A comparison of OH nightglow volume emission rates as measured by SCIAMACHY and SABER

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Abstract. Hydroxyl (OH) short-wave infrared emissions arising from OH(4-2, 5-2, 8-5, 9-6) as measured by channel 6 of the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) are used to derive concentrations of OH(v=4, 5, 8, and 9) between 80 km and 96 km. Retrieved concentrations are used to simulate OH(5-3, 4-2) integrated radiances at 1.6 μm and OH(9-7, 8-6) at 2.0 μm as measured by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument, which are not fully covered by the spectral range of SCIAMACHY measurements. On average, SABER "unfiltered" data is on the order of 40% at 1.6 μm and 20% at 2.0 μm larger than the simulations using SCIAMACHY data. "Unfiltered" SABER data is a product, which accounts for the shape, width, and transmission of the instrument's broadband filters, which do not cover the full ro-vibrational bands of the corresponding OH transitions. It is found that the discrepancy between SCIAMACHY and SABER data can be reduced by up to 50%, if the filtering process is carried out manually using published SABER interference filter characteristics and latest Einstein coefficients from the HITRAN database. Remaining differences are discussed with regard to model parameter uncertainties and radiometric calibration.

1 Introduction

Hydroxyl (OH) airglow stems from spontaneous emissions of metastable excited OH molecules which are mainly produced by the exothermic reaction of H and O_3 in the upper mesosphere and lower thermosphere (UMLT). Its emission layer peaks at an altitude of approx. 87 km and extends about 8 km (Baker and Stair, 1988; Hong et al., 2010). OH airglow covers a broad spectral region from the ultraviolet to near-infrared spectral range and is of importance for studying photochemistry and dynamics in the UMLT region.

Since first confirmed by Meinel (1950), OH airglow emissions have been widely observed using various remote spectroscopic techniques (e.g., Offermann and Gerndt, 1990; von Savigny et al., 2004; Kaufmann et al., 2008; Smith et al., 2010; Zhu et al., 2012). The measurements obtained in such studies have been analyzed for various purposes. For example, rotational temperature can be obtained from OH emissions as a proxy for kinetic temperature under the assumption of rotational local thermodynamic equilibrium (LTE) (Offermann et al., 2010; Zhu et al., 2012; Liu et al., 2015). Gravity waves passing through the OH airglow layer can be **monitored** to study the dynamics and energy balance in the UMLT (Xu et al., 2015). The understanding of OH relaxation mechanisms with different species can be improved by studying different OH band emissions in the UMLT (Kaufmann et al., 2008; Xu et al., 2012; von Savigny et al., 2012). Another important application of OH airglow is to derive trace constituents in the UMLT, such as H and O abundances (Kaufmann et al., 2013; Mlynczak et al., 2018; Panka et al., 2018; Zhu and Kaufmann, 2018).

OH nightglow has been globally measured, among others, by SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) operating since 2002, and SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) observing from 2002 to 2012. SABER performed observations successfully over a 17-year period, **covering one and half solar cycles, and is still measuring**, and many outstanding achievements have been accomplished using these data (e.g., Xu et al., 2007; Smith et al., 2008; Mlynczak et al., 2010; Hong et al., 2010). The OH data obtained by SABER have been used by different investigators (Smith et al., 2010; Mlynczak et al., 2013; Panka et al., 2018; Mlynczak et al., 2018) to derive atomic oxygen abundance in the UMLT; however, deviations of up to 60% were found in comparison with atomic oxygen data derived from $O(^1S)$ green-line measurements obtained by SCIAMACHY and WINDII (Wind Imaging Interferometer) (Kaufmann et al., 2014; Zhu et al., 2015). This large deviation promoted a discussion on the absolute values of atomic oxygen abundance (Mlynczak et al., 2018; Panka et al., 2018; Zhu and Kaufmann, 2018). Mlynczak et al. (2018) derived new atomic oxygen data from SABER OH 2.0 µm absolute radiance measurements in the UMLT under the constraints of the global annual mean energy budget. Panka et al. (2018) also retrieved atomic oxygen data from SABER OH 1.6 μm and 2.0 μm radiance ratios as an alternative approach. Further new atomic oxygen data were recently derived by Zhu and Kaufmann (2018) from SCIAMACHY nighttime OH(9-6) band measurements using rate constants measured in the laboratory by Kalogerakis et al. (2016), which agree with atomic oxygen data derived from SCIAMACHY $O(^1S)$ green-line and O_2 A-band measurements within a range of 10-20% (Zhu and Kaufmann, 2019). While the agreement between new atomic oxygen data obtained by SABER and SCIAMACHY has improved, systematic deviations of up to 50% still persist (Zhu and Kaufmann, 2018). This systematic difference needs to be addressed in future studies.

In this study, OH nightglow limb spectra measured by SCIAMACHY were used to derive OH **spectrally averaged radiances at 1.6 µm and 2.0 µm as measured by SABER**. The **obtained radiances** were compared to SABER OH **radiometric** measurements to investigate whether systematic differences exist between the two datasets.

2 OH nightglow measurements and auxiliary data

From 2002 to 2012, OH Meinel-band near-infrared emissions were measured simultaneously by SCIAMACHY on the Envisat and by SABER on the TIMED (Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics) satellite. The spectral range of both instruments covers several OH emission bands stemming from different vibrational states (Kaufmann et al., 2008; Mlynczak et al., 2013). The SCIAMACHY instrument on Envisat operated in a sun-synchronous orbit with an equator crossing local solar time of 10 a.m./p.m. The limb spectra used here were observed by SCIAMACHY in a dedicated mesosphere/thermosphere mode and the limb observational range covered 24 tangent altitudes from 73 km to 148 km with a vertical sampling of 3.3 km. SCIAMACHY was a multi-channel grating spectrometer and its channel 6 measured OH spectra arising from **upper vibrational states in the range of 2 to 9** at a spectral resolution of 1.5 nm. **The measurement error of SCIAMACHY channel 6 is about 1.2% (Zoutman et al., 2000)**. Channel 6 covers a spectral range from 971 nm to 1773 nm (Lichtenberg et al., 2006). In this study, only the spectral range of channel 6 up to **1589** nm was used due to the reduced performance of the detector beyond this wavelength (Lichtenberg et al., 2006). It should be noted that SCIAMACHY channel 7 and 8 covered spectral ranges of 1934-2044 nm and 2259-2386 nm, respectively, but unfortunately suffered from ice condensation on their detectors (Lichtenberg et al., 2006).

SABER is a multi-channel radiometer and observes radiometric OH(9-7, 8-6) ro-vibrational lines with wavelengths around 2.0 $\mu\mathrm{m}$ (channel 8) and OH(5-3, 4-2) band emissions at about 1.6 $\mu\mathrm{m}$ (channel 9) (Xu et al., 2012). The altitude range of the observation covers 60-180 km with vertical resolution of approx. 2 km (Mertens et al., 2009). **To the authors' knowledge, there are no publicly available references on the observed accuracy of the SABER OH channels, except for a presentation named "SABER Instrument Performance and Measurement Requirements" published on http://saber.gats-inc.com/overview.php, which is the official source of SABER data products. According to this document, the estimated accuracy of the 1.6 and 2.0 $\mu\mathrm{m}$ channel data is about 3% at 80-90 km and about 20% at 90-100 km.** Since the SABER instrument is a radiometer, individual OH ro-vibrational emission lines cannot be resolved. Figure 1 shows simulated OH airglow emissions in the spectral range between 1000 nm and 2400 nm; spectral ranges covered by the instruments are shaded in different colors.

Since the spectral coverage of SCIAMACHY and SABER does not coincide, we can not compare their measurements directly. However, both instruments observed ro-vibrational lines stemming from the same upper vibrational states. This offered us an opportunity to calculate the number densities of the OH upper vibrational states and then simulate the same ro-vibrational emission bands for the purposes of comparison. In our study, OH limb spectra measured by SCIAMACHY at 1078-1100 nm, 1297-1325 nm, 1377-1404 nm, and 1575-1588 nm were used, as shown in Figure 2. The spectral ranges covered ro-vibrational lines in the OH(5-2), OH(8-5), OH(9-6) and OH(4-2) bands, respectively, with low rotational quantum numbers N ($N \leq 3$) to **reduce** the potential uncertainty that can be introduced by over-populated high-N rotational states (Cosby and Slanger, 2007; Noll et al., 2015; Oliva et al., 2015); **details are discussed later**. From these measurements, number densities of OH(v=4, 5, 8, and 9) are obtained, which are used to simulate corresponding SABER measurements.

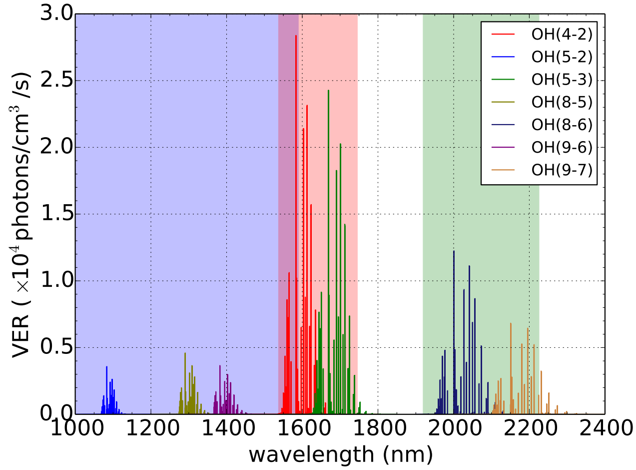

Figure 1. Simulated OH airglow emission bands used in this study in a spectral range between 1000 nm and 2400 nm. Shaded light blue region covers a spectral range observed by SCIAMACHY channel 6; shaded light red and light green regions cover two spectral ranges measured by SABER channel 9 and 8, respectively.

For comparison, SABER V2.0 data were used, including OH in-band and “unfiltered” 1.6 µm and 2.0 µm data (Mlynczak et al., 2013). The in-band OH radiance data comprised raw data that did not take into account filter transmission, while the “unfiltered” OH radiance data consider the interference filter characteristics measured in the laboratory (Xu et al., 2012). **The unfiltering process depends on the spectral shape of the underlying ro-vibrational distribution of the emission. This shape has to be determined by a model, which depends on the rotational temperature and on the transition probabilities (Einstein coefficients). Beside using the official in-band and “unfiltered” data, separate in-band and “unfiltered” datasets were obtained from the SCIAMACHY measurements, using the bandpass filter transmission of Baker et al. (2007) and various Einstein coefficient datasets, for details see later. In this procedure, we also considered OH(3-1) and OH(7-5) emission lines observed by SABER 1.6 µm and 2.0 µm channels, respectively, and their contributions to the two channels were calculated based on SCIAMACHY OH(3-1) and OH(7-4) measurements.** In order to enhance the signal-to-noise ratio and to obtain a large number of coincident measurements with both instruments, monthly zonal median data in 5-degree latitude bins were used. Since the SCIAMACHY instrument can not measure nighttime temperature in the UMLT, co-located SABER measurements were also used here. The coincidence criteria selected were $\pm 2.5°$ in latitude and one hour in local time.

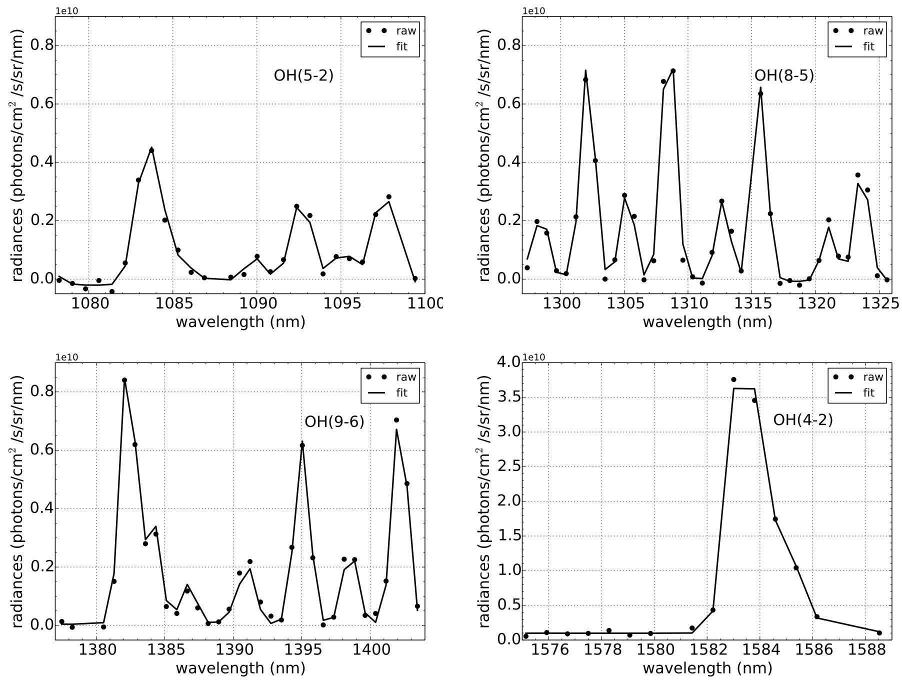

Figure 2. Monthly zonal median OH(4-2), OH(5-2), OH(8-5), and OH(9-6) limb spectra at tangent altitude about 86 km for September 2005 in a latitude range 35°N-40°N. **raw: the raw limb spectra measured by SCIAMACHY; fit: simulated limb spectra as measured by SCIAMACHY from retrieval results.**

3 Methodology

3.1 OH emission model

The exothermic reaction of H and O_3 in the atmosphere was identified by Bates and Nicolet (1950) as the major source of vibrationally excited hydroxyl radicals (OH*) near the mesopause region.

$$H + O_3 \rightarrow OH^*(v \leq 9) + O_2 \tag{R1}$$

Metastable excited OH* can be de-excited via radiative, chemical, and collisional relaxation processes. OH($v \leq 8$) is not only initially populated by the reaction of H + O_3, but is also produced by the deactivation of higher vibrational states of OH* via radiative relaxation and quenching. The number density of OH(v) can be obtained from its emission line measurements by dividing **by** the corresponding Einstein coefficients. The volume emission rate $V_{v-v'}(i)$ of an arbitrary ro-vibrational line within a vibrational band OH($v - v'$) can be calculated as

$$V_{v-v'}(i) = n_v \cdot \frac{g_v(i) \cdot \mathrm{e}^{-E_v(i)/(k \cdot T)}}{Q_v(T)} \cdot A_{v-v'}(i) \tag{1}$$

n_v is the total number density of the corresponding upper vibrational state v and $A_{v-v'}(i)$ is the Einstein coefficient of the specific state-to-state transition from vibrational level v to v'. $E_v(i)$ and $g_v(i)$ are the rotational energy and degeneracy of the upper rotational state of the ith line considered. k is the Boltzmann **constant** and T is the temperature. $Q_v(T)$ is the rotational partition sum of OH(v). **This formula is only valid under rotational local thermodynamic equilibrium (LTE) conditions and deviations are discussed later.**

3.2 Retrieval model

SCIAMACHY measured integrated OH spectra along the line of sight in the tangent altitude range from approx. 73 km to approx. 149 km. **The SCIAMACHY OH limb measurements can be expressed as**

$$\boldsymbol{y} = \boldsymbol{F}(\boldsymbol{x}, \boldsymbol{b}) + \boldsymbol{\epsilon} \tag{2}$$

$\boldsymbol{y}$ corresponds to the measured SCIAMACHY OH limb spectra. $\boldsymbol{F}$ is the functional formula of the forward model involving equation 1. $\boldsymbol{x}$ represents the number densities (n_v) of the corresponding upper vibrational state of the emission lines. $\boldsymbol{b}$ is the parameter vector of the forward model, **e.g.**, Einstein coefficients. $\boldsymbol{\epsilon}$ represents stochastic measurement errors. The retrieval can be regarded as an approach to solving an **inversion** problem in the presence of indirect measurements of the properties **of interest**. **In our setup we assume that each atmospheric layer emits OH airglow homogeneously, and we set the retrieval grid to be identical to the tangent altitude grid of the averaged OH limb measurements. To improve the efficiency of the retrieval, to suppress noise in the solution, and to achieve a smooth transition of the retrieved quantities into model data at the upper boundary, a regularization term is added to the minimization (Rodgers, 2000):**

$$\boldsymbol{x}_{i+1} = \boldsymbol{x}_a + (\boldsymbol{K_i^T S_\epsilon^{-1} K_i} + \boldsymbol{S_a^{-1}})^{-1} \boldsymbol{K_i^T S_\epsilon^{-1}} [\boldsymbol{y} - \boldsymbol{F}(\boldsymbol{x}_i, \boldsymbol{b}) + \boldsymbol{K_i}(\boldsymbol{x}_i - \boldsymbol{x}_a)] \tag{3}$$

$\boldsymbol{x}_i$ reaches the optimal estimate solution when the retrieval converged. $\boldsymbol{K_i}$ corresponds to the first derivative matrix of the forward model, named the Jacobian matrix. $\boldsymbol{x}_a$ represents the a-priori knowledge of the total number densities of OH(v), and $\boldsymbol{S_a^{-1}}$ is the regularization matrix. $\boldsymbol{S_\epsilon}$ is a diagonal error covariance matrix of $\boldsymbol{y}$.

4 Results and discussion

4.1 Error analysis

The confidence level of simulated volume emission rates (VERs) can be assessed by considering three main aspects: the uncertainty of the auxiliary atmospheric quantities, i.e., temperature; the uncertainty of rate constants, i.e., Einstein coefficients; and the potential uncertainty introduced by over-populated high rotational states due to non-local thermodynamic equilibrium (non-LTE) effects. The temperature uncertainty in the SABER measurements includes random and systematic errors; Dawkins et al. (2018) summarized SABER temperature uncertainties. **We consider only systematic errors in SABER temperatures, because monthly mean data are used.** The SABER systematic temperature uncertainty is approx. 1.5 K at 70-80 km, 4 K at

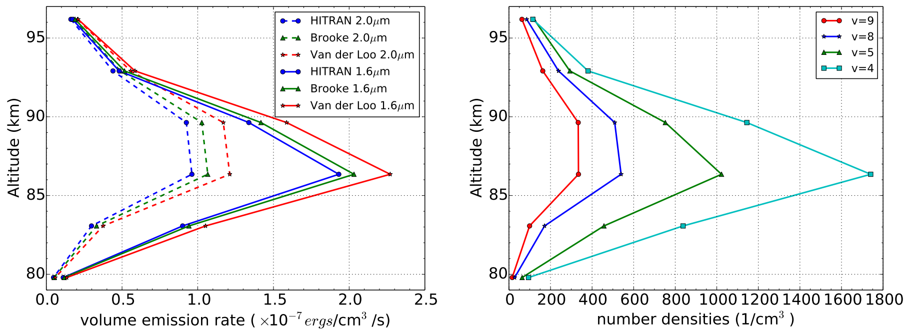

Figure 3. Simulated SABER "unfiltered" OH 1.6 μm and 2.0 μm volume emission rates from SCIAMACHY data using Einstein A values of HITRAN, Brooke et al. (2016), and van der Loo and Groenenboom (2007, 2008) at 20°N-40°N for October 2007 (left); **Corresponding retrieved OH number densities of vibrational states 9, 8, 5, and 4 from SCIAMACHY data using HITRAN database (right).**

90 km, and 5 K at 100 km, respectively. Accordingly, VERs are affected by temperature uncertainties by less than 1% between 80 km and 96 km on average, as obtained by Xu et al. (2012) in their investigation of the temperature dependence of the band Einstein coefficients as well.

Many OH Einstein coefficient datasets can be found in the OH research community (see, e.g., Liu et al. (2015)). We consider the values given in the latest HITRAN molecular spectroscopic database (Gordon et al., 2017) and the OH Einstein A values calculated by van der Loo and Groenenboom (2007, 2008) and Brooke et al. (2016). **The uncertainty of the Einstein coefficient affects simulated VERs in two ways: In the retrieval of vibrationally excited OH from SCIAMACHY data and in the simulation of the SABER measurements.** Figure 3 (left) shows simulated SABER "unfiltered" OH 1.6 μm and 2.0 μm VER profiles obtained from SCIAMACHY measurements using these three Einstein coefficient datasets. **Corresponding OH number density profiles as derived using Einstein coefficients from the HITRAN database at vibrational states 9, 8, 5, and 4 are also given.** Highest VERs are obtained by using the Einstein coefficients calculated by van der Loo and Groenenboom (2007, 2008) and the lowest are obtained by using the HITRAN database. The differences between them are approx. 26% for the simulation of SABER 2.0 μm VERs and approx. 19% for the simulation of SABER 1.6 μm VERs. Similar values were also obtained if we used data for other latitude bins or time periods. **The same procedure was also applied to the simulation of SABER 2.0 μm and 1.6 μm in-band data, giving similar results. Therefore, we used these results as a proxy to estimate related uncertainties of the Einstein coefficients.**

Cosby and Slanger (2007); Noll et al. (2015); Oliva et al. (2015) reported that middle and higher excited rotational states ($N \geq 4$) of OH do not meet the LTE hypothesis and that these levels are overpopulated. An estimation of the non-LTE contribution was performed by Oliva et al. (2015) based on cross-dispersed cryogenic spectrometer measurements in the spectral range of 0.97 μm to 2.4 μm. A combination of two Boltzmann distribution equations with cold and hot OH rotational temperatures was used to predict the observed intensities of OH emission lines. Kalogerakis et al. (2018) re-analyzed the data used by Oliva et al. (2015) to estimate the OH rotational temperatures following the approach taken by Cosby and Slanger (2007) and Oliva et al. (2015). They found that the thermalization of every OH vibrational level is incomplete.

The low spectral resolution of SCIAMACHY spectra does not allow to estimate this effect from the measured data. Therefore, we performed model simulations using the same approach and parameter sets as Oliva et al. (2015) to quantify the effect of incomplete thermalization on the spectral ranges used in this study. We calculated OH 1.6 µm and 2.0 µm VERs by considering only the cold rotational temperature and then obtained them using cold and hot temperatures together as Oliva et al. (2015) and Kalogerakis et al. (2018) did. It was found that differences between them are less than 2% for both SABER channels. The SABER 1.6 µm and 2.0 µm channels also observe emission lines from OH(3-1) and OH(7-5), respectively. We estimated their influence on spectrally integrated radiances by the derivation of the corresponding emissions using SCIAMACHY OH(3-1) and OH(7-4) nightglow measurements. These simulations show that the contributions of OH(7-5) and OH(3-1) to the two channels are about 3% and 1% on average, respectively.

In summary, the uncertainty of the Einstein coefficient dominates the error budget for the in-band and "unfiltered" data, which is on the order of 20% and 26% for the SABER 1.6 µm and 2.0 µm VER simulations, respectively.

4.2 Comparison of SABER measurements and simulations

An intercomparison between 1.6 µm and 2.0 µm in-band and "unfiltered" VERs as measured by SABER and corresponding simulations using SCIAMACHY data and HITRAN OH Einstein coefficients is given in Figure 4 for two different latitudes in September 2005. **Error bars shown in Figure 4 represent the root mean square value of all uncertainties discussed in the subsection 4.1. The top two plots show a comparison of the "unfiltered" data and the bottom two figures show the in-band data**. SABER measurements are always larger than the simulations using SCIAMACHY data. **For the "unfiltered" data, deviations of SABER OH 1.6 µm measurements with respect to the corresponding simulations increase with altitude from 30-45% at 83 km to 55-80% at 96 km, depending on latitudes. The difference of SABER OH 2.0 µm measurements with respect to the corresponding simulations is 16% at 86 km.** At 96 km, it reaches 70% in latitude bins 0°-20°N and approx. 90% in 20°N-40°N.

Surprisingly, for the in-band data, the differences for the 1.6 µm and 2.0 µm channels are significantly smaller at most altitudes. They vary in a range of 8-28% (21-50%) and 8-60% (28-100%) from 83 km to 96 km at 0°-20°N (20°N-40°N). It should be noted that SCIAMACHY and SABER have a resolution of about 3.3 km and 2 km, respectively. A linear interpolation has been applied to SABER data to make a comparison with SCIAMACHY data. This may underestimate the SABER data at peak altitudes and overestimate the SABER data at two wings besides the peak altitudes.

Figure 5 shows the global spatial distributions of SABER OH 2.0 µm VERs (bottom) and the corresponding simulations (top) using SCIAMACHY data for the year 2007. **A strong annual variation with a maximum in April and a semi-annual oscillation are visible in the radiance data over the equator region, as it was also found by Teiser and von Savigny (2017) in a study of SCIAMACHY OH(3-1) and OH(6-2) volume emission rates.** It is obvious that SABER VERs are significantly larger than corresponding simulated values based on SCIAMACHY observations, as already stated. Comparing the SABER OH 1.6 µm VERs and the corresponding simulations leads to the same conclusion (not shown).

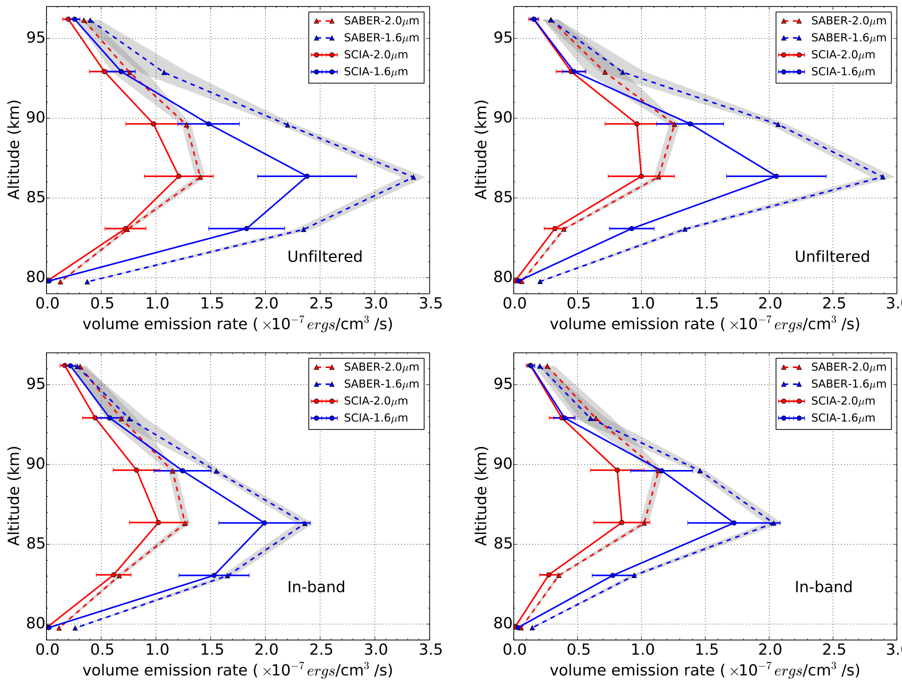

Figure 4. SABER 1.6 µm and 2.0 µm “unfiltered” (top) and in-band (bottom) volume emission rates and corresponding simulations from SCIAMACHY data for September 2005 at latitude bins 0°-20°N (left) and 20°N-40°N (right). The horizontal lines represent error bars considering the total uncertainties discussed in subsection 4.1. The grey shaded area represents the observed accuracy of SABER 1.6 µm and 2.0 µm channels.

Figure 6 shows two pairs of scatter plots which elucidate the consistency of SABER “unfiltered” 1.6 µm (left) and 2.0 µm (right) VERs and corresponding simulated values based on SCIAMACHY observations. **Again, SABER data are systematically larger than the SCIAMACHY simulations. The SABER 1.6 µm channel data (left column in Figure 6) are 44% larger for the “unfiltered” data and 23% larger for the in-band data, if all altitudes and latitudes are considered simultaneously in one fit. For the 2.0 µm data (right column in Figure 6), the differences are 23% and 35% on average, respectively.**

To illustrate whether this difference changes on long time scales, figure 7 shows the ratio of SABER “unfiltered” and in-band data to the corresponding simulations based on SCIAMACHY data from 2003 to 2011. For the OH 1.6 µm “unfiltered” (in-band) data, the ratio value varies roughly between 1.2 (1.0) and 1.3 (1.2) for 2003-2009, reaching 1.1 for 2010 and 1.36 for 2011. The ratio varies between 1.0 (1.1) and 1.1 (1.2) for the OH 2.0 µm “unfiltered” (in-band) data. The data indicate that there are no significant variations in the slope of SABER data versus SCIAMACHY simulations from 2003 to 2011 and that there is a systematic bias between them in general.

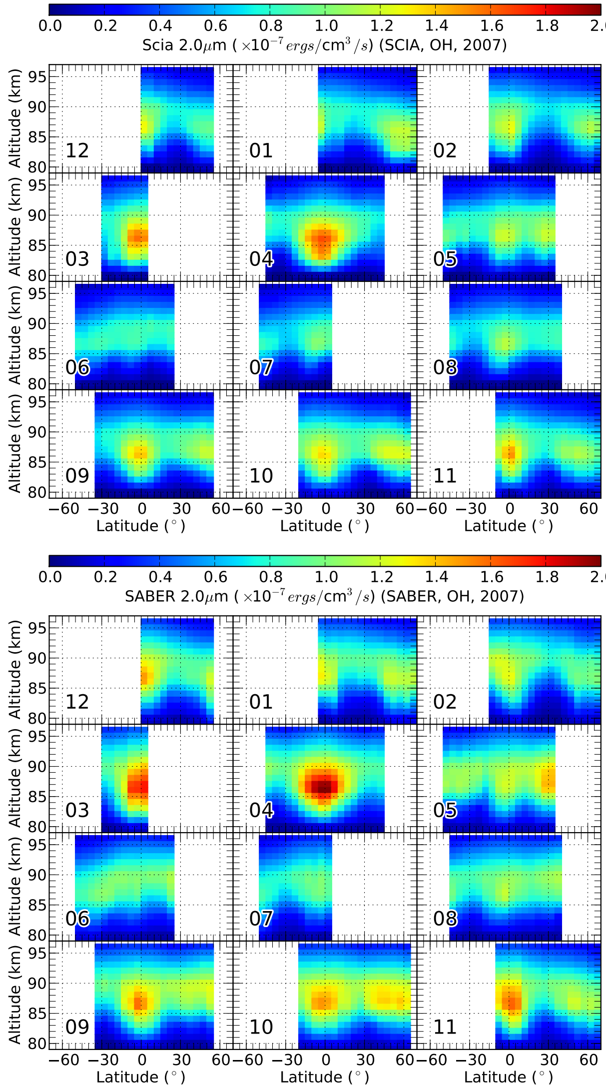

Figure 5. Latitude-altitude cross sections of monthly zonal median SABER "unfiltered" 2.0 μm volume emission rates (bottom) and corresponding simulations (top) from SCIAMACHY data for the year 2007. The numbers represent the month of the year.

5 Conclusions

Near-infrared OH nightglow emissions measured by SCIAMACHY channel 6 were used in this study to simulate SABER 1.6 μm and 2.0 μm radiance measurements to assess systematic differences between the two measurements. Two different SABER data products are used for this comparison: So called in-band data, which are the data directly obtained from the measurements and "unfiltered" data. For the latter, the shape, width, and transmission of the instrument's broadband filters has been considered, and the fraction of OH lines passing the interference filter has been

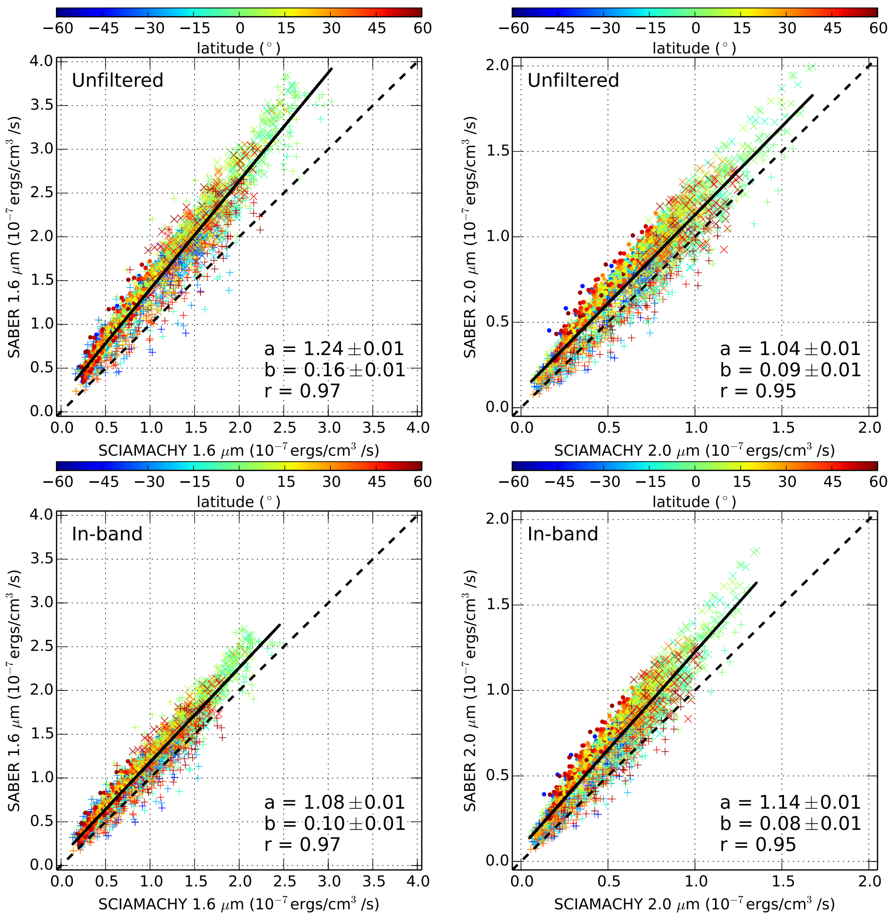

Figure 6. Scatter plots of SABER 1.6 μm (left) and 2.0 μm (right) volume emission rates versus the corresponding simulations using SCIAMACHY data for the year 2007. The color bar shows the latitude. The plus marker indicates the data at 80-85 km, the x marker represents the data at 86-90 km, and the point marker shows the data at 91-95 km. The solid line shows the linear fit to the data. a and b represent the slope and y-intercept of the fitting line, respectively. r represents the correlation coefficient of the fitting.

"upscaled" to obtain total band intensities of the corresponding vibrational transitions (Xu et al., 2012). If, however, in-band data is used, the data user has to apply the broadband filter transmission curve to the model data himself. This procedure has decisive advantages, because no a-priori assumptions have to be made to upscale partial measurements of OH vibrational bands to total band intensities. This allows to use consistent datasets of Einstein coefficients in all processing steps.

When SABER OH in-band data are compared to model simulations using SCIAMACHY data, the typical differences are 35% for 2.0 μm and 23% for 1.6 μm radiances, whereas the differences are 23% and 44% for the "unfiltered" data, respectively. The significance or uncertainty of these differences is affected by uncertainties in the Einstein coefficients used to "map" SCIAMACHY to SABER data. For the in-band and "unfiltered" data, this uncertainty is estimated to be

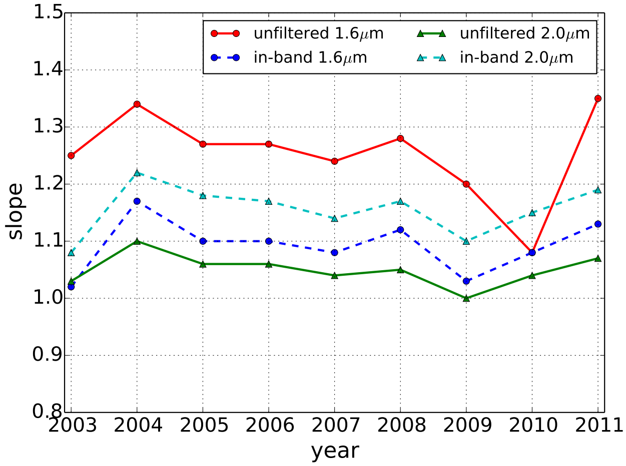

Figure 7. Slope of SABER 2.0 μm and 1.6 μm volume emission rates versus the corresponding simulations using SCIAMACHY data from 2003 to 2011.

about 20% for the OH 1.6 μm channel and 26% for the OH 2.0 μm channel. Considering the radiometric uncertainty of both instruments, which is estimated to be about 1% for SCIAMACHY and 3-20% for SABER, OH 2.0 μm in-band and "unfiltered" data agree within their combined uncertainties; OH 1.6 μm in-band data also agree remarkably well, but not for the "unfiltered" 1.6 μm data.

The OH 2.0 μm data measured by SABER and O(^{1}S) green line emission and OH(9-6) nightglow observed by SCIAMACHY were used in the past to obtain atomic oxygen abundances. Significant differences in atomic oxygen absolute values were reported (Kaufmann et al., 2014; Mlynczak et al., 2018; Zhu and Kaufmann, 2018). These differences are of similar magnitude as uncertainties in the Einstein coefficients and other model parameters used in the retrieval of those data.

Data availability. The SCIAMACHY Level 1b Version 8 data used in this study are available at ftp://scia-ftp-ds.eo.esa.int. SABER Version 2.0 data are available at http://saber.gats-inc.com. Derived OH volume emission rate data are available on request.

Competing interests. The authors declare that they have no conflict of interest.

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Reply to comments of Reviewer #1

We thank the reviewer for carefully reading the manuscript and his constructive and helpful comments and suggestions. They helped us to improve the paper in several aspects. We considered them point by point as illustrated below. We like to remark that line numbers mentioned in the reviewers comments refer to the first submission of the paper. We re-run the retrieval code to simulate OH radiances as measured by SABER from SCIAMACHY spectra and corrected radiance contamination to the previous unfiltered 1.6 μm simulations from other band emission lines due to the selected wavelength range. This problem was found when we run the retrieval using Einstein coefficients obtained by van der Loo and Groenenboom [2007, 2008] as suggested by the reviewer #2. The abstract was rephrased to make it more clear. Following the reviewer #3, we also simulated the in-band data as measured by SABER without considering the filter transmission effect for comparison.

Specific Comments*:*

Line 5*: "OH 1.6 μm and 2.0 μm radiances as measured by SABER were retrieved from OH limb measurements recorded by SCIAMACHY"*
This sentence is somewhat misleading, particularly the "retrieved from". In your study, OH concentration profiles were retrieved from SCIAMACHY limb measurements and these concentrations were then used to "simulate" SABER measurements, right? I suggest rephrasing the sentence - right now the sentence also suggests that SCIAMACHY measurements around 2.0 micron were used, which is not the case.
Reply: Following the reviewers' suggestion, we rephrased the abstract to make it more clear and to be well understood. Please refer to the abstract for details.

Line 7*: "Systematic deviations of up to 88% were found"*
In my opinion, the abstract is too negative and not representative of the obtained results. Only the large differences are mentioned. However, the mean differences are on the order of 10% for the 2.0 micron channel and 35% for the 1.6 micron channel. I suggest mentioning this as well.
Reply: We agree with the reviewer's suggestion. The mean difference is calculated using the formula:

$$\sum^{N} \frac{Radiance_{saber} - Radiance_{scia}}{Radiance_{scia}} / N$$

The average differences are on the order of 20% for the 2.0 μm channel and 40% for the 1.6 μm channel. The detailed description is here:

On average, SABER "unfiltered" data is on the order of 40% at 1.6 μm and 20% at 2.0 μm larger than the simulations using SCIAMACHY data.

Line 46: *"absolute volume radiances"*
Do you mean volume emission rates? To my knowledge "volume radiance" is not standard terminology. Radiance (usually) has the units: photons/s/m^2/sr (and /nm in case of "spectral radiance")
Reply: Thanks for the reviewer pointing out this issue. We changed "volume radiance" to "spectrally averaged radiances at 1.6 μm and 2.0 μm as measured by SABER".

Figure 1: *y-axis label: is this really a "radiance"? Are the units correct? Radiance should also include a solid angle dependence, right? I assume this should be "volume emission rate"?*
I also suggest mentioning in the figure caption, whether these are modelled or measured spectra.
Reply: Yes, the unit is "volume emission rate", not "radiance". The label has been changed to "VER". The spectra are modelled, which is also mentioned in the caption.

Line 59: *"In this study, only the spectral range of channel 6 up to 1650 nm"*
I think you only used wavelengths up to about 1600 nm. Channel 6+ (having a different detector material) starts shortly below 1600 nm. This would also be consistent with the shading in Figure 1.
Reply: We only use the spectral range of channel 6 up to about 1589 nm. This was corrected accordingly in the main text and in Figure 1.

Line 86: *"monthly zonal median data"*
The median was probably determined for each altitude separately? Was there a specific reason to use the median rather than the mean?
Reply: Yes, the median was determined separately for each altitude. There was no specific reason for using the median rather than the mean, because we tested the median and mean spectra before and found no big differences between them.

Line 96: *"by dividing the corresponding Einstein"→ "by dividing BY the corresponding Einstein"*
Reply: Corrected.

Line 102: *"Boltzmann factor"→"Boltzmann constant"?*
Reply: Corrected.

Line 107: *"the SCIAMACHY OH limb measurements can be expressed as"*
The SCIAMACHY OH limb measurements can also be expressed in this form

without the 2 conditions mentioned in the first part of the sentence. I suggest just stating that the SCIAMACHY measurements can be expressed in this form and that the two assumptions are made.
Reply: Following the reviewer's suggestion, the sentence was rephrased as below:
The SCIAMACHY OH limb measurements can be expressed as

$$\boldsymbol{y} = \boldsymbol{F}(\boldsymbol{x}, \boldsymbol{b}) + \boldsymbol{\epsilon}$$

In our setup we assume that each atmospheric layer emits OH airglow homogeneously, and we set the retrieval grid to be identical to the tangent altitude grid of the averaged OH limb measurements.

Line 109: *"measured SCIAMACHY OH limb spectra measured."*
Please delete one of the "measured"
Reply: Done.

Line 112: *"of interested properties"*
I suggest to replace this by "properties of interest". If the properties are interested in the retrievals, we dont know :)
Reply: Yes, we definitely agree :). It is corrected.

Line 113: *"In general, the inverse problem is ill-conditioned"*
This is only minor point and Im not asking for changes, but in your case, with the retrieval altitude grid being identical with the tangent height grid, the inverse problem is not ill-posed in the sense that there are more unknowns than knowns, right?
Reply: A well-posed problem should meet the three Hadamard criteria: 1. Having a solution; 2. Having a unique solution; 3. Having a solution that depends continuously on the parameters or input data. An ill-posed problem is the one which does not meet at least one of the criteria. In our case, we do the retrieval from the SCIAMACHY limb spectra and there are more knowns (sampling points) than the unknowns, but the solution is not unique. That is why we call it ill-conditioned.

Line 114: *"inverse issue"→"inverse problem"?*
Reply: Corrected.

Figure 3: *Perhaps colors can be used to highlight the 2 and 1.6 micron profiles? The symbols are quite small and difficult to identify.*
Related to Figure 3: I think it is also worthwhile to show some sample OH(v) concentration profiles. They are the intermediate data product linking the SCIAMACHY and SABER measurements and are, therefore, quite important for this study.

Reply: The colors are used to highlight the 2 and 1.6 micron profiles. As suggested by the reviewer, corresponding OH(v) concentration profiles are added in Figure 3.
A sentence is added in the main text:
Corresponding OH number density profiles as derived using Einstein coefficients from the HITRAN database at vibrational states 9, 8, 5, and 4 are also given.
A sentence is added in the caption of Figure 3:
Corresponding retrieved OH number densities of vibrational states 9, 8, 5, and 4 from SCIAMACHY data using HITRAN database (right).

Line 159/160: *I suggest mentioning explicitly what reference profile was used to determine the relative differences. In case of large differences, this choice of reference will be important.*
Reply: The reference data are simulations from SCIAMACHY data. The sentences are modified:
For the "unfiltered" data, deviations of SABER OH 1.6 μm measurements with respect to the corresponding simulations increase with altitude from 30-45% at 83 km to 55-80% at 96 km, depending on latitudes. The difference of SABER OH 2.0 μm measurements with respect to the corresponding simulations is 16% at 86 km.

Line 161: *"It was also found the positive deviations of SABER"*
Please rephrase, something is wrong here.
Same sentence and Fig. 4: I suggest discussing the difference between in-band and unfiltered SABER data in a few additional sentences. It took me a while to figure out whats shown in Figure 4.
Reply: This sentence was deleted and Figure 4 has been updated by adding a comparison of SABER in-band data and corresponding simulations using SCIAMACHY data. The difference between SABER in-band and unfiltered data has been discussed in Line 84-89. To make it more clear, some sentences are added in the main text.
The top two plots show a comparison of the "unfiltered" data and the bottom two figures show the in-band data.

Line 165: *"A strong annual oscillation was found over the equator region in April"*
"A strong annual variation ... in April" doesnt really make sense, does it. You mean an annual variation with a maximum in April, I guess? There is also a semi-annual component in your figures, as, e.g. also clearly seen in Teiser & v. Savigny, JASTP, 161, 28-42, 2017.

Reply: Thanks for the reviewer pointing out this problem. The sentence was rephrased.
A strong annual variation with a maximum in April and a semi-annual oscillation are visible in the radiance data over the equator region, as it was also found by Teiser and von Savigny [2017] in a study of SCIAMACHY OH(3-1) and OH(6-2) volume emission rates.

General comment: *Another general comment on the comparison of SCIAMACHY and SABER profiles: The SCIAMACHY and SABER volume emission rate profiles have different vertical resolutions. SCIAMACHY has a vertical resolution of about 4 km, SABER rather 2 km. The potential effects of this difference should be discussed, too. Im not asking for more simulations etc., but only a qualitative discussion of the expected effects on the comparisons and the agreement.*
Reply: As pointed out by the reviewer, SCIAMACHY has a vertical resolution about 3.3 km and the vertical resolution of SABER is around 2 km. A linear interpolation has been performed to the SABER data for the purpose of making a comparison with SCIAMACHY data. This means that we may underestimate the SABER data at peak altitudes and overestimate the data at two wings besides the peak altitudes. A discussion is given in the first paragraph of section 4.2:
It should be noted that SCIAMACHY and SABER have a resolution of about 3.3 km and 2 km, respectively. A linear interpolation has been applied to SABER data to make a comparison with SCIAMACHY data. This may underestimate the SABER data at peak altitudes and overestimate the SABER data at two wings besides the peak altitudes.

Figure 7: *y-axis label and caption: "slop" → "slope"*
Reply: Corrected.

References

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Reply to comments of Reviewer #2

We thank the reviewer for carefully reading the manuscript and his/ her constructive and helpful comments and suggestions. They helped us to improve the paper in several aspects. We considered them point by point as illustrated below. We like to remark that line numbers mentioned in the reviewers comments refer to the first submission of the paper. We re-run the retrieval code to simulate OH radiances as measured by SABER from SCIAMACHY spectra and corrected radiance contamination to the previous unfiltered 1.6 μm simulations from other band emission lines due to the selected wavelength range. This problem was found when we run the retrieval using Einstein coefficients obtained by van der Loo and Groenenboom [2007, 2008] as suggested by the reviewer #2. The abstract was rephrased to make it more clear. Following the reviewer #3, we also simulated the in-band data as measured by SABER without considering the filter transmission effect for comparison.

Specific Comments*:*

Abstract*: When reading the abstract for the first time, some parts are rather confusing. The meaning of the first three sentences is not clear and one needs to read the manuscript further for the abstract to make more sense. Somehow the references to the words "as measured" do not help and the second sentence "on the retrieval model to perform an inversion of OH(v) number densities in order to simulate OH ro-vibrational emission radiances using a non-linear regularized global fit technique" only complicates things further. The abstract needs to be well understood by itself and without referring to the rest of the manuscript. It must be clear to the readers that there are two sets of coincident / co-located measurements by these space-based instruments and one set is used to simulate the other and compare with it.*
It seems to me the abstract (and possibly the manuscript in general) understates the uncertainties of the Einstein coefficients and exaggerates the observed deviations between the SCHIAMACHY observations and SABER simulations. Additional comments will be discussed below.
Reply: Thank the reviewer for pointing out this issue. Most part of the abstract was rephrased to make it more clear to the readers. For details, please refer to the abstract. Following the reviewer's suggestion, Einstein coefficients calculated by van der Loo and Groenenboom [2007, 2008] were also considered in this work to estimate the uncertainties of the Einstein coefficients.

Main Manuscript*:*

1: *I am somewhat concerned that the truncation of the "overpopulated higher rotational levels" of the SCHIAMACHY spectra introduces systematic errors in this analysis. Non-local thermodynamic equilibrium conditions imply that we are dealing with a distribution that is not a true Boltzmann distribution. This applies to all rotational levels, including the ones with low rotational quantum numbers. For the lowest OH vibrational levels, it appears this effect is less significant and may be neglected in many cases, but the deviations become increasingly important for the highest vibrational levels and can, for example, lead to significant errors in the determination of the rotational temperatures. There is a sentence mentioning the authors performed a check of the effect of non-local thermodynamic equilibrium conditions and found it to be approximately 2%. It would be helpful to reconsider these checks and whether additional assessment is needed, and also provide some brief information on what these checks entailed. Moreover, it seems the SABER transmission windows include additional lines from other bands, e.g., there are a few lines of the 7-5 band in the 2.0-micron window. By neglecting these lines another systematic error is introduced, once again effectively "underestimating" the SCHIAMACHY measurements. Verifying that the above effects do not introduce significant bias in the simulation procedure and explicitly stating it would strengthen the manuscript.*

Reply: As said by the reviewer, non-LTE conditions affect all rotational levels deviating from a Boltzmann distribution with kinetic temperature. From the work of Oliva et al. [2015] and Kalogerakis et al. [2018], each vibrational state follows a Boltzmann distribution at low rotational levels, but with a different rotational temperature T_{cold}, which may differ from the kinetic temperature. Monthly zonal median OH airglow measurements from SCIAMACHY and monthly zonal mean temperature from SABER were used in the work. We can not use the SCIAMACHY measurements to investigate the non-LTE effect due to the low spectral resolution, as Oliva et al. [2015] and Kalogerakis et al. [2018] did based on cross-dispersed cryogenic spectrometer measurements in the spectral range of 0.97 μm to 2.4 μm. A theoretical study using the method of Oliva et al. [2015] has been performed. A weighted combination of two Boltzmann distribution equations with cold and hot OH rotational temperatures (T_{cold} and T_{hot}) was used to predict the observed intensities of OH emission lines. T_{cold} and T_{hot} were taken from the figure 2 of Oliva et al. [2015], as well as the fractions of the cold and hot molecules. Firstly, the calculated OH(9-7) band radiance is less than 1% larger than the one only considering the cold molecules. Secondly, the bandpass of the SABER interference filters capture the hot and the cold fractions of the rotational distribution. Therefore, this redistribution of energy is averaged out. Last but not least, Xu et al. [2012] investigated the temperature

dependence of the band-averaged Einstein coefficient. They found that the OH(9-7) band Einstein coefficient only changes by approx. 0.35% when the temperature increases from 200 K to 250 K. Therefore, the Non-LTE effect on the band-averaged radiance is less important than for rotational temperature retrieval. A detailed description of the checks are added in the text.
The low spectral resolution of SCIAMACHY spectra does not allow to estimate this effect from the measured data. Therefore, we performed model simulations using the same approach and parameter sets as Oliva et al. [2015] to quantify the effect of incomplete thermalization on the spectral ranges used in this study. We calculated OH 1.6 μm and 2.0 μm VERs by considering only the cold rotational temperature and then obtained them using cold and hot temperatures together as Oliva et al. [2015] and Kalogerakis et al. [2018] did. It was found that differences between them are less than 2% for both SABER channels.
The OH 1.6 μm and 2.0 μm channels include additional lines from OH(3-1) and OH(7-5), respectively. We assume two ideal filters for these two channels with upper cut-off wavenumbers at 5150 cm^{-1} for 2.0 μm channel and 6400 cm $^{-1}$ for 1.6 μm channel. OH(7-4) and OH(3-1) nightglow emissions have been observed by SCIAMACHY channel 6 and the same retrieval procedure described in the main text applied to them to derive OH(7-5) and OH(3-1) emissions. The contributions of OH(7-5) and OH(3-1) to the two channels are about 3% and 1%, respectively. A statement is added in the main text as below:
The SABER 1.6 μm and 2.0 μm channels also observe emission lines from OH(3-1) and OH(7-5), respectively. We estimated their influence on spectrally integrated radiances by the derivation of the corresponding emissions using SCIAMACHY OH(3-1) and OH(7-4) nightglow measurements. These simulations show that the contributions of OH(7-5) and OH(3-1) to the two channels are about 3% and 1% on average, respectively.

2: *I find it rather difficult to accept the notion that the role of Einstein coefficients introducing bias is not significant. The fact that two rather similar sets of Einstein A coefficients were used provides some idea as to what differences can be expected, but the possibility of significant absolute systematic errors introduced by the coefficients cannot be excluded. The conversion of SCHIAMACHY observations to SABER simulations essentially depends on the ratio of the respective Einstein coefficients for the vibrational levels of interest, e.g., the ratios A(9-6)/A(9-7) and A(8-5)/A(8-6) for the SABER 2.0-micron channel. The values of these ratios for the HITRAN coefficient set* *are 13% larger than those of Brooke et al., but approximately 26% larger than the Einstein coefficient set of van der Loo and Groenenboom (2007, 2008). With older A coefficient sets, the discrepancies can be much larger, but it is quite reasonable to consider that these three most recent Einstein coefficient sets are the most appropriate choices available.*

Reply: Following the reviewer's suggestion, Einstein coefficients calculated by van der Loo and Groenenboom [2007, 2008] are also considered in the work. As said by the reviewer, the differences of the band-averaged Einstein coefficient ratios between HITRAN and those of van der Loo and Groenenboom (2007, 2008) are the largest by comparing the three Einstein coefficient datasets. The resultant differences of the retrieved VERs for 1.6-micron and 2.0-micron are 19% and 26%, respectively. The differences can potentially explain most of the deviations between SABER data and the simulations from SCIAMACHY data. The main text has been modified accordingly.

3: *Figure 1 displays the region of overlap between the two instruments (note: it is difficult to view the shaded area, please modify this figure to make it legible). Would it be meaningful to make another comparison by using the overlapping spectral region of the 4-2 band to simulate the SABER 1.6-micron channel? If the fraction of the 4-2 band that is covered is substantial, then such a comparison would be direct to some extent and would rely less on Einstein coefficients. Maybe testing one or two examples would clarify whether there is anything meaningful to be learned and any additional effort is warranted.*

Reply: As suggested by the reviewer, the shaded area in Figure 1 is highlighted to make it more legible. The overlapping spectral region by SCIAMACHY and SABER only covers about half of OH(4-2) emissions. In addition, there are a few OH(3-1) lines in the bandpass of SABER 1.6μm channel. In total, SCIAMACHY measurements cover only about 30% of the total radiances in the SABER 1.6μm channel directly. Therefore, the use of Einstein coefficients to transfer SCIAMACHY to SABER measurements cannot be avoided.

Technical Corrections:

Line 22: *"imaged" or "monitored" may be more appropriate verb choices rather than "captured"*

Reply: "monitored" is used.

Lines 112, 113, 114: *"inverse" or "inversion"?*

Reply: It is "inversion". Corrected.

Lines 162-163: *"It was also found the positive deviations of SABER in-band data from the simulated values, especially for OH 2.0 μm data." Something*

is missing in this phrase.
Reply: This sentence is deleted because a more detailed description is given: **Surprisingly, for the in-band data, the differences for the 1.6 μm and 2.0 μm channels are significantly smaller at most altitudes. They vary in a range of 8-28% (21-50%) and 8-60% (28-100%) from 83 km to 96 km at 0°-20°N (20°N-40°N).**

Line 167: *"than the corresponding" instead of "than corresponding"*
Reply: Corrected.

Figure 7: *"slope" instead of "slop" in the label for the y axis and "slop" instead of "slops" in the caption*
Reply: Corrected.

Line 211: *reference pages are missing*
Reply: Added.

Lines 244: *"Astrophys. J." This is the only journal that appears as an abbreviation (the preferred AMT format).*
Reply: We changed every journal's name to their abbreviation.

Line271 : *"Astrophysics" instead of "Atrophysics" (but still needs abbreviated title).*
Reply: The abbreviation of the journal is used.

References

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Reply to comments of Reviewer #3

We thank the reviewer for carefully reading the manuscript and his/ her constructive and helpful comments and suggestions. They helped us to improve the paper in several aspects. We considered them point by point as illustrated below. We like to remark that line numbers mentioned in the reviewers comments refer to the first submission of the paper. We re-run the retrieval code to simulate OH radiances as measured by SABER from SCIAMACHY spectra and corrected radiance contamination to the previous unfiltered 1.6 μm simulations from other band emission lines due to the selected wavelength range. This problem was found when we run the retrieval using Einstein coefficients obtained by van der Loo and Groenenboom [2007, 2008] as suggested by the reviewer #2. The abstract was rephrased to make it more clear. Following the reviewer #3, we also simulated the in-band data as measured by SABER without considering the filter transmission effect for comparison.

General comments*:*

1)*: Although the differences found between the instruments are important themselves, the authors should expand the laconic sentence that "the differences may be explained by the radiometric calibration of both instruments". I believe both instruments have been well characterized and estimates of their errors been given. The authors should discuss if the differences found are or not within the calibration errors of the instruments. Could they attribute the differences to a given instrument? e.g. on the basis that the calibration errors are smaller for one instrument than for the other?*

Reply: The observed accuracy of SABER 1.6 μm and 2.0 μm channels is about 3% at 80-90 km and about 20% at 90-100 km ("SABER Instrument Performance and Measurement Requirements" published on http://saber.gats-inc.com/overview.php). The propagated radiometric uncertainty of SCIAMACHY channel 6 is about 1.2% [Zoutman et al., 2000]. Both instruments have been well characterized. The differences of SABER data and the simulations from SCIAMACHY data are not within combined calibration errors of two instruments. However, we simulated OH radiances as measured by SABER using Einstein coefficients calculated by van der Loo and Groenenboom [2007, 2008] as recommended by the reviewer #2 and found that the uncertainty resulted from different datasets of Einstein coefficient could potentially explain the large differences of SABER data and the simulations from SCIAMACHY data.

2)*: I would also like the authors comment on the expected impact of these differences on the retrieved atomic oxygen from both datasets. Can the*

current O differences discussed in the introduction be explained by these differences? Would they reconcile the O differences or, on the other hand, would they still support or even enlarge the O differences?
Reply: We have analyzed the impact of these differences on the retrieved atomic oxygen from the two datasets and found these radiance differences almost reconcile the retrieved atomic oxygen differences, especially at low altitudes. A paragraph is added at the end of the text:
The OH 2.0 μm data measured by SABER and O(^{1}S) green line emission and OH(9-6) nightglow observed by SCIAMACHY were used in the past to obtain atomic oxygen abundances. Significant differences in atomic oxygen absolute values were reported [Kaufmann et al., 2014, Mlynczak et al., 2018, Zhu and Kaufmann, 2018]. These differences are of similar magnitude as uncertainties in the Einstein coefficients and other model parameters used in the retrieval of those data.

Minor comments and suggested minor changes and typos*:*

Line 8*: Worth to state here already which one (SABER/SCIA) is larger/smaller.*
Reply: Stated.

Line 30*: Just over 1+1/2 solar cycles. Worth mentioning it is still measuring.*
Reply: A sentence is added:
covering one and half solar cycles, and is still measuring

Lines 44-48*: Consider some merging. Some information is somehow duplicated*
Reply: The duplicated sentence in line 44-45 was deleted.

Legend of Fig. 1*: Include that they are "simulated radiances".*
Reply: "Simulated" is included.

Line 56*: Delete "between two adjacent tangent heights". It is redundant.*
Reply: Deleted.

Line 57*: from vibrational states 2 to 9 at → from UPPER vibrational states in the range of 2 to 9 at ...*
Reply: Corrected.

Line 58*: Bring all that information (particularly the radiometric calibration) to the discussion on the reason of the differences in Sec. 4.2 below.*
Reply: Done.

Line 62*: Start new paragraph with "The SABER ..."*
Reply: Done.

Lines 73-76: *Consider remove or re-write and merge with the next paragraph the sentence "The SCIAMACHY channel ... for SABER".*
Reply: The sentence was merged with the next paragraph.

Legend of Fig. 2: *Explain the meaning of the "fit" and "raw" symbols in the legend, so the reader do not have to read the text for understanding it.*
Reply: An explanation is given in the caption of Figure 2.
raw: the raw limb spectra measured by SCIAMACHY; fit: simulated limb spectra as measured by SCIAMACHY from retrieval results.

Line 80: *Mention here that rotational non-LTE is considered, and that it will be assessed later in the paper.*
Reply: It is mentioned in the text.
details are discussed later.

Near the end of page 4: *About the method used when comparing SCIA and SABER radiances. Although probably the effects are small, I think it is more consistent to apply the SABER filters to the computed SCIA spectra and compared directly to the measured SABER radiances. In the way it has been done, by comparing with the "unfiltered" SABER radiances, the authors rely on the method used in SABER for unfiltering the radiances, e.g., in an OH model, which might be different, from that used in the retrieved OH radiances from SCIA.*
Reply: We agree with the reviewer for applying the SABER filters to the simulated radiance data from SCIAMACHY spectra. We applied bandpass filters of SABER 1.6 μm and 2.0 μm channels to the simulated OH radiances from SCIAMACHY measurements, including contributions of OH(7-5) and OH(3-1) emissions. Corresponding discussions are given in the text.

Line 86: *monthly zonal MEAN?*
Reply: We have tested monthly zonal median and mean spectra before and found no big differences between them.

Line 97: *... dividing BY ..*
Reply: Corrected.

Line 97: *State that this equation is valid under the assumption of rotational LTE. And that rotational NLTE is considered later. Should not E_v be actually $E_{rotational}$ in Eq. 1?*
Reply: A statement is added as below:
This formula is only valid under the rotational local thermodynamic equilibrium (LTE) condition and deviations are discussed later.

Here, $E_v(i)$ represents the rotational energy of the upper rotational state of the ith line and is equivalent to the $E_{(v,J)}(i)$.

Line 111: *"b" not only includes the Einstein coefficients, but also the other factors accompanying n_v in Eq. 1.*
Reply: Yes, i.e. → **e.g.**

Line 114: *issue → problem? Full stop → comma? Consider re-writing.*
Reply: re-written. **inverse issue → inversion problem**; Full stop → comma

Line 126: *median → MEAN?*
Reply: Yes, here is "mean".

Line 128: *I believe the estimated effects of the temperature errors include not only the effects of temperature on the Einstein coefficient but also on the rotational populations (see Eq. 1).*
Reply: Yes, we agree with the reviewer. According to Equation 1, the change of temperature will redistribute the rotational populations first, and then affects the band-average Einstein coefficient. The effects of temperature on the band-averaged Einstein coefficient and on the rotational populations are not independent with each other. Both of them have been considered in the estimated effects.

Line 132: *Probably worth to be clarified that the Einstein coefficient errors enter not only through the retrieval of SCIA, as it is described in the paragraph above, but also through the A of the transitions of the SABER measured bands (which was not described in the paragraphs above).*
Reply: The estimation of the Einstein coefficient errors in the text have considered these two aspects: one enters through the retrieval of SCIAMACHY data; another one enters through the simulation when using the Einstein coefficient of the SABER measured bands. A sentence is added in the text;
The uncertainty of the Einstein coefficient affects simulated VERs in two ways: In the retrieval of vibrationally excited OH from SCIAMACHY data and in the simulation of the SABER measurements.

Lines 138-139: *Consider rewriting this sentence (somehow redundant with previous one).*
Reply: The sentence is rephrased:
Therefore, we used these results as a proxy to estimate related uncertainties of the Einstein coefficients.

Line 165: *"A strong annual oscillation..." In the radiances or in the differences?*

Reply: It is the radiance and specified:
A strong annual variation with a maximum in April and a semi-annual oscillation were found in the radiance data over the equator region, as it was also found by Teiser and von Savigny [2017] in a study of SCIAMACHY OH(3-1) and OH(6-2) volume emission rates.

Line 169: *Delete "here".*
Reply: Deleted.

Fig. 4: *I would suggest to use different line styles for SCIA and SABER? and/or use larger symbols.*
Reply: Different line styles were used for SCIAMACHY and SABER data.

Lines 187-189: *Please see my two major points above.*
Reply: Considered.

Fig. 6 Right panel: *The error of "b" is 0.00. Please, revise it.*
Reply: Revised.

Fig. 7: *Slop → slope? Both, in the legend and in the y-axis label. Is there any reason for the sudden drop in the slope in 2010? Please comment on it.*
Reply: The word "slope" is correct. The sudden drop in the slope in 2010 results from very discrete fitting data points in 2010 for SABER 1.6 μm channel by comparing to other years.

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