measurements. In the case of solar occultation, we use the sun as well known target in space to derive a very precise knowledge of the viewing direction. For lunar occultation the moon as fixed target is used, but the procedure to derive the tangent heights is less precise. All retrieval results presented in this paper use corrected tangent heights.

Figure 2 illustrate the scanning sequence of the usual solar occultation measurements. In the first part, SCIAMACHY scans the estimated sunrise region above the horizon. When the geometric centre of the sun reaches a tangent height of 17.2 km, the FOV starts to move up with a pre-calculated elevation rate up to an altitude of about 290 km. During the whole sequence, the sun is scanned up and down over the full solar disk.

The scanning sequence above the atmosphere (without refraction effects) is used to determine the exact position of the top and bottom edge of the sun, from which easily the centre of the solar disk can be derived. The measured intensities over one scan across the solar disk are fitted with a 4th order polynomial, the zeros of this polynomial give the upper and lower boundary of the solar disk with a precision about 10 times smaller than the height of the field of view (FOV).

Using the ENVISAT Orbit propagator software CFI (ESA, 2006) and the actual orbit parameters delivered with each SCIAMACHY product, the precise tangent altitude above Earth's surface for the line satellite – centre of the solar disk can be calculated for each position in orbit. Therefore, we can calculate directly a precise tangent height at the time SCIAMACHY is pointing to the centre of the solar disk. The difference between this true tangent height and the one given in the product (calculated from the mirror positions and the (uncertain) satellite attenuation) for that time gives a precise tangent height correction, which is used during profile retrieval.

During lunar occultation, SCIAMACHY is pointing to the moon. The viewing direction is adjusted by the sun/moon follower towards the brightest point on the moon. With the assumption, that the brightest point is at the centre of the moon, we can also derive tangent

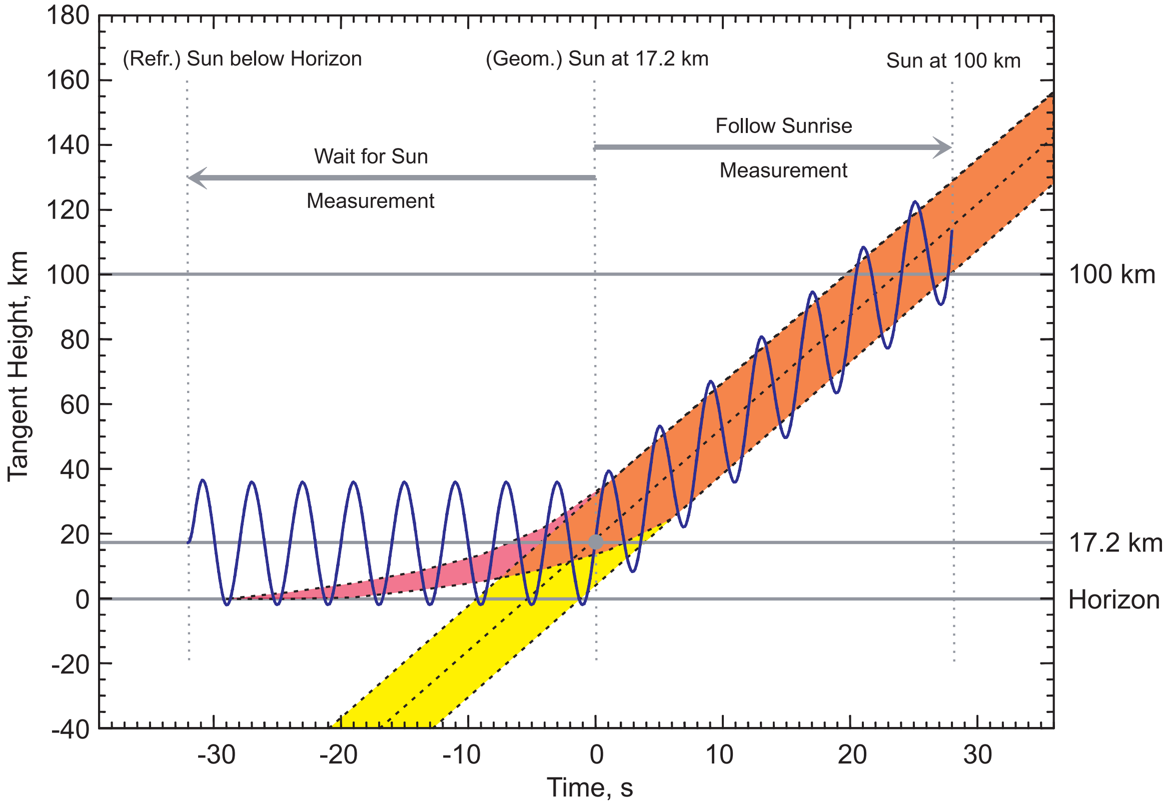

Figure 2. Schematic view of a solar occultation measurement sequence. Tangent height in km is plotted vs. time in seconds. The blue line represents the movement of SCIAMACHY's FOV, the shaded areas illustrate the refracted and the imaginary true Sun, respectively.

heights using the CFIs. In vertical direction, this assumption is reasonable, but the accuracy of the derived tangent heights have to be further investigated.

2.2. Retrieval scheme

Scientific SCIAMACHY occultation products to the best of our knowledge are only retrieved at IUP/IFE, University of Bremen. The first published version (i.e version 2.1) reported in Meyer (2004) and Amekudzi (2005) uses the GOMETRAN occultation version radiative transfer model for computing the atmospheric radiance and its Jacobian. In addition, version 2.1 products were derived from SCIAMACHY occultation level-0 (un-calibrated) data, and a-priori trace gases profiles and temperature were taken from the US standard atmosphere (NASA, 1976). The current products, version 2.2, uses the SCIATRAN version 2.1 radiative transfer code (Rozanov et al., 2005) for the forward modelling and the retrieval. The global fitting method coupled with the differential optical depth approach is used to fit simultaneously NO_2 and ozone in the spectral window of 430–460 nm and 520–580 nm respectively at the spectral resolution of the SCIAMACHY instrument. In the current retrieval scheme, the a priori trace gases profiles are taken from the MPI data base. In solar occultation the Fortuin and Kelder ozone climatology (Fortuin and Kelder, 1998), for lunar occultation ECMWF analysis temperature and pressure information are used. In addition, the current products are inferred from level-1b version 5.04 data and a different method (described in section 2.1) is used to correct the tangent height information.

The nitrate radical, NO_3, has two strong absorption peaks, i.e. absorption band at 623 and 662 nm. We utilized both absorption bands to retrieve number density profile of NO_3. The absorption bands near 623 nm and 662 nm, however have significant contributions from other absorbers such as O_3, O_2, O_4, and H_2O. To accurately fit and retrieve NO_3 profiles, these strong absorbers were fitted in addition to NO_3. As O_2 and H_2O are line absorber, their absolute cross sections were calculated using line-by-line spectral simulation code. Broadband absorption features of the atmosphere and instrument from the measured spectrum were removed by subtracting a third order polynomial. Furthermore, NO_2, O_3, and NO_3 profiles are retrieved using the optimal estimation method described in Rodgers (1976, 2000). Smoothing constraint parameters (Twomey-Tikhonov regularisation) are applied to smooth the retrieved profiles.

Table 1. Number of co-location of SCIAMACHY occultation measurements with satellite instruments HALOE, SAGE II and POAM used in this paper.

	used co-locations			
	solar (< 500 km)		lunar (< 1000 km)	
Instrument	O_3	NO_2	O_3	NO_2
HALOE	129	117	80	44
SAGE II	230	225	92	—
POAM	—	—	41	—

3. THE SATELLITE INSTRUMENTS HALOE, SAGE II AND POAM III

HALOE was launched on the Upper Atmosphere Research Satellite (UARS) spacecraft in September 1991, operations stopped in November 2005. The experiment uses solar occultation to measure vertical profiles of ozone and other trace gases. Version 17 of the HALOE ozone products were extensively validated against ground based and airborne ozone measurements as well as satellite measurements Brühl et al. (1996). In most cases, the relative deviation was below 10 % in the stratosphere and the lower mesosphere. A comparison of HALOE version 18 ozone profiles with SAGE II measurements showed an even better agreement than with version 17, mainly in the lower stratosphere Jianjun et al. (1997). For this work, the current version 19 of HALOE data was used.

The solar occultation instrument SAGE II which was launched on the Earth Radiation Budget Satellite (ERBS) in October 1984 and stopped operation in August 2005. For ozone, an uncertainty of less than 10 % in the altitude range 15 – 60 km is give in Cunnold et al. (1989). In this paper, the current version 6.2 is used for the comparisons.

The Polar Ozone and Aerosol Measurement III (POAM III) is carried by the SPOT-4 spacecraft sponsored by the Centre National d'Etudes Spatiales (CNES), launched in March 1998. The instrument failed on December 2005. For ozone, an accuracy of about 5 % to 10 % from 20 – 60 km was derived in Lucke et al. (1999). POAM III also used solar occultation geometry, in this paper, version 4 of the POAM product is used.

Table 1 lists the number of co-location used in this study for the validation of the SCIAMACHY's lunar and solar occulation profiles.

4. SOLAR OCCULTATION

Solar occultation measurements are performed each orbit at Northern latitudes when ENVISAT, coming from the nightside observes a sunrise (whereas a viewer at the tangent point has a sunset!). Until the end of 2005, 13209 occultation measurements are available. Within this dataset, all co-locations with less than 500 km distance between the tangent points and with not more than 12 hours time difference are used for the validation results presented here. As the NO_2 concentration has a diurnal cycle, here the comparisons are restricted to the sunset measurements of HALOE and SAGE-II, therefore the local time at the tangent points within the comparisons is always at sunset. Thus, no photochemical correction is needed here, in contrast to NO_2 profiles from SCIAMACHY lunar occultation or limb measurements.

All coincidences with HALOE are found in September only with latitudes around 60° N . Therefore, we divided the HALOE comparisons into yearly sets from 2002 to 2004. No matches are available in 2005, as HALOE operations are already limited at that time. In case of SAGE II, the matches are better distributed over the year, so we could separate into seasonal sets: January to March, April to June and July to September, no matches are available for October to November. The seasons also differ in latitude, compare Figure 1.

Figure 3 and Figure 4 show the validation results for ozone profiles. In case of HALOE, for all years we have a very good agreement from 17 km up to 50 km with deviations mostly below 10 %. In general, SCIAMACHY shows 0–10 % higher ozone values than HALOE. For two seasons, SAGE II gives similar results: For January – March and July – September the deviation from 17 km up to 50 km, respectively 17 km up to 47 km is mostly within 10 %. However, for April – June SCIAMACHY shows about 10 % to 18 % higher ozone concentrations than SAGE II. The reasons for this behaviour has to be investigated.

In Figure 5 and Figure 6, the validation results for NO_2 profiles are given. HALOE has no matches of sunset measurement for 2002. For 2003 and 2004, above 24 km the agreement is within 20 %. Below this altitude, SCIAMACHY shows higher values up to 100 %. For SAGE II, in January – March season, the profiles of the two instrument match almost completely within 20 % up to an altitude of 38 km. For July – September, the dataset agree within 20 % for between 22 km and 38 km. Again, the season April to June has worse results: between 30 km and 37 km, SCIAMACHY shows up 40 % higher NO_2 concentrations than SAGE II. The unusual form of the mean SCIAMACHY profile for this season indicates a problem in our SCIAMACHY retrieval, which has to be investigated. For April – June and July – September, at the lower altitudes (below 22 km) SCIAMACHY shows lower concentration than SAGE II, which is in contrast to the HALOE results (also in September!). We have to investigate further independent measurement to judge the quality of our profiles at the lowest altitudes, as the used satellite occultation instruments are also less sensitive here.

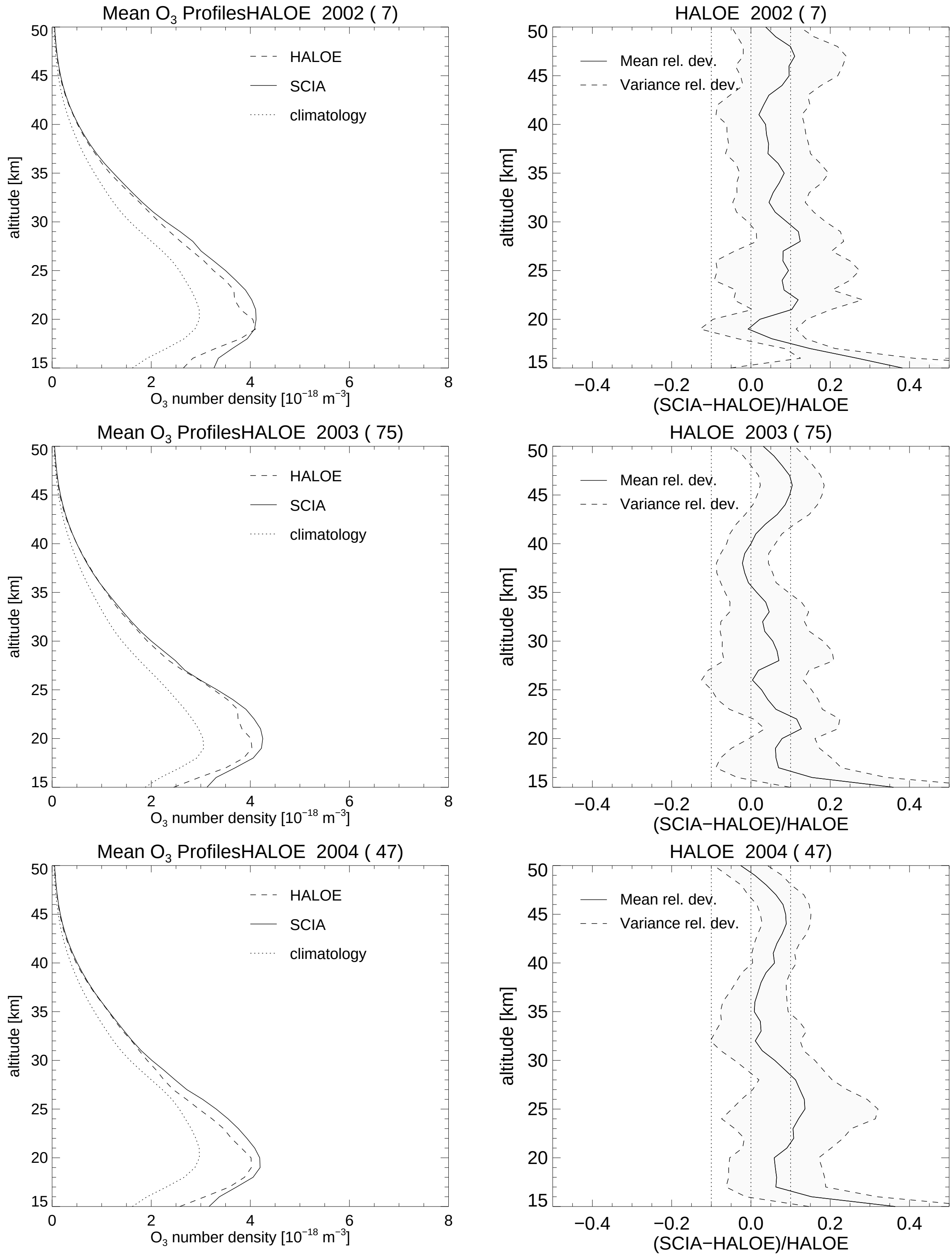

Figure 3. Validation results of ozone profiles from SCIAMACHY solar occultation with HALOE. Left column shows the mean profiles of the dataset (climatology is the a-priori profile used in the SCIAMACHY retrieval). Right column shows the mean relative deviation and its variance. From top to down: 2002 with 7 co-locations, 2003 with 75 co-location and 2004 with 47 co-locations.

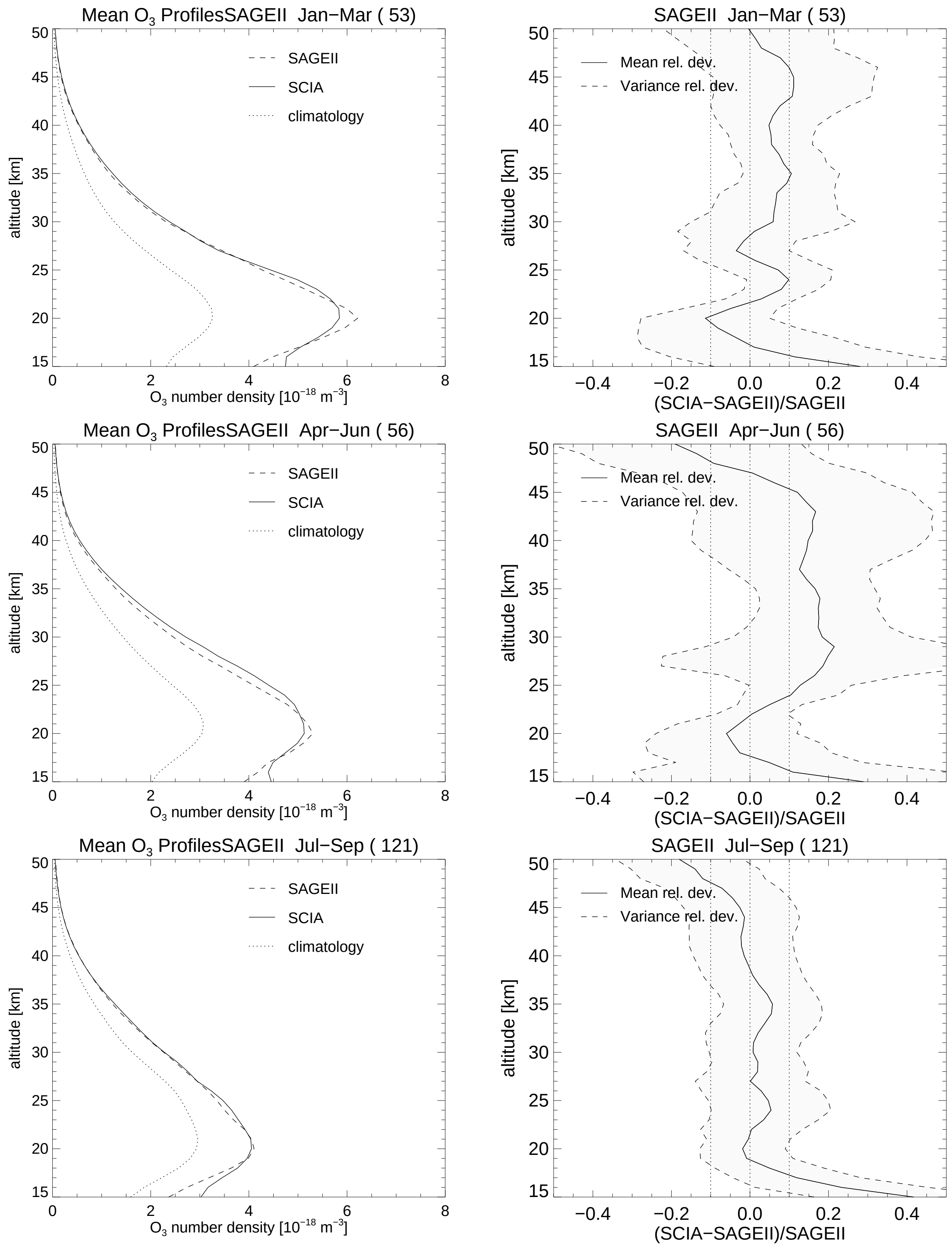

Figure 4. Validation results of ozone profiles from SCIAMACHY solar occultation with SAGE II, like Figure 3. From top to down: season January to March with 53 co-location, season April to June with 56 co-locations and season July to September with 121 co-locations.

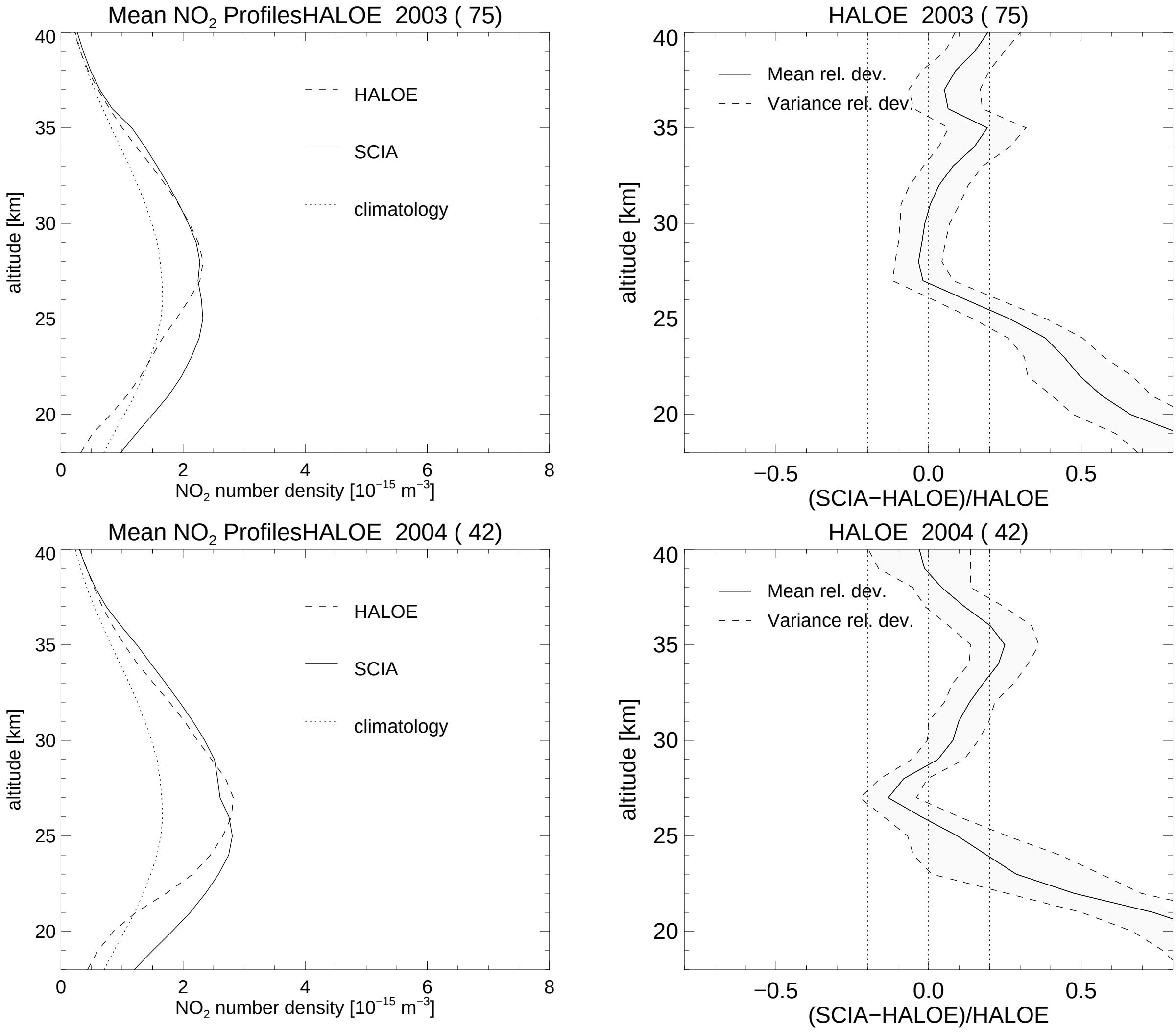

Figure 5. Validation results of NO_2 profiles from SCIAMACHY solar occultation with HALOE, like Figure 3. From top to down: 2003 with 75 co-location and 2004 with 42 co-locations.

5. LUNAR OCCULTATION

The co-location criteria applied for lunar occultation (ozone and NO_2) validation is with a distance less than 1000 km and within 12 hours.

The SCIAMACHY–HALOE validation presented here is based on 80 correlative measurements , 28 coincidences in 2003 and 52 for 2004. The mean profiles of the SCIAMACHY-HALOE validation is shown in Figure 7 In general we find good agreement with a slightly positive bias in their mean profiles. For the 2004 results, an altitude offset of approximately 1 km is observed near the ozone maximum. The mean relative deviations (rmd) and the standard deviations (rms) of the relative deviations for each year are displayed in Figure 8. The rmd are between -5 to +15 % in the altitude range of 18–45 km. The rms of the relative deviations are often less than 25 %.

Within a maximum distance of the tangent points of 1000 km, 92 correlative measurements are found and used for a statistical analyses of the SCIAMACHY–SAGE II comparison, plotted in Figure 9. Above 22 km, both instruments fit very well within -5 to +10 % mean difference. Below 22 km the SCIAMACHY instrument gives slightly lower ozone number density values. The rms of the relative deviations are around 10 % to 25 % in the altitude range of 22–42 km.

For the SCIAMACHY–POAM III comparison, up to now only a 2003 dataset is used. The statistics of the validation carried out with POAM III instrument are presented in Figure 10. In general, we found very good agreement above 22 km, with mean relative deviations between -5 % to +5 %. The rms of the relative deviations are within 5 % to 20 % between the altitude range of 20–45 km.

NO_2 in the stratosphere is a relatively short-lived trace gas, and it has a significant diurnal variability, which makes validation of NO_2 measurements difficult. In particular, as SCIAMACHY in lunar occultation mode mea-

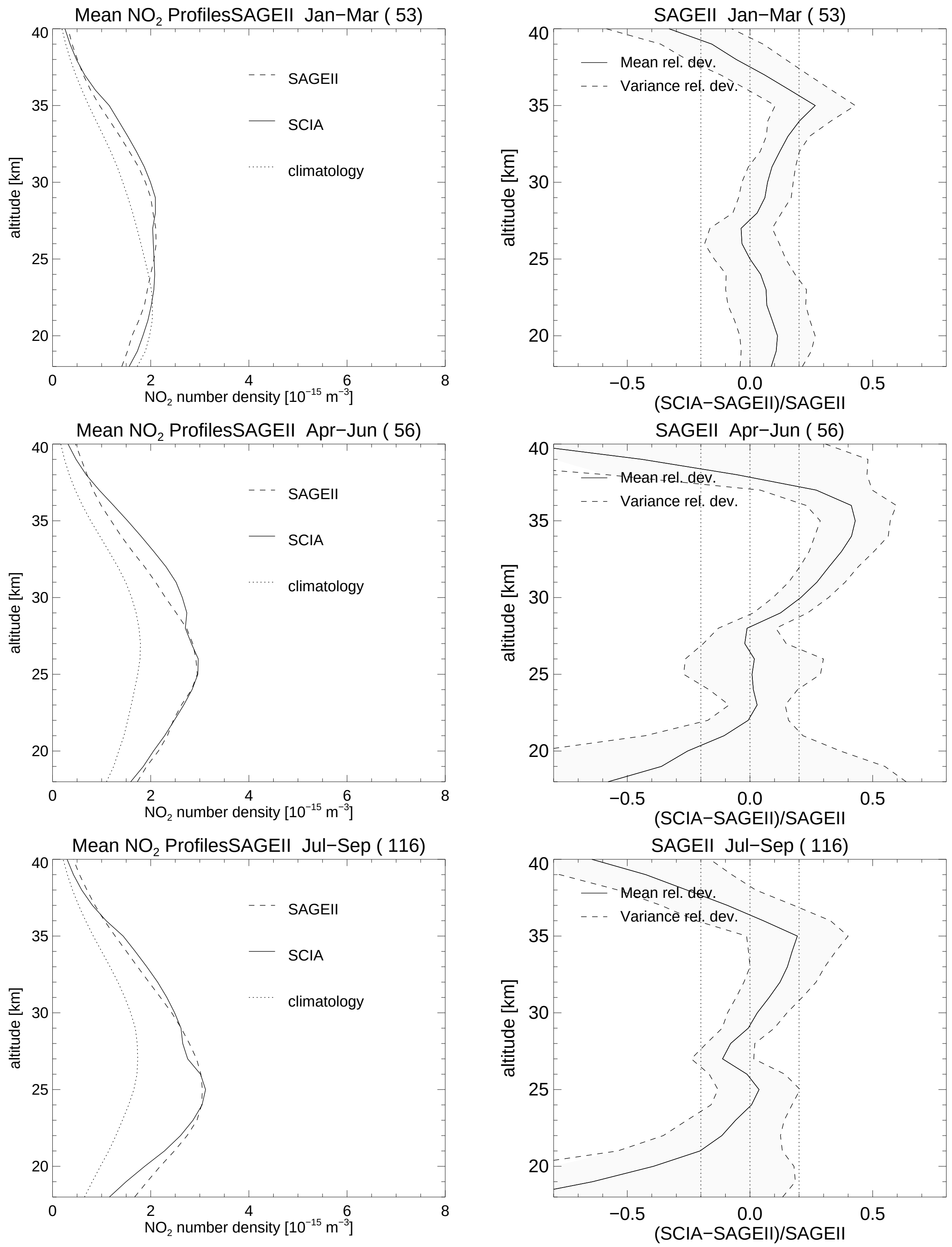

Figure 6. Validation results of NO_2 profiles from SCIAMACHY solar occultation with SAGE II, like Figure 4. From top to down: season January to March with 53 co-location, season April to June with 56 co-locations and season July to September with 116 co-locations.

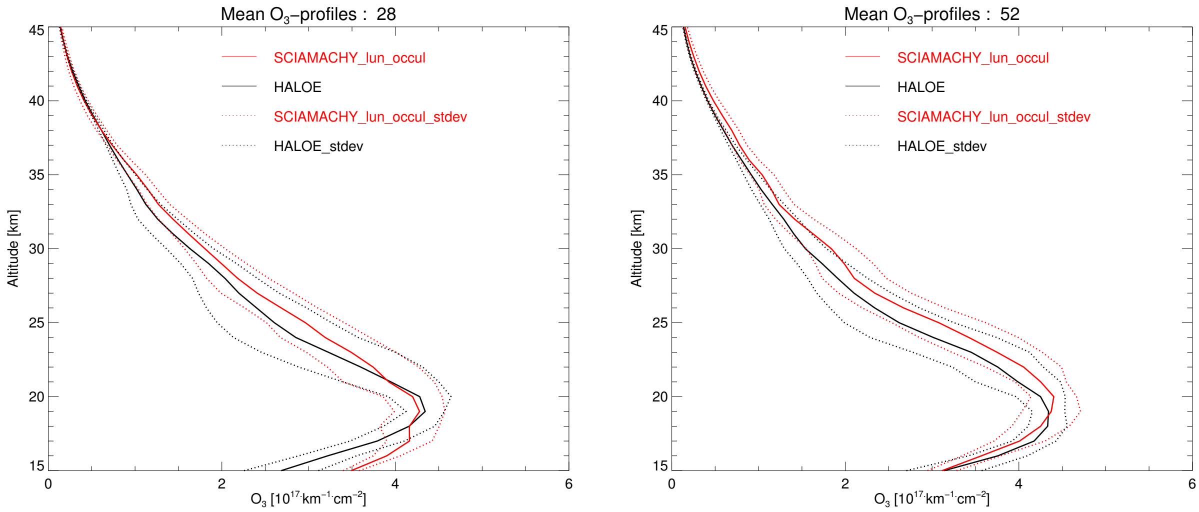

Figure 7. SCIAMACHY-HALOE mean ozone profiles for 2003 (28 coincidences) and 2004 (52 coincidences). Red is the SCIAMACHY result and black the HALOE result. The dotted lines are the standard deviations of the mean profiles.

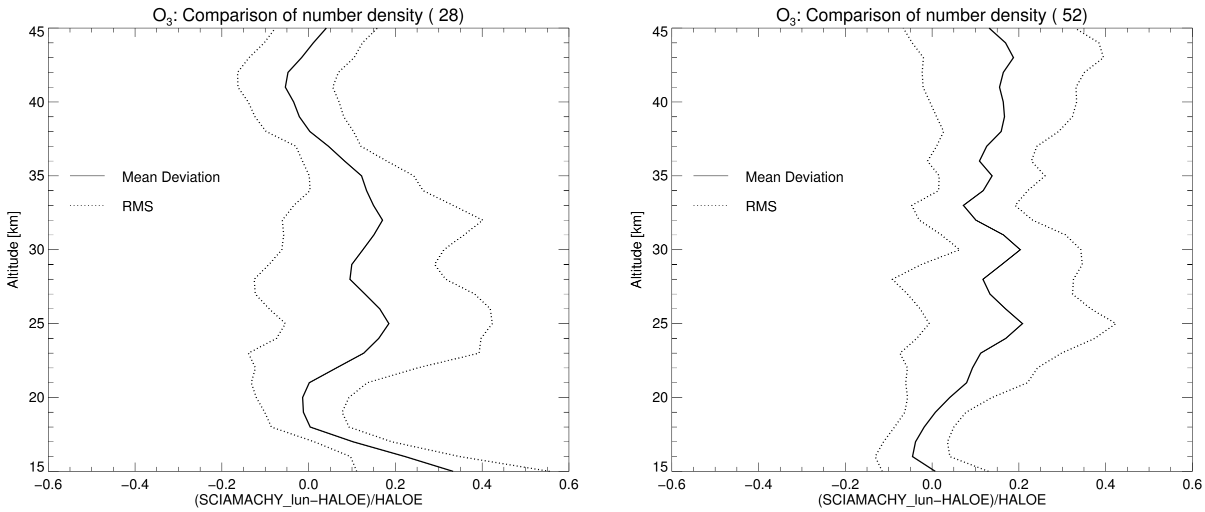

Figure 8. The mean relative deviations (solid line) and the standard deviation of the relative deviations (dotted line) for SCIA-HALOE comparisons. Top 2003 results and bottom 2004 results.

sures a few hours (1–3 hrs) after sunset and a few hours before sunrise, it is more difficult to get correlative measurements both in location and local-time. To carry out validation study for SCIAMACHY measured lunar occultation NO_2 profiles at SZA $\geq 95°$ with solar occultation measurement at SZA around 90°, we used the photochemical correction scheme described in detail in Bracher et al. (2005) to scale HALOE NO_2 to concentrations at SCIAMACHY's SZAs.

Example profiles of 2003 and 2004 SCIAMACHY version 2.2 comparisons with HALOE NO_2 photochemically scaled to SCIAMACHY SZA are shown in Figure 11 . Generally, we observed good agreement above 23 km for the 2003 results and a good agreement above 25 km for 2004 results. Below these altitudes some discrepancies are observed.

The statistical results are displayed in Figures 12 for 2003 and 13 for 2004. The dotted lines are the respective standard deviations of the profiles. For 2003, we found an agreement between 23–38 with relative mean deviations in range of -12 % to +18 %. The standard deviations in the same altitude range are in the range of 4 % to 20 %. For 2004, we found agreement between 26–38 km with the mean relative deviations in the range of -22 % to 15 %. The standard deviations in the same altitude range are 6 %–20 %. The observed biases are likely due to uncertainties in the model input parameters. The nighttime model uncertainties, according to Bracher et al. (2005) is

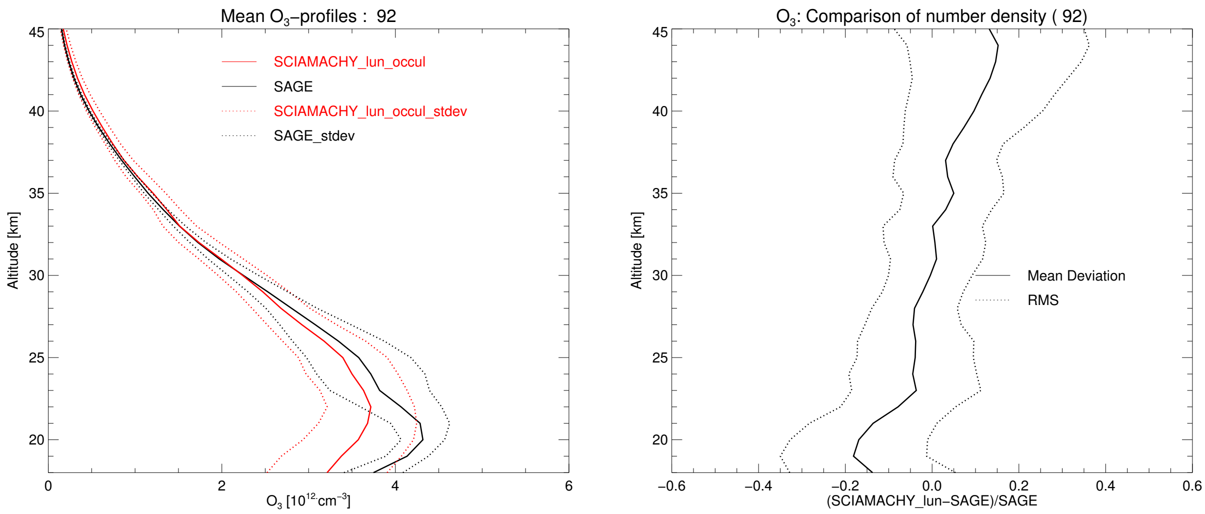

Figure 9. ***Top:*** *Mean profiles of 92 co–located SAGE II and SCIAMACHY measurements in 2004.* ***Bottom:*** *Mean relative deviation and the standard error of the mean relative deviation between 92 co–located SAGE II and SCIAMACHY measurements in 2004.*

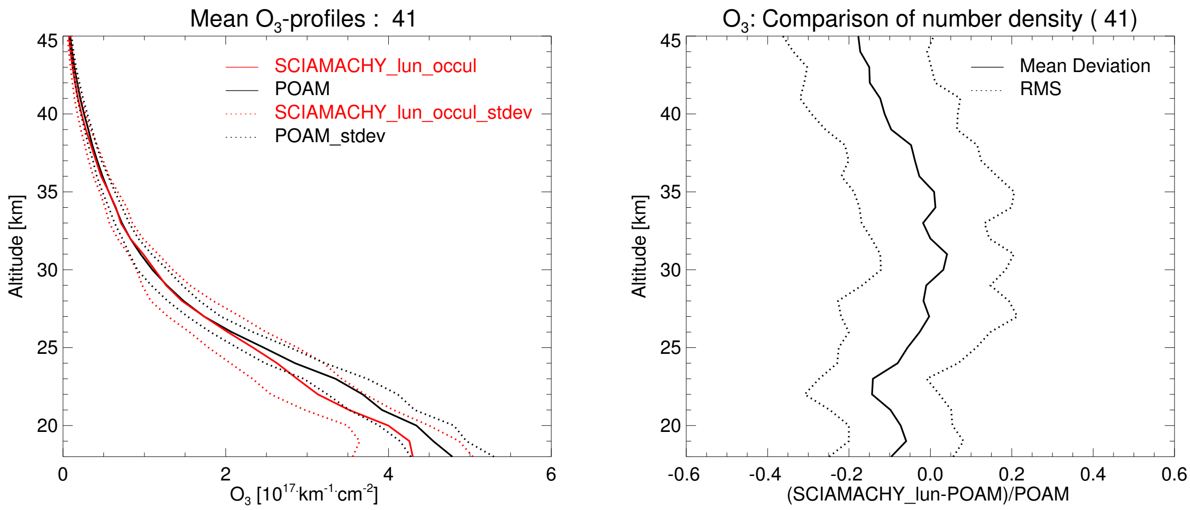

Figure 10. Left:SCIAMACHY-POAM mean ozone profiles for 2003 (41 coincidences). Right: the mean relative deviations (solid line) and the standard deviations of the relative deviations (dotted line) of the 41 SCIA-POAM III co–llocated observations.

approximately 14 % between 17 and 40 km. The largest contributions to the overall model uncertainty are the inaccuracies in the NO_2 photolysis rate and ECMWF analysed temperature. In addition, the observed biases could be due to large co-location radius, as differences in air masses strongly affect the concentration NO_2.

6. SCIAMACHY NO_3 MODEL COMPARISONS

We carried out a preliminary validation on the retrieved NO_3 profiles from SCIAMACHY lunar occultation measurements, by comparing the retrieved profiles to model calculated NO_3 results. Two model schemes were used, a photochemical model scheme and a relatively simple steady–state model. The photochemical model scheme is similar to the photochemical correction method used for the NO_2 validation. This model scheme uses a comprehensive photochemistry of the stratosphere. details of this model are given in [Sinnhuber et al. (2003); Bracher et al. (2005) and references therein]. The model is constrained by temperature and pressure profiles from ECMWF analyses and ozone and NO_2 profiles from SCIAMACHY observations. NO_2 was constrained by scaling the modelled NO_y (in particular NO, NO_2, N_2O_5, and HNO_3) until the modelled NO_2 agrees with measured NO_2 at the time of the SCIAMACHY measurements (Amekudzi et al.,

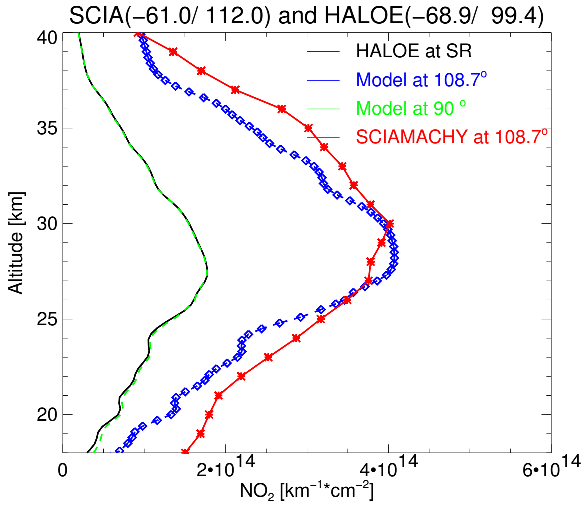

Figure 11. Examples of NO_2 profiles from SCIAMACHY lunar occultation version 2.2 compared with HALOE for 2003 (left) and 2004 (right). Red the SCIAMACHY result, blue the HALOE photochemically scaled to SCIAMACHY SZA, green the model result at HALOE SZA, and black the HALOE NO_2 profile.

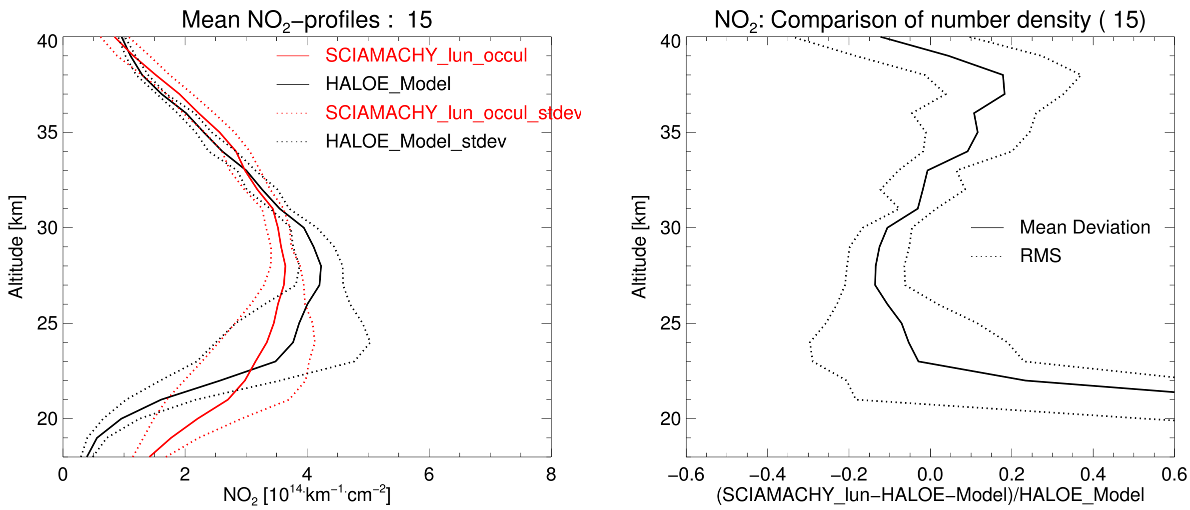

Figure 12. Left: mean NO_2 profile and corresponding standard deviation for 15 co-located events in 2003, SCIAMACHY version 2.2 in red and HALOE in black. Right: the mean relative deviation (solid line) and the standard deviation of the relative deviation (dotted line).

2005b).

The steady–state model assumed that in the absence of heterogeneous processes, the nighttime NO_3 chemistry in the stratospheric is governed by NO_2, O_3, and N_2O_5 molecules, i.e.

$$NO_2 + O_3 \longrightarrow NO_3 + O_2 \tag{1}$$

$$NO_3 + NO_2 + M \longrightarrow N_2O_5 + M \tag{2}$$

$$N_2O_5 + M \longrightarrow NO_3 + NO_2 + M. \tag{3}$$

At steady state the concentration of NO_3 can be calculated as

$$[NO_3] = \frac{k_1[O_3]}{k_2[M]} + \frac{k_3[N_2O_5]}{k_2[NO_2]}, \tag{4}$$

where k_1, k_2 and k_3 are the reaction rate constants of (Reactions 1, 2, and 3) respectively and M is the number density of air. The second term on the right hand side of Equation 4 accounts for the production of NO_3 due to the thermal decomposition of N_2O_5. If this term is neglected, then the night time steady state concentration of NO_3 is simple and depends only on ozone and temperature, given as

$$[NO_3] = \frac{k_1\,[O_3]}{k_2\,[M]}. \tag{5}$$

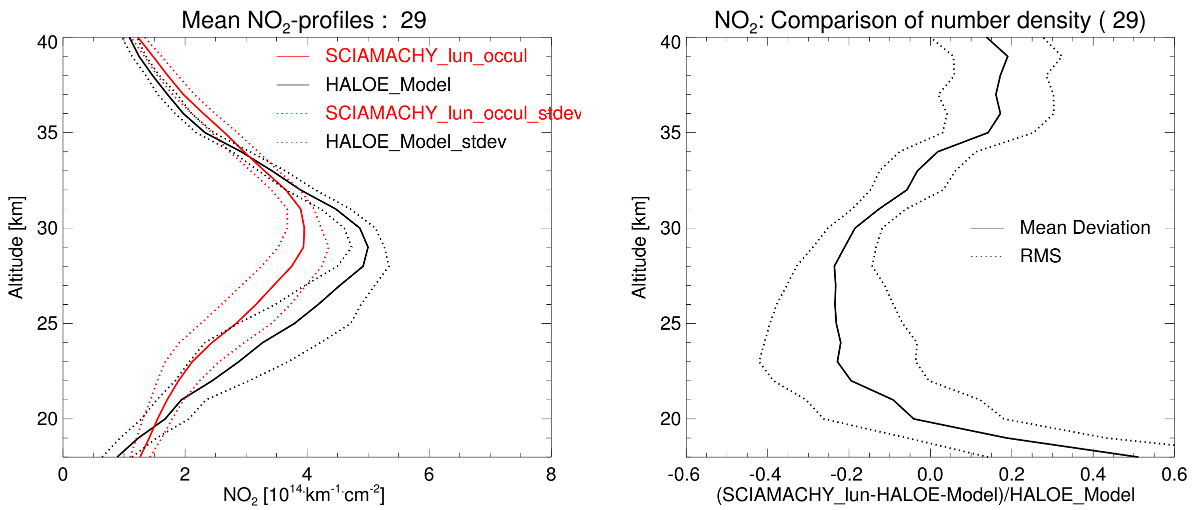

Figure 13. Left: mean NO_2 density profile and corresponding standard deviation for 29 co-located events in 2004, SCIAMACHY version 2.2 in red and HALOE in black. Right: the mean relative deviation (solid line) and the standard deviation of the relative deviation (dotted line).

We used Equation 5 for the steady state model calculation. As input parameters, SCIAMACHY lunar occultation retrieved ozone (Amekudzi et al., 2005a) and ECMWF temperature and pressure analyses are used.

Figure 14 show example profiles of the comparison of retrieved NO_3 with calculations from both the photochemical and steady state models. In general we found very good agreement between retrieved and photochemical model calculated NO_3 within the expected retrieval uncertainty of 35 % between the altitude range of 24–50 km and with the simple model up to 40 km.

In order to verify the consistency in the retrieved NO_3 profiles, the retrieved NO_3 profiles are plotted as a function of corresponding NO_3 concentrations calculated from the steady state model. Contribution of NO_3 concentrations above 40 km were removed from this study, as it was shown from Figure 14 that steady state condition cannot be assumed above 40 km for NO_3. These results are displayed in Figure 15. We found very good agreement between the retrieved NO_3 and the steady state model NO_3 with correlation coefficients in the range of 0.8–0.98.

7. CONCLUSIONS

By using the sun as well–known target in space, the pointing problems of the SCIAMACHY and the ENVISAT platform can be circumvented, which otherwise is a prominent source of error for SCIAMACHY occultation and limb retrievals. Also the moon as a fixed target in space improves the pointing information, although the precision of our method has to be further investigated.

SCIAMACHY solar occultation gives reliable profiles of ozone and NO_2 for the Northern hemisphere as proven in this paper by comparison with co-located measurements of HALOE and SAGE II. For ozone, we found deviations mostly within 0% to +10% from 17 – 47 km. Only exception is (in the comparison with SAGE II) the season April to June with deviations of +10 to +18 % from 24 – 45 km. For NO_2 , we found -5% to +20% deviations from 24 – 37 km, again with the exception of the season April to June with deviations up to +40 % around 35 km. The difficulties in this season have to be further investigated. The lowest altitudes of the NO_2 profiles need additional comparisons, as we found here contradictory results.

The validation results of ozone, NO_2, and NO_3 retrieved from SCIAMACHY lunar occultation have been presented. The retrieved ozone profiles were compared with retrieved ozone results from HALOE, SAGE II, and POAM III instruments. We found that the relative mean deviations are in the range of +10 % to +20 % between 25 and 35 km, below 25 km negative biases are observed in the range of -10 % to 0 %. We compared the SCIAMACHY lunar occultation NO_2 profiles to correlative HALOE v19 NO_2 profiles photochemically scaled to SCIAMACHY lunar occultation SZA and obtained promising results. The mean relative deviations of these comparisons are in the range of -22 % to 18 % between 23 to 38 km. The standard deviations in the same altitude are in the range of 4 % to 20 %. Our current understanding of stratospheric NO_3 chemistry at the location of measurements have been verified with models. We found good agreement with the models within the expected uncertainty of 35 % from 24 to 48 km, demonstrating that we have reasonable understanding of NO_3 chemistry in the polar stratosphere. Furthermore we checked the consistency of our retrieved NO_3 with the steady state model and found very good agreement with correlation coefficient in the range of 0.83–0.98.

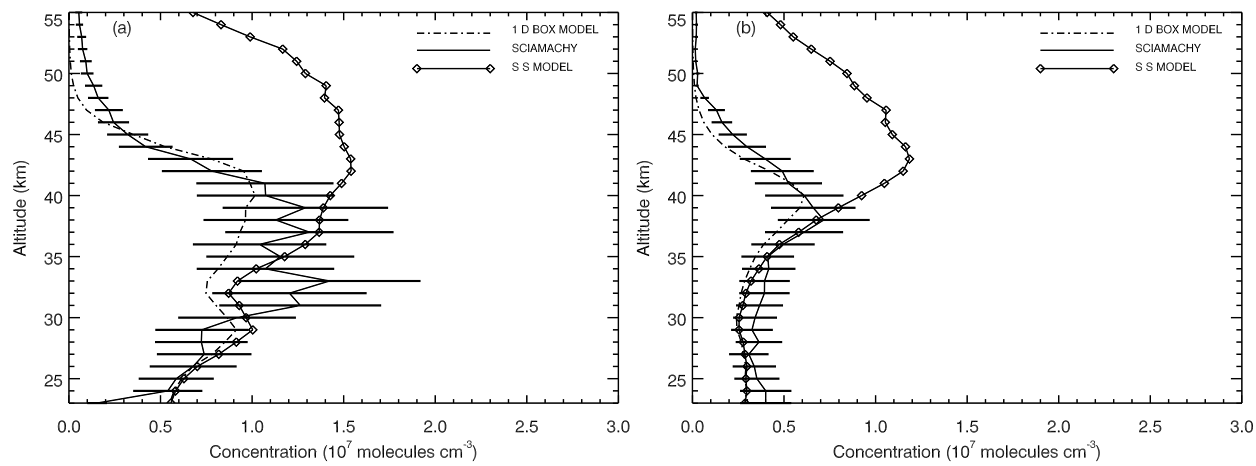

Figure 14. NO_3 profile retrieved compared with NO_3 profile calculated from the photochemical and steady state models. Solid line is the retrieval result, the dashed-dotted line is the photochemical model output and the solid line with diamond points is the steady state model results. (a) Example of NO_3 profiles for 14th March, 2003 (at SZA of 110°). (b) Example of NO_3 profile for 12th April, 2003 (at SZA of 115°).

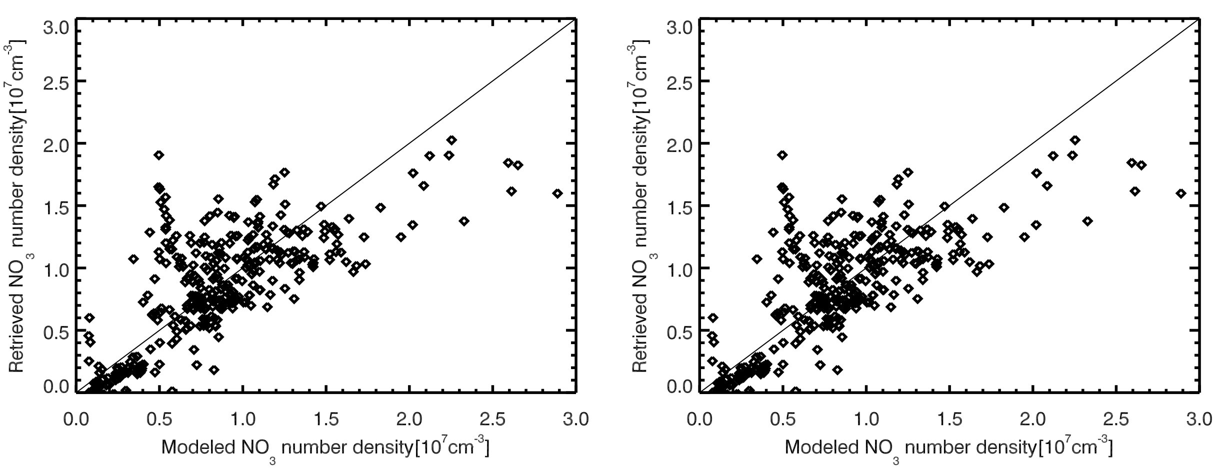

Figure 15. Retrieved NO_3 concentration from SCIAMACHY lunar occultation as a function of NO_3 calculated from the steady state model output. (a) The result for latitude band of (60– 65° S), the correlation coefficient for this graph is 0.83. (b) The result for latitude band of (66–72° S) the correlation coefficient for this graph is 0.98

The validation activity has to be extended by using ground-based instruments, especially to improve our knowledge about the lower altitudes, as the occultation instruments used here also have limited sensitivity at the lowest altitudes. In the solar occultation retrieval algorithm, the selection of the appropriate solar reference measurement above the atmosphere has to be improved, as currently only a fixed measurement is used. We also will go ahead to retrieve profiles of further minor absorbers such as OClO and BrO.

We will process the complete lunar occultation dataset and finalise the validation of ozone, NO_2. Finally we will compare our complete retrieved NO_3 results with the photochemical model outputs.

ACKNOWLEDGEMENT

We are thankful to the European Space Agency(ESA) for providing SCIAMACHY level-1 data. We are also thankful to the HALOE team (at Hampton University, especially J.M. Russell III, and at NASA LaRC, especially E. Thompson), and the SAGE II group (at NASA LaRC, especially Larry Thomason, and the NASA Langley Radiation and Aerosols Branch) for providing us with data from these instruments and information about data and instruments. This work was funded in parts by the German Ministry of Education and Research (BMBF) via grant 07UFE12/8 and via the AFO2000 project SACADA, the DLR-Born via grant 50EE0502, the University of Bremen and the state of Bremen.

Amekudzi, L. K. (2005). *StratosphericO_3, NO_2, and NO_3 number density profiles from SCIAMACHY lunar occultation spectroscopic measurements: Retrieval, validation and interpretation*. PhD thesis, Universität Bremen. ISBN 3-8325-1131-8, Logos Verlag Berlin.

Amekudzi, L. K., Bracher, A., Meyer, J., Rozanov, A., Bovensmann, H., and Burrows, J. P. (2005a). Lunar occultation with SCIAMACHY: First retrieval results. *Advances in Space Research*, 36:906–914.

Amekudzi, L. K., Sinnhuber, B.-M., Sheode, N. V., Meyer, J., Rozanov, A., Lamsal, L. N., Bovensmann, H., and Burrows, J. P. (2005b). Retrieval of stratospheric NO_3 vertical profiles from SCIAMACHY lunar occultation measurement over the antarctic. *J. Geophys. Res.*, 110(D20304).

Bovensmann, H., Burrows, J. P., Buchwitz, M., Frerick, J., Noël, S., Rozanov, V. V., Chance, K. V., and Goede, A. P. H. (1999). SCIAMACHY: Mission objectives and measurement modes. *Journal of the Atmospheric Sciences*, 56(2):127–150.

Bracher, A., Sinnhuber, M., Rozanov, A., and Burrows, J. P. (2005). Using photochemical models for the validation of NO_2 satellite measurements at different solar zenith angles. *Atmos. Chem. and Phys.*, 5:393–408.

Brühl, C., Drayson, S., III, J. R., Crutzen, P., McInerney, J., Purcell, P., Claude, H., Gernandt, H., McGee, T., McDermid, I., and Gunson, M. (1996). Haloe occultation experiment ozone channel validation. *Journal of Geophysical Research*, 101(D6):10217–10240.

Cunnold, D. M., Chu, W. P., Barnes, R. A., McCormick, M. P., and Veiga, R. E. (1989). Validation of SAGE II ozone measurements. *J. Geophys. Res.*, 94:8447–8460.

ESA (2006). Envisat cfi software. http://eop-cfi.esa.int/CFI/cfi_software.html.

Fortuin, P. and Kelder, H. (1998). An ozone climatology based on ozonesonde and satellite measurements. *Journal of Geophysical Research*, 103(D24):31709–31734.

Jianjun, L., Mohnen, V., Yue, G., Atkinson, R., and Matthews, W. (1997). Intercomparison of stratospheric ozone profiles obtained by stratospheric aerosol and gas experiment II, halogen occultation experiment, and ozonesondes in 1994–1995. *Journal of Geophysical Research*, 102(D13):16137–16144.

Lucke, R. L., Korwan, D. R., Bevilacqua, R. M., Hornstein, J. S., Shettle, E. P., Chen, D. T., Daehler, M., Lumpe, J. D., Fromm, M. D., Debrestian, D. J., Neff, B., Squire, M., König-Langlo, G., and Davies, J. (1999). The polar ozone and aerosol measurement POAM-III instrument and early validation results. *J. Geophys. Res.*, 104(D15):18785–18799.

Meyer, J. (2004). *Solar Occultation Measurements with SCIAMACHY in the UV-Vis-IR Wavelength Range*. PhD thesis, Universität Bremen. ISBN 3-8325-1130-X, Logos Verlag Berlin.

Meyer, J., Bracher, A., Rozanov, A., Schlesier, A. C., Bovensmann, H., and Burrows, J. P. (2005). Solar occultation with SCIAMACHY: algorithm description and first validation. *J. Atmos. Chem. and Phys*, 5:1589–1604.

NASA (1976). U.S. standard atmosphere supplements. Technical report, U.S. Government Printing, Washington, D.C.

Rodgers, C. D. (1976). Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation. *Reviews of Geophysics and Space Physics*, 4:609–624.

Rodgers, C. D. (2000). *Inverse Methods for Atmospheric Sounding: Theory and Practise*. World Scientific, Singapore.

Rozanov, A., Rozanov, V., Buchwitz, M., Kokhanovsky, A., and Burrows, J. (2005). Sciatran 2.0 - A new radiative transfer model for geophysical applications in the 175-2400 nm spectral region. *Adv. Space Res.*, 36(5):1015–1019.

Sinnhuber, M., Burrows, J. P., Chipperfield, M. P., Tackman, C. H., Kallenrode, M.-B., Künzi, K., and Quack, M. (2003). A model study of the impact of magnetic field structure on atmospheric composition during solar proton events. *Geophys. Res. lett.*