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## Intercomparison of ozone profile measurements from ASUR, SCIAMACHY, MIPAS, OSIRIS, and SMR

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[1] The airborne submillimeter radiometer (ASUR) was deployed onboard the Falcon research aircraft during the scanning imaging absorption spectrometer for atmospheric cartography (SCIAMACHY) validation and utilization experiment (SCIAVALUE) and the European polar stratospheric cloud and lee wave experiment (EuPLEx) campaigns. A large number of ozone profile measurements were performed over a latitude band spanning from 5°S to 80°N in September 2002 and February/March 2003 during the SCIAVALUE and around the northern polar latitudes in January/February 2003 during the EuPLEx. Both missions amassed an ample microwave ozone profile data set that is used to make quantitative comparisons with satellite measurements in order to assess the quality of the satellite retrievals. In this paper, the ASUR ozone profile measurements are compared with measurements from SCIAMACHY and Michelson interferometer for passive atmospheric sounding (MIPAS) on Environmental Satellite and optical spectrograph and infrared imager system (OSIRIS) and submillimeter radiometer (SMR) on the Odin satellite. The cross comparisons with the criterion that the ASUR measurements are performed within  $\pm 1000$  km and  $\pm 6$  hrs of the satellite observations show a good agreement with all the four satellite sensors. The differences in data values are the following:  $-4$  to  $+8\%$  for ASUR-SCIAMACHY (operational product, v2.1), within  $\pm 15\%$  for ASUR-SCIAMACHY (scientific product, v1.62), up to  $+6\%$  for ASUR-MIPAS (operational product v4.61) and ASUR-MIPAS (scientific product v1-O<sub>3</sub>-1), up to  $17\%$  for ASUR-OSIRIS (v012), and  $-6$  to  $17\%$  for ASUR-SMR (v222) between the 20- and 40-km altitude range depending on latitude. Thus, the intercomparisons provide important quantitative information about the quality of the satellite ozone profiles, which has to be considered when using the data for scientific analyses.

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### 1. Introduction

[2] Satellite sensors become more and more important in monitoring the Earth's environment because of their global coverage and almost daily temporal resolution. New sensors

are deployed to supplement the existing space-borne sensors and execute novel measurement techniques for a better understanding of the current atmospheric composition and climatic change. The Environmental Satellite (Envisat), which was launched in 2002, and the Odin satellite, which is in orbit since 2001, are new instrument platforms to observe the atmosphere from space.

[3] It is necessary to assess the quality of the data from a newly installed sensor by well-tested and proven instruments. This assessment usually enhances sensor performance by improved calibration, refined algorithms, and possible debugging. Aircraft platforms have a high level of flexibility to gather data for intercomparison with satellite observations in order to assess the quality of the sensor retrievals. Their range allows for terrain-independent measurements and wide latitudinal coverage compared to ground-based sensors although the ground-based data have certain other advantages. Furthermore, the measurements offer the closest match in time and geolocation. This is important, in particular, for

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regions of atmospheric variability, such as in the northern hemispheric winter stratosphere. Therefore the airborne measurements allow the combination of the different satellite observations, which never measure air masses simultaneously. The flexibility and the latitudinal spreading of the aircraft measurements during the scanning imaging absorption spectrometer for atmospheric cartography (SCIAMACHY) validation and utilization experiment (SCIAVALUE) and the European polar stratospheric cloud and lee wave experiment (EuPLEx) missions provide the fundamentals for the comparisons within this study.

[4] Validation of space-borne sensors are usually carried out with a large amount of correlative data, including high-resolution sondes and lidar measurements with known accuracy, which are observed in all seasons to make a good statistics out of the comparisons. Furthermore, a criterion should be selected for the comparisons so that the temporal resolution should address the natural variability and that the spatial resolution should resolve relevant gradients in the measurements. The comparison performed in this study is limited to the airborne submillimeter radiometer (ASUR) measurements that are observed in two seasons. Therefore it can be referred to as a cross comparison of the ozone profiles instead of a validation of the satellite data. Nevertheless, the study gives an opportunity to make a cross comparison of the satellite data themselves to check the quality of the sensor retrievals. A statistical analysis is also performed from the comparison results, which will be useful to the scientific community while using the satellite data, as well as to those who are working on error estimation of the satellite data. Therefore this cross comparison also serves as a primary stage of the validation of the new satellite data.

[5] We present intercomparison of the ASUR ozone profile measurements with data retrieved from the space-borne limb sensors SCIAMACHY and Michelson interferometer for passive atmospheric sounding (MIPAS) on Envisat, as well as optical spectrograph and infrared imager system (OSIRIS) and submillimeter radiometer (SMR) on Odin. Data of ASUR already contributed to the validation of microwave limb sounder on Upper Atmospheric Research Satellite [Crewell *et al.*, 1997], of improved limb atmospheric sounder on Advanced Earth Observing Satellite [Sugita *et al.*, 2002; Kanzawa *et al.*, 2003], and of SMR on Odin [Urban *et al.*, 2005a]. This paper is arranged in the following manner: (2) brief description of the relevant satellite sensors, (3) presentation of the ASUR sensor and ozone profile retrieval method, (4) the airborne measurement campaigns, (5) selection criteria for ASUR measurements for the comparison, (6–9) description of the satellite data analysis for the intercomparison and results, (10) discussion of the results, and (11) concluding remarks.

## 2. Satellite Sensors

### 2.1. SCIAMACHY on Envisat

[6] Envisat is one of the largest European satellites, which is in a polar sun-synchronous orbit with a period of about 100 min and ascending nod crossing time at 1000 hours local time. SCIAMACHY is an atmospheric chemistry payload onboard the Envisat satellite. It measures a range of atmospheric constituents (e.g., ozone) in limb-, nadir-, and occultation-viewing geometries. The sensor consists of eight

channels covering a spectral range between 220 nm and 2.4  $\mu\text{m}$  with a spectral resolution of 0.1–1.5 nm. In the limb observation mode, the spectrometer slit is projected parallel to the horizon in-flight direction by the combination of limb and nadir mirror. The instantaneous field of view spans 2.6 km in the vertical direction and 110 km in the horizontal direction at the tangent point. Further information about the SCIAMACHY limb scanning is presented in section 5 (paragraph 2). The instrument and its measurement modes are described in detail by Bovensmann *et al.* [1999].

### 2.2. MIPAS on Envisat

[7] The MIPAS Fourier transform spectrometer measurements provide high-resolution ( $0.035\text{ cm}^{-1}$ ) gaseous emission spectra at the Earth's limb. It operates from 4.15 to 14.6  $\mu\text{m}$  in which many atmospheric molecules have significant emission features. The field of view at the limb tangent point is 3 km in the vertical direction and 30 km in the horizontal direction. The line-of-sight viewing range in the vertical is 5–200 km (tangent height), and in the horizontal, it covers a range of  $35^\circ$  around the rearward direction and about  $30^\circ$  for side-viewing geometries. The sensor performs rearward viewing in the antflight direction and in sideways. The rearward scanning is used for most measurements since it provides a good Earth coverage including polar latitudes. The sideways range is important for special events like volcano eruptions. A detailed account on the instrument is given by Fischer and Oelhaf [1996].

### 2.3. OSIRIS on Odin

[8] Odin is a Swedish-led satellite that is in a sun-synchronous, near-terminator orbit with the ascending node at 1800 hours local time [Murtagh *et al.*, 2002]. OSIRIS is one of the two instruments on Odin that consists itself of two parts: optical spectrograph and infrared imager system. The optical spectrograph used for this study measures scattered sunlight in the Earth's limb over the wavelength range of 280–810 nm with  $\sim 1$  nm spectral resolution. It has a field of view of  $1.288'$  in the vertical direction, equivalent to  $\sim 1$  km of height at the tangent point. OSIRIS normally collects a spectral image approximately once in every 2.5 s. The duration of each scan ranges from 70 to 130 s, which corresponds to a horizontal resolution of  $\sim 500$  to  $\sim 1000$  km along the satellite track. Further details on the OSIRIS instrument design and performance are provided by Llewellyn *et al.* [2004].

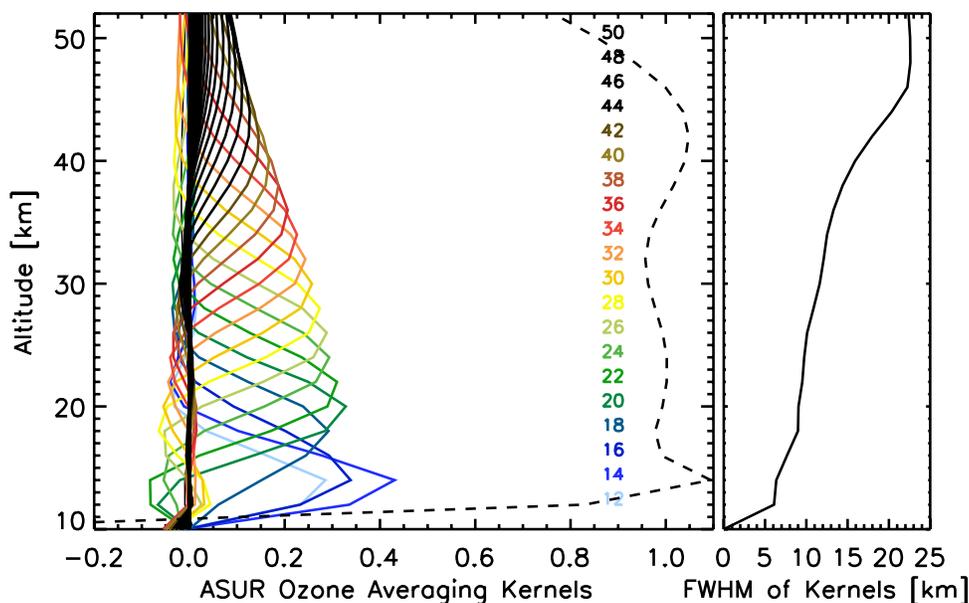
### 2.4. SMR on Odin

[9] The Odin/SMR instrument comprises four tunable single-sideband Schottky-diode heterodyne receivers in the 486- to 581-GHz spectral range. A telescope of 1.1 m diameter is used for passive observations of thermal emissions from the Earth's limb. The channels are tunable over 17 GHz. Atmospheric measurements are spectrally resolved using two autocorrelator spectrometers with a processed bandwidth of 700 MHz and a spectral resolution of 2 MHz. The sensor characteristics and measurement features are described in detail by Frisk *et al.* [2004].

## 3. Airborne Measurements With ASUR

### 3.1. Instrument

[10] The measurements compared with the satellite data were carried out by ASUR [Mees *et al.*, 1995; von König *et*



**Figure 1.** The averaging kernels of ASUR ozone retrievals and resolution defined by the full width at half maximum (FWHM) of the averaging kernels for a typical ozone measurement. The dashed line is the sum of the averaging kernels.

*al.*, 2000]. ASUR is a passive heterodyne sensor operating in a tuning frequency range of 604–662 GHz, which has a very low system noise temperature due to its superconductor-insulator-superconductor mixer system [*de Valk et al.*, 1997]. The sensor is equipped with two spectrometers: an acousto-optical spectrometer (AOS) and a chirp transform spectrometer (CTS). The AOS has a total bandwidth of 1.53 GHz with a resolution of 1.26 MHz, whereas the CTS has a bandwidth of 178 MHz with a resolution of 278 kHz. The AOS is mainly used for stratospheric measurements, whereas the high-resolution CTS is used for probing mesospheric constituents [e.g., *Kleinböhl*, 2004]. The stratospheric measurements performed with the AOS are used in this study. Apart from ozone, ASUR measures a range of stratospheric molecules like ClO, HCl, HNO<sub>3</sub>, and N<sub>2</sub>O. The sensor is operated onboard a high-flying research aircraft to avoid signal absorption due to the tropospheric water vapor. Mounted on the right side of the aircraft, the receiver looks upward at a constant stabilized zenith angle of 78°.

### 3.2. Retrieval Method

[11] Ozone lines are present in the spectral windows of all other molecules in the ASUR spectra. A line in the HCl spectrum at 625.371 GHz is used for the ozone retrieval, for which the AOS center frequency corresponds to an HCl line at 625.918 GHz. Since the line center of both molecules is close enough, a joint retrieval is possible. The raw spectra are calibrated and integrated to achieve a reasonable signal-to-noise ratio. Sensitivity tests showed that the integration of 80 s or 15 spectra is enough for a reasonable inversion of ozone. The AOS data are binned to 4 MHz channel spacing so that the individual channels are uncorrelated. The optimal estimation method (OEM) [*Rodgers*, 1976, 2000], together with an in-house radiative transfer model for a nonscattering atmosphere, is applied to invert the measured spectra. Since the sensor measures the thermal emissions from rotational

lines of the observed molecules, the shape of the pressure-broadened lines contains information about the altitude of the emitting species.

[12] The OEM allows to employ an a priori profile in the retrievals to stabilize the inversion problem. This a priori information is a climatological ozone mixing ratio profile as a function of altitude for the subarctic winter stratosphere, which is taken from the work of *Fortuin and Kelder* [1998]. The square root of the a priori values is given as its covariance spectrum in the inversion. Sensitivity tests show that the ozone retrieval is robust and is insensitive to changes in the a priori values used in the retrieval. So a single a priori profile is employed in the retrieval from the tropics to the Arctic. The retrieved profile has a horizontal resolution of 20 km derived from the integration time and aircraft speed and a vertical resolution of 6–18 km ranging from the lower to the upper stratosphere.

[13] The averaging kernels and the full width at half maximum (FWHM) of the averaging kernels, a measure of vertical resolution of ASUR ozone retrievals, are shown in Figure 1. Averaging kernel function at a certain altitude indicates the contribution of other altitude levels to the retrieved result at the altitude under consideration. If the sum of the averaging kernels is 1, then the retrieved information comes from the measurement, and if the sum is below 0.5, the retrieved information is mainly dominated by the a priori values. Therefore, between 16 and 50 km, the ASUR ozone retrievals are not influenced by the a priori information. Accuracy of the individual measurements has been determined by spectral line parameters, accuracy of the meteorological data, and signal-to-noise ratio. The accuracy of a typical ASUR O<sub>3</sub> profile has been estimated as 0.3 ppm (parts per million) or 10%, whichever is greater, and the precision, which is limited by the measurement noise, of a typical measurement is 0.1 ppm. Further information on the profile retrieval from ASUR measurements can be found in

the studies of *Wehr et al.* [1995], *Bremer et al.* [2002], and *Kuttippurath* [2005].

[14] An error in the instrument calibration led to systematically high values in earlier publications with the ASUR measurements [*Bremer*, 2002; *Bremer et al.*, 2002], which has been rectified for this study. That is, the ASUR measurements have been validated in the past with a large number of airborne lidar, ozonesonde, satellite, and ground-based microwave measurements. During these validation exercises, a constant high bias of 12% was observed in the ASUR ozone measurements. This high bias has been studied in detail, and sensitivity studies have shown that the reason for this positive bias can be attributed to the uncertainties either in the cold load reflectivity or the window transmission [*Kuttippurath*, 2005; *Bremer et al.*, 2002]. Though it was not possible to distinguish which of these processes is the reason for the high bias, the bias has shown a very stable value of 12% throughout the large set of validation data. Therefore the bias of 12% is deducted from the ASUR ozone volume mixing ratios (VMRs) prior to the comparisons.

[15] Since ASUR ozone profiles have a rather poor vertical resolution as compared to satellite measurements, a direct comparison between the profiles is not desirable. Therefore, as proposed by *Rodgers* [2000], the high-resolution profiles are reduced into the resolution of ASUR ozone profiles by convolution using the ASUR ozone averaging kernel matrix and the ASUR a priori profile. The convoluted/smoothed profile is the sum of the ASUR a priori profile, and the difference between the satellite ozone profile and the ASUR a priori profile, weighted by the averaging kernel matrix of ASUR ozone.

## 4. Measurement Campaigns

### 4.1. SCIAVALUE

[16] SCIAVALUE was the campaign performed aboard the Falcon research airplane, operated by the German Aerospace Center, Oberpfaffenhofen, to validate the SCIAMACHY on Envisat. Apart from ASUR, the UV-Vis airborne multi-axis differential optical absorption spectrometer [*Bruns et al.*, 2004] and the ozone lidar experiment [*Wirth and Renger*, 1996] were the other Falcon payloads during the campaign. The mission took place in two deployments that were conducted in two different seasons covering a latitudinal span from Spitzbergen (78°N) to the Seychelles (5°S) to validate the sensor data in various atmospheric conditions. The first deployment was in September 2002, and the second deployment was in February–March 2003. A total of 29 flights, 14 in the first and 15 in the second deployment, were performed. Details of the ASUR measurement flights are listed in Table 1, and the ozone measurements are shown in Figures 2 and 3. The campaign is described in detail by *Fix et al.* [2005].

### 4.2. EuPLEx

[17] The EuPLEx mission was part of the European atmospheric research program validation of international satellites and study of ozone loss (VINTERSOL), which was conducted in January and February 2003. A number of ground-based and airborne instruments based at Kiruna (Sweden) performed measurements in and around the

northern polar vortex during the mission. Since a number of newly launched satellite measurements were available, the campaign measurements were coordinated to meet the requirements for validation of the satellite sensors as well. The ozone profile measurements taken by ASUR, aboard the Falcon, during the campaign were used. The ASUR measurement flights during the campaign are listed in Table 1, and a description of the mission can be found in the paper of *Kuttippurath* [2005].

## 5. Colocation Criteria

[18] ASUR measurements that were performed within  $\pm 1000$  km and  $\pm 6$  hrs of the satellite observations are considered except for the OSIRIS coincidence where the time criterion applied is 8 hrs. This criterion is reasonable to resolve the natural variability and gradients in the measurements (as discussed in section 1, paragraph 3). Considering the average stratospheric wind speeds, the satellites have a reasonable chance to meet the same air mass, which was measured by ASUR within the time-distance criterion too. However, under polar vortex conditions, there can be large differences in the mixing ratios inside and outside of the vortex. Therefore care has been taken while finding the difference between ASUR and satellite ozone profiles, so that both profiles are either from inside of the vortex or from outside of the vortex region. There were a few profiles in the edge region, which were not accounted for in the analysis, though the measurements were within the selected time-distance criterion. The vortex edge regions at 475 K and 550 K levels were determined by applying the criterion of *Nash et al.* [1996] using the European Center for Medium-range Weather Forecasting (ECMWF) meteorological analysis. Since diurnal variation of stratospheric ozone is very small, the temporal criterion of 6 or 8 hrs ( $\frac{1}{4}$ th of a day) is thus reasonable for the comparisons.

[19] Limb profiles are usually the intrinsic average along the chord of their observation, which sets a limitation to the horizontal resolution of the measurements. That is, in the limb geometry, the line of sight of the instrument follows a slant path tangentially through the atmosphere. The detected radiation is scattered/emitted along the line of sight into the field of view of the instrument. For instance, the geometrical field of SCIAMACHY is 2.8 km in vertical direction and 110 km in horizontal direction. The Earth's limb is viewed in flight direction and scanned from a tangent height of about 0 to 100 km in 3.3 km intervals. At every tangent altitude, a horizontal scan is performed, covering about 960 km at the tangent point. So the limb observations scale an average of 1000 km perpendicular to the orbit track and 400 km along the flight track. Although there are differences in the fields of view and the scan sequences, the overall measurement characteristics of the limb sensors are similar. Therefore the averaging was also considered while selecting the criterion for the intercomparisons.

[20] The difference is calculated from the individual profile comparison ( $\Delta$  ozone = ASUR ozone-satellite ozone). The individual  $\Delta$  profiles are then averaged over the climatic regimes: the tropics/low latitudes (5°S–30°N), the midlatitudes (30°–60°N), and the Arctic/high latitudes (60°–90°N). The results are presented in terms of the climatic regions, as well as the average of all the  $\Delta$  profiles

**Table 1.** The ASUR Measurements During SCIAVALUE and EuPLEx and Coincident Measurements With the Respective Satellite Sensors During the Observations<sup>a</sup>

Flight Number	Fight Date	Falcon Flight Track	Colocated Measurements With the Satellite Sensors
SCIAVALUE 2002			
1	03–09–2002	Munich–Kiruna	OL
2	04–09–2002	Kiruna–Ny Ålesund–Kiruna	OL, IPF
3	05–09–2002	Kiruna–Keflavik	
4	06–09–2002	Keflavik–Kangerlussuaq	OL
5	07–09–2002	Kangerlussuaq–Keflavik	OSI, SMR
6	07–09–2002	Keflavik–Munich	OSI, SMR
7 <sup>b</sup>	15–09–2002	Munich–Palma de Mallorca	
8	17–09–2002	Palma de Mallorca–Djerba–Niamey	IFE, OL, IPF
9	18–09–2002	Niamey–Nairobi	IFE, OL, IPF, IMK
10	19–09–2002	Nairobi–Seychelles	IFE, OL, IPF, IMK, OSI
11	24–09–2002	Seychelles–Nairobi	OL, IPF, OSI
12	25–09–2002	Nairobi–Niamey–Djerba	IFE, OL, IPF, IMK, OSI, SMR
13	26–09–2002	Djerba–Palma de Mallorca	IFE, OL, IPF, IMK, OSI, SMR
14	28–09–2002	Palma de Mallorca–Munich	OL, IPF
EuPLEx 2003			
15	14–01–2003	Munich–Kiruna	IPF
16 <sup>b</sup>	15–01–2003	In the Arctic	
17	19–01–2003	In the Arctic	IPF
18	23–01–2003	In the Arctic	IPF
19	26–01–2003	In the Arctic	IPF
20	07–02–2003	In the Arctic	IPF, OSI
21	08–02–2003	In the Arctic	IPF, OSI
22	09–02–2003	In the Arctic	IPF
23 <sup>b</sup>	12–02–2003	Kiruna–Munich	
SCIAVALUE 2003			
24	19–02–2003	Munich–Basel–Tozeur	IFE, OL, IPF, IMK, SMR
25	20–02–2003	Tozeur–Niamey–Yaounde	
26 <sup>b</sup>	23–02–2003	Yaounde–Nairobi	
27	24–02–2003	Nairobi–Mombasa–Seychelles	IFE, OL, IPF, IMK
28	26–02–2003	Seychelles–Nairobi	IFE, OL, IPF, IMK
29	28–02–2003	Nairobi–Douala	IPF, IMK, SMR
30	01–03–2003	Douala–Niamey–Tozeur	IFE, OL, IPF
31 <sup>b</sup>	03–03–2003	Tozeur–Munich	
32	10–03–2003	Munich–Kiruna	IFE, OL, IPF, IMK, OSI, SMR
33	12–03–2003	Kiruna–Ny Ålesund–Kiruna	IFE, OL, IPF, IMK, OSI
34	13–03–2003	Kiruna–Keflavik	OL, IPF, IMK, OSI, SMR
35	14–03–2003	Keflavik–Kangerlussuaq	IFE, OL, IPF, OSI, SMR
36	15–03–2003	Kangerlussuaq–Keflavik	IPF, OSI, SMR
37	17–03–2003	Keflavik–Munich	OSI, SMR
38	19–03–2003	Munich–Munich	IPF

<sup>a</sup>The sensors are represented by the notations: OSI = OSIRIS, OL = SCIAMACHY OL, IFE = SCIAMACHY IFE, IPF = MIPAS IPF, IMK = MIPAS IMK, and SMR = SMR.

<sup>b</sup>no ASUR ozone measurements.

from the tropics to the Arctic. Availability of colocated measurements for different sensors with the ASUR measurements is shown in Table 1.

[21] A sensitivity test was carried out with two other selection criteria for the ASUR measurements: (a)  $\pm 500$  km in 3 hrs and (b)  $2^\circ$  latitude  $\times$   $10^\circ$  longitude in 2 hrs. However, the resultant  $\Delta$  profile shapes did not differ significantly from those obtained from the present criterion. So in order to have more coincident measurements and thus to make a better statistical analysis, the criterion of  $\pm 1000$  km and  $\pm 6$  hrs was adopted for this analysis. Further details on the feasibility and usefulness of the selected criterion are discussed in section 10 (paragraph 9).

## 6. ASUR-SCIAMACHY Comparison

### 6.1. Data Analysis

[22] Two SCIAMACHY data sets are analyzed for this study: the official European Space Agency off-line product version 2.1 (hereafter OL, the new version is v 2.5) and the

in-house scientific product version 1.62 (hereafter IFE [Institute für Fernerkundung], the latest version). The OL data availability for geophysical validation is limited, but a few verification orbits were provided. The OL retrievals make use of the ozone absorption in the UV region at 319–333 nm (the Huggins band), and four ozone profiles per state are retrieved using the OEM. According to *Brinksma et al.* [2005], the VMRs are retrieved from the partial column using a crude pressure and temperature climatology. The retrievals are slightly constrained by the a priori profiles used in the inversion. About 20% of the latest version of the data showed unrealistic values, and the rest of the data showed no systematic deviations below 24 km. Furthermore, the OL 2.1 data have no pointing correction and, hence, the profiles are expected to show an altitude shift. Because of the large uncertainties and bias in the lower stratospheric mixing ratios of OL 2.1, we use the data from 25–50 km only. Because of the limitations of the data, there is no accuracy estimation performed yet. However, the review of preliminary validation of the OL showed an

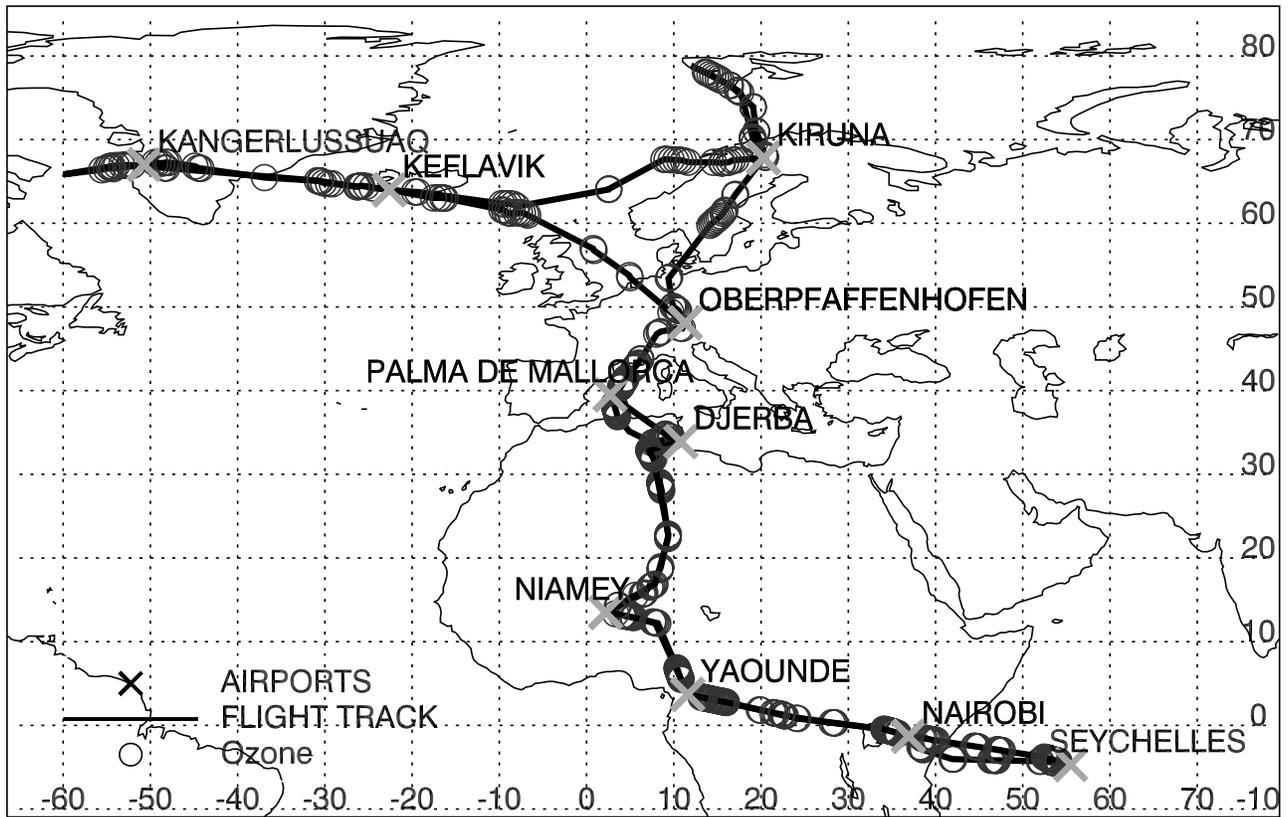


Figure 2. Flight path of the Falcon aircraft and ASUR ozone measurements during the SCIAVALUE 2002 deployment.

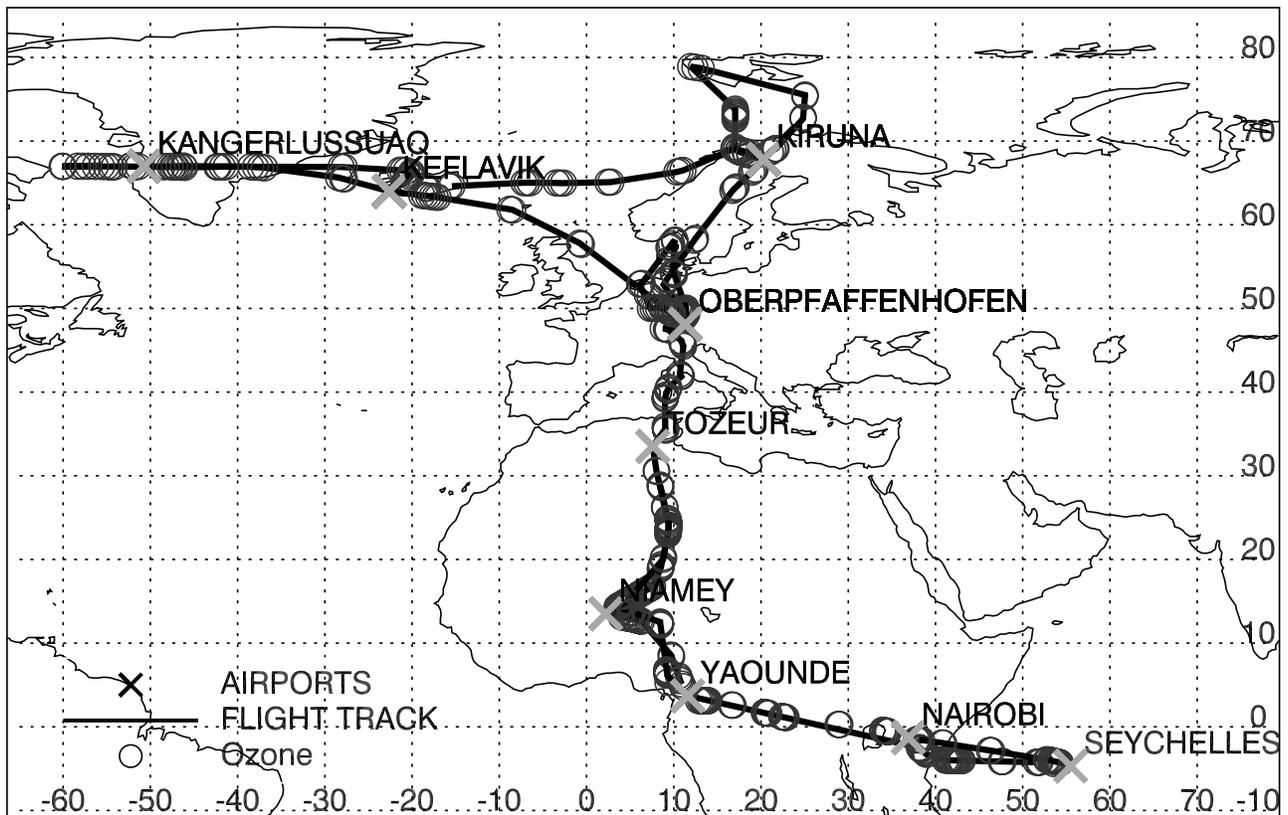


Figure 3. Same as Figure 2, but for SCIAVALUE 2003.

agreement within 10%, compared to other ground-based data [Fourier transform infrared (FTIR) spectrometer, lidar, microwave radiometers, sondes], and within 30% with satellite data [Halogen Occultation Experiment (HALOE), Stratospheric Aerosol and Gas Experiment II (SAGE II), SAGE III, and Solar Backscatter Ultraviolet (SBUV/2) instrument] [Brinksma *et al.*, 2004]. A new version of the data is in the offing with a new retrieval algorithm similar to that of IFE. There is no official documentation/publication on OL data yet. However, some information about the data can be found in the study of Brinksma *et al.* [2004].

[23] The IFE retrievals employ an algorithm similar to the one used by Flittner *et al.* [2000] and McPeters *et al.* [2000] for the Shuttle Ozone Limb Sounding Experiment (SOLSE) and by von Savigny *et al.* [2003] for the OSIRIS on Odin. The retrievals are based on the Chappuis band (525–675 nm) of ozone in the visible wavelengths [von Savigny *et al.*, 2005a, 2005b]. A linearized version of OEM is applied together with the radiative transfer model SCIAMACHY [Kaiser *et al.*, 2004] to retrieve ozone concentration profiles in an altitude range of 15–40 km. The retrieved profiles have an altitude resolution of about 4 km. The vertical sampling is 3.3 km. The IFE retrievals use SBUV climatology as the a priori, and the effect of the a priori profile on the retrieval is insignificant down to 18 km [Brinksma *et al.*, 2005]. Though the instrumental error is smaller than 1%, the retrieval errors due to the errors in the assumptions of albedo, aerosol profile, and background atmosphere are relatively larger (between 6 and 10%). The precision or variability is estimated to be 6–7% [Rozanov *et al.*, 2003; Brochi and Pommereau, 2005].

[24] The OL and IFE products have coincident measurements during 18 and 11 ASUR measurement flights, respectively, which covered most of the SCIAVALUE campaign period in September 2002 and February–March 2003. The vertical coverage numbers of the analyzed SCIAMACHY OL and IFE profiles are 24–50 and 15–40, respectively. The IFE ozone concentration profiles are converted into VMR profiles using synoptic pressure and temperature profiles from the National Center for Environmental Prediction (NCEP), which were used for retrieving the ASUR ozone profiles too. Because of the limited vertical resolution of ASUR ozone, the SCIAMACHY ozone profiles are convolved with the ASUR ozone averaging kernels (shown in Figure 1) for the comparisons. Typical examples of individual profile comparisons for the coincident measurements at low, mid, and high latitudes are shown in Figure 4.

[25] The SCIAMACHY limb data from the beginning of the mission to December 2003 are affected by the errors in the tangent height information. Tangent height errors of up to 3 km (and more in a few extreme cases) have been detected with various methods [Kaiser *et al.*, 2004]. The tangent height errors could be traced back to inaccurate knowledge of the spacecraft attitude and/or position. The limb pointing was found to be very accurate after the updates of the orbit propagator model on Envisat, which occur twice a day. Between these updates, the pointing slowly deviates from nominal pointing. For the SCIAMACHY IFE ozone profile retrievals used here, a pointing retrieval employing the Tangent Height Retrieval by UV-B Exploitation (TRUE) method [Kaiser *et al.*, 2004] was performed for every limb measurement, and the retrieved tangent height offset was

corrected prior to the retrieval of the ozone profiles. However, even after the correction, an offset of up to 1 km has been found, for which the low-latitude profiles show lower peak altitudes and the high-latitude profiles show higher peak altitudes.

## 6.2. Results

[26] Figure 5 (left panel) shows the statistics derived from the comparison between the ASUR and the SCIAMACHY OL ozone profiles at different climatic regions. There are 38 coincidences in the Arctic, 117 in midlatitude, and 230 in the tropics. The ASUR-OL deviation is up to 20% in the tropics and the Arctic at 26–40 km. The deviation in midlatitude is between –20% and 7% for the same altitude range. The difference is relatively larger in the Arctic and in the tropical lower stratosphere. It should be noted that the lower stratospheric values are very sensitive, and if one of the profiles deviates from the other with even for a small fraction of parts per million, it can lead to a huge change in percentage scale. This is very evident in the tropical lower stratosphere, where the absolute difference (in parts per million) is small but the difference in percentage is very high (these will be discussed in section 10, paragraph 2).

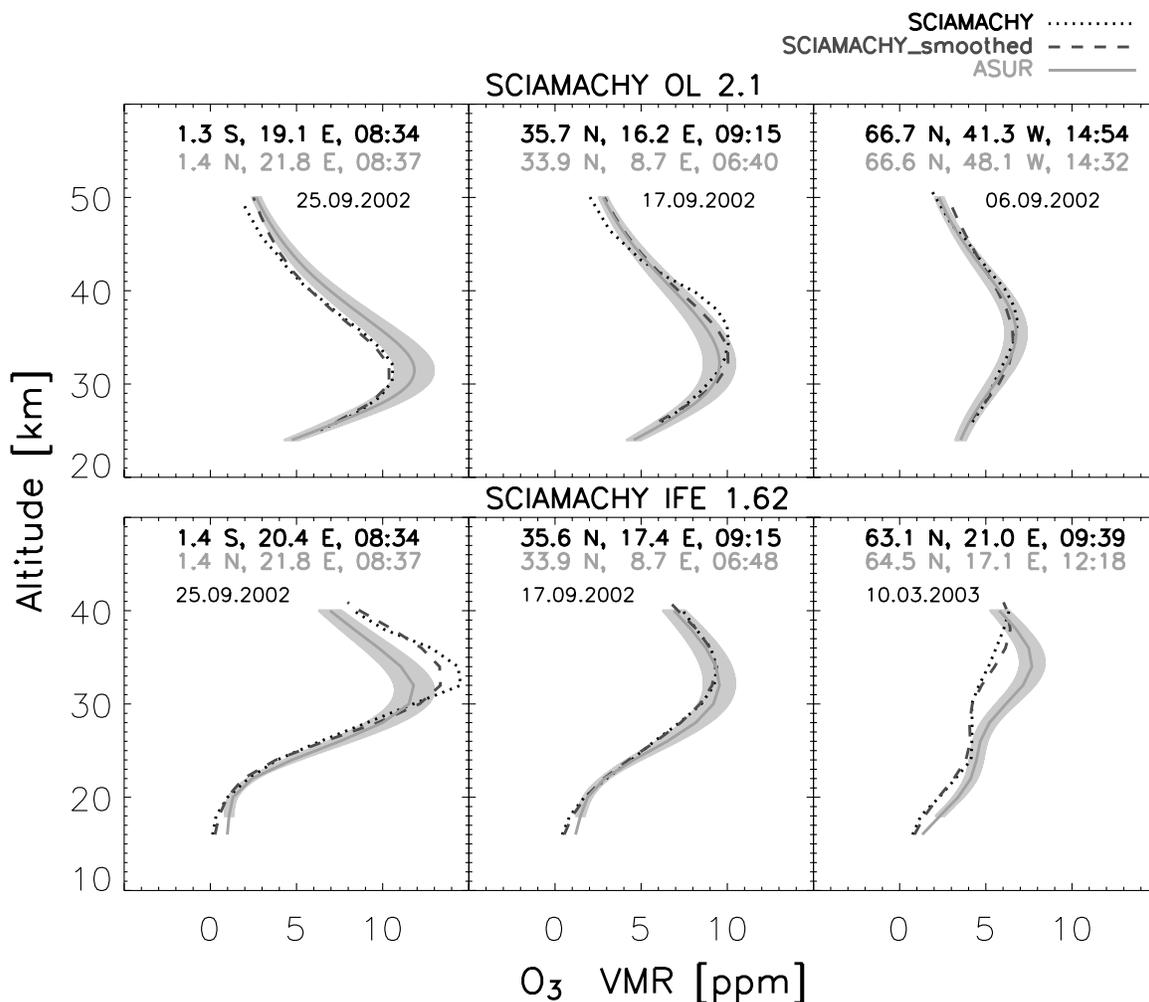
[27] Figure 5 (right panel) depicts the statistical analyses derived from the comparison between the ASUR and the IFE profiles. From the 67 Arctic coincident measurements, the ASUR-IFE difference is within  $\pm 30\%$ . The deviation deduced from 54 midlatitude coincident measurements is between –4% and 30%. The differences are, however, relatively larger in the tropics—about –15% to 40% as shown by the 124 collocated measurements. The maximum difference is found in the tropical lower stratosphere.

## 7. ASUR-MIPAS Comparison

### 7.1. Data Analysis

[28] The MIPAS off-line product Instrument Processing Facility (IPF) version 4.61 (hereafter IPF) and the scientific product Institut für Meteorologie und Klimaforschung Karlsruhe (IMK) version 1-O<sub>3</sub>-1 (hereafter IMK) are analyzed. The IPF and IMK data discussed in this analysis are taken in the standard observation mode, consisted of rearward limb scans covering an altitude range of 6–68 km in 17 steps. The vertical sampling is 3 km from 6 to 42 km, 5 km from 47 to 52 km, and 8 km from 60 to 68 km.

[29] The IPF retrieval processor uses the spectral windows at 763.375–766.375, 1039.375–1040.325, and 1122.8–1125.8  $\text{cm}^{-1}$  for the ozone retrievals. The IPF ozone vertical profiles are retrieved using an optimized retrieval model [Carli *et al.*, 2004] with an altitude resolution of about 3 km in the stratosphere. The global fit approach retrieval scheme applied does not use any a priori profiles, but an initial guess profile derived from the climatologies is utilized (<http://www.ifac.cnr.it/retrieval/auxiliary.html>). Therefore the influence of a priori values on the retrieval is insignificant. The calculated noise for an ozone measurement is 2–4%, and the estimated total error is around 10% at 15–50 km. The dominant contributions to the total error are spectroscopic, gain calibration, instrumental line shape, and residual errors in the line of sight. Further details of the IPF retrievals can be found in the work of Raspollini *et al.* [2006].



**Figure 4.** Typical examples of the individual SCIAMACHY-ASUR coincident profiles in the tropics, the midlatitude, and the Arctic for the off-line (OL) and scientific (IFE) products. The gray shade on the ASUR ozone profile shows its estimated accuracy. The coordinates and date of the measurements are noted in the plots.

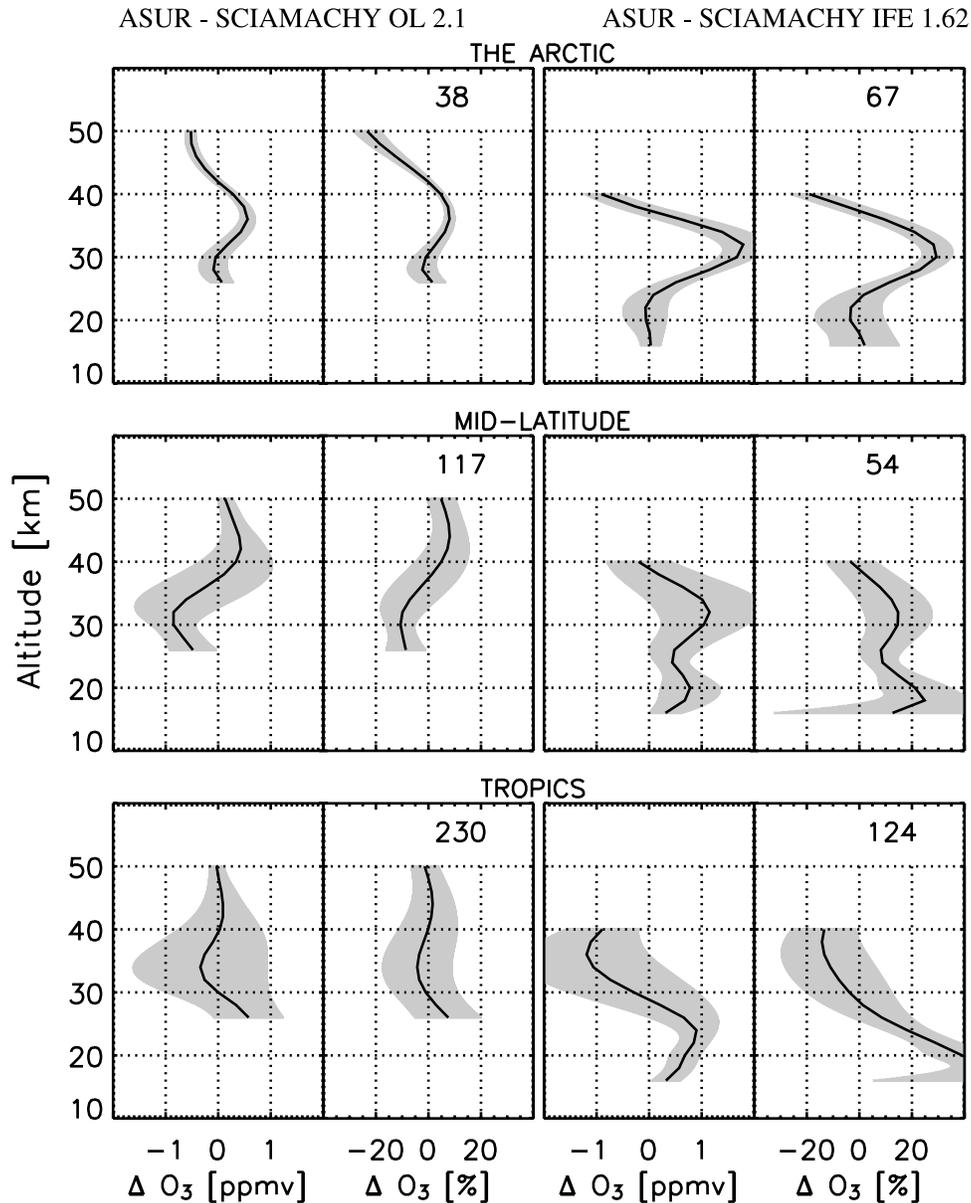
[30] The spectral windows at 741–791 and 1020–1170  $\text{cm}^{-1}$  are chosen for the ozone retrievals at the IMK processor. The retrieval uses a constrained global fit approach, and the retrieval grid has an altitude spacing of 1 km up to 44 and 2 km between 40 and 70 km. The altitude resolution is similar to that of IPF, about 3 km in the stratosphere. Climatological ozone profiles are used as the a priori information in the retrievals. Influence of a priori profile on the retrieval is very small and affects the shape of the profile (i.e., small-scale structures only, not to the abundances themselves). This problem has been solved in the recent versions of the data. The noise error is below 4% (0.2 ppm), and the total error is around 10% (up to 0.65 ppm) at 10–45 km at high latitudes. In the tropics, the noise error is below 3%, and the total error is 5–10% (up to 1.2 ppm) at 25–50 km. The uncertainties in the spectroscopic data are the dominant error source in both cases. Though the error estimation is based on the version V2-O<sub>3</sub>-2, the end-to-end comparison of the different versions of the IMK retrievals shows an agreement within  $\pm 0.4$  ppm at 20–60 km [Glatthor *et al.*, 2005, 2006].

[31] The IPF data have coincident observations with 19 ASUR measurement flights during SCIAVALUE and 6 during EuPLEx. The ASUR collocation measurements during 11 SCIAVALUE flights are used for the comparisons with the IMK data. The vertical range of the analyzed MIPAS ozone profiles is 16–50 km. The VMR profiles are convolved with the ASUR ozone averaging kernels for the comparisons to account for the lower vertical resolution of ASUR ozone. Typical coincident measurements at different latitude regions are depicted in Figure 6.

## 7.2. Results

[32] Figure 7 (left panel) shows the comparison statistics derived from the ASUR and MIPAS IPF ozone. There are 418 collocated measurements in the Arctic, 111 in the midlatitude, and 181 in the tropics. The difference ASUR-IPF in the Arctic and midlatitude is within  $\pm 7\%$  between 20 and 40 km. However, deviation in the tropics is up to 40%, which is maximum in the lower stratosphere.

[33] Figure 7 (right panel) illustrates the statistics derived from comparison between the ASUR and the IMK ozone profiles. A deviation of  $-10$  to 7% is found in the Arctic



**Figure 5.** The absolute ( $\Delta$  = ASUR-SCIAMACHY ozone VMR in parts per million) and percentage ( $\Delta$  VMR in percent) difference between the ASUR and the SCIAMACHY ozone profiles in the Arctic (top), the midlatitudes (middle), and the tropics (bottom). The left panel stands for ASUR-OL, while the right panel stands for ASUR-IFE for each latitude section as noted in the plots. The thick black line indicates the mean  $\Delta$  profile at each section, and the shaded area represents the standard deviation from the mean profile. The number of averaged  $\Delta$  profiles at each climatic region is also noted in the plots.

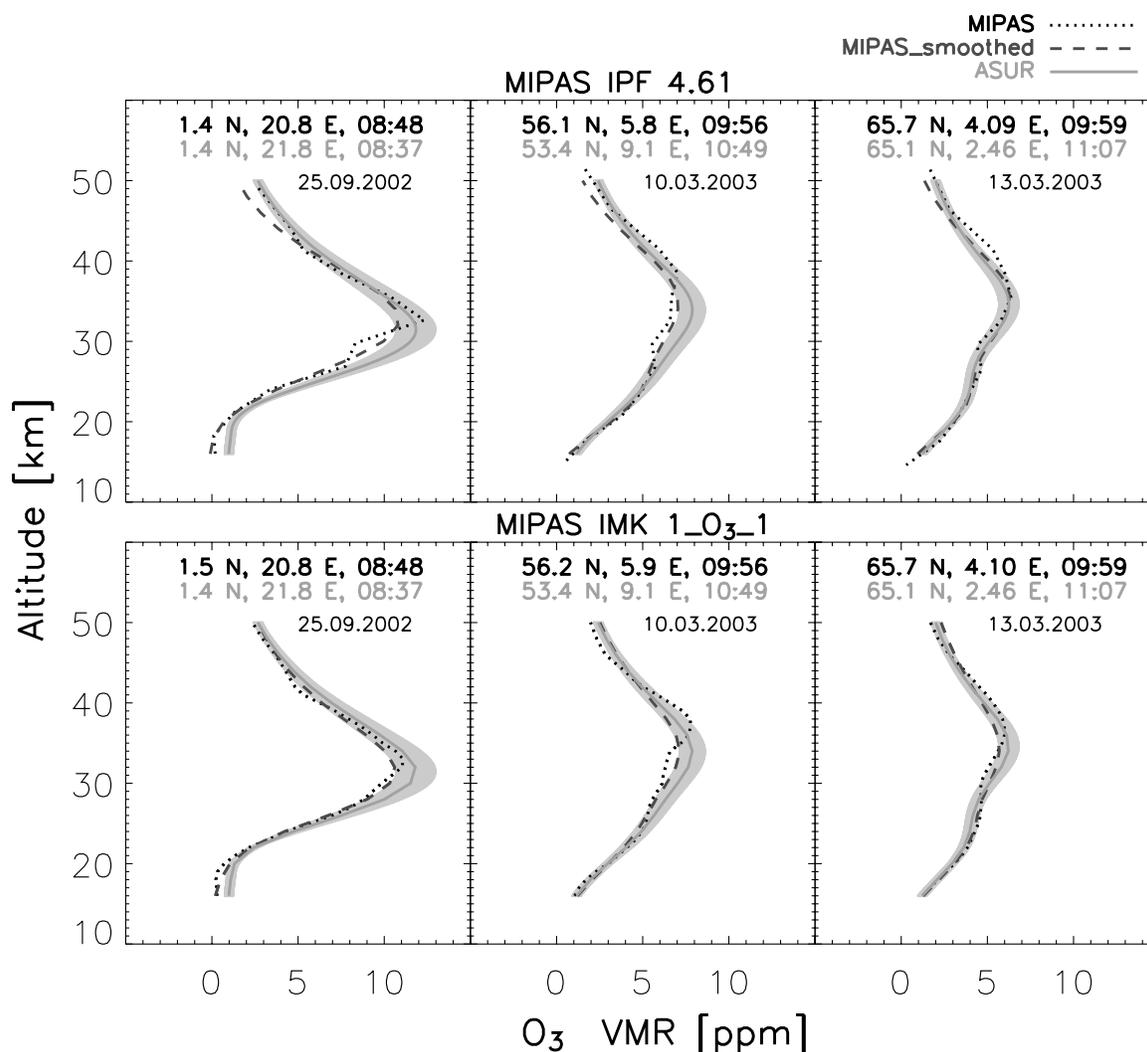
from the 123 coincident measurements at 20–40 km. Nevertheless, the difference in midlatitude is up to +6% from the 45 instances in the same altitude range. The tropical profiles also show a similar feature with a deviation of up to +14% between 20 and 40 km, where the maximum difference is found in the lower stratosphere as inferred from the 34 coincident measurements.

## 8. ASUR-OSIRIS Comparison

### 8.1. Data Analysis

[34] The stratospheric ozone profiles are retrieved, in number density, from the OSIRIS limb radiance data in

the Chappuis absorption band (532–672 nm). Profiles are calculated between 10 and 50 km on a 2-km vertical grid using the paired radiance method developed by *Flittner et al.* [2000] and *McPeters et al.* [2000] for the Shuttle Ozone Limb Sounding Experiment. This method was adopted to OSIRIS retrievals by *von Savigny et al.* [2003]. The a priori information for OSIRIS ozone retrievals comes from a set of reference atmospheres organized by *McLinden et al.* [2002]. The retrieved values are insensitive to the a priori profile used in the inversion at 15–35 km. The vertical resolution of the retrieved profiles is 2 km. The effect of the OSIRIS instrument noise on the stratospheric ozone retrieval leads to a maximum error of <2% at 15 km,



**Figure 6.** Same as Figure 4, but for MIPAS.

<1.3% at 20 km, <1.5% at 25 km, <3% at 30 km, and <5% at 35 km. The accuracy of individual profile is calculated to be better than 10% at 15–35 km [von Savigny *et al.*, 2003].

[35] The ASUR coincident measurements in September 2002 and February–March 2003 during 12 SCIAVALUE flights and in January–February 2003 during 2 EuPLEX flights are considered. In this paper, OSIRIS ozone version 012 is analyzed from 16 to 40 km [von Savigny *et al.*, 2003; Petelina *et al.*, 2004]. It should be noted that, as the time difference between the Envisat and the Odin measurements over the same geographic area is about 8 hrs, the coincidence criteria adopted for this study had to be increased to 8 hrs or less in time. To facilitate the comparisons, the OSIRIS ozone number density profiles are converted into VMR profiles using the synoptic meteorological data collected from NCEP and then convolved with the ASUR ozone averaging kernels. Typical examples of the individual ASUR-OSIRIS coincident profiles in the tropics, the mid-latitudes, and the Arctic (as specified in section 5) are shown in Figure 8.

## 8.2. Results

[36] The comparison results for the OSIRIS and ASUR ozone comparisons in the tropics, the mid-latitudes, and the Arctic, as well as for all of these regions combined, are shown in Figure 9. The total number of coincidences is 363 with the majority—253 instances in the Arctic, 62 instances in the midlatitudes, and 48 instances in the tropics. The ASUR-OSIRIS deviation is within 15% in the tropics between 18 and 40 km. The agreement between the profiles is very good in the mid and high latitudes below 30 km, where the differences are within  $\pm 3\%$ . However, above 30 km, the difference is relatively large, which is up to 25%. This deviation is maximum at the altitude of ozone maximum VMRs as well.

## 9. ASUR-SMR Comparison

### 9.1. Data Analysis

[37] Stratospheric mode measurements of a small ozone line centered at 501.5 GHz are used based on the version CTSO-222 retrievals of the Chaicirc;ne de Traitement

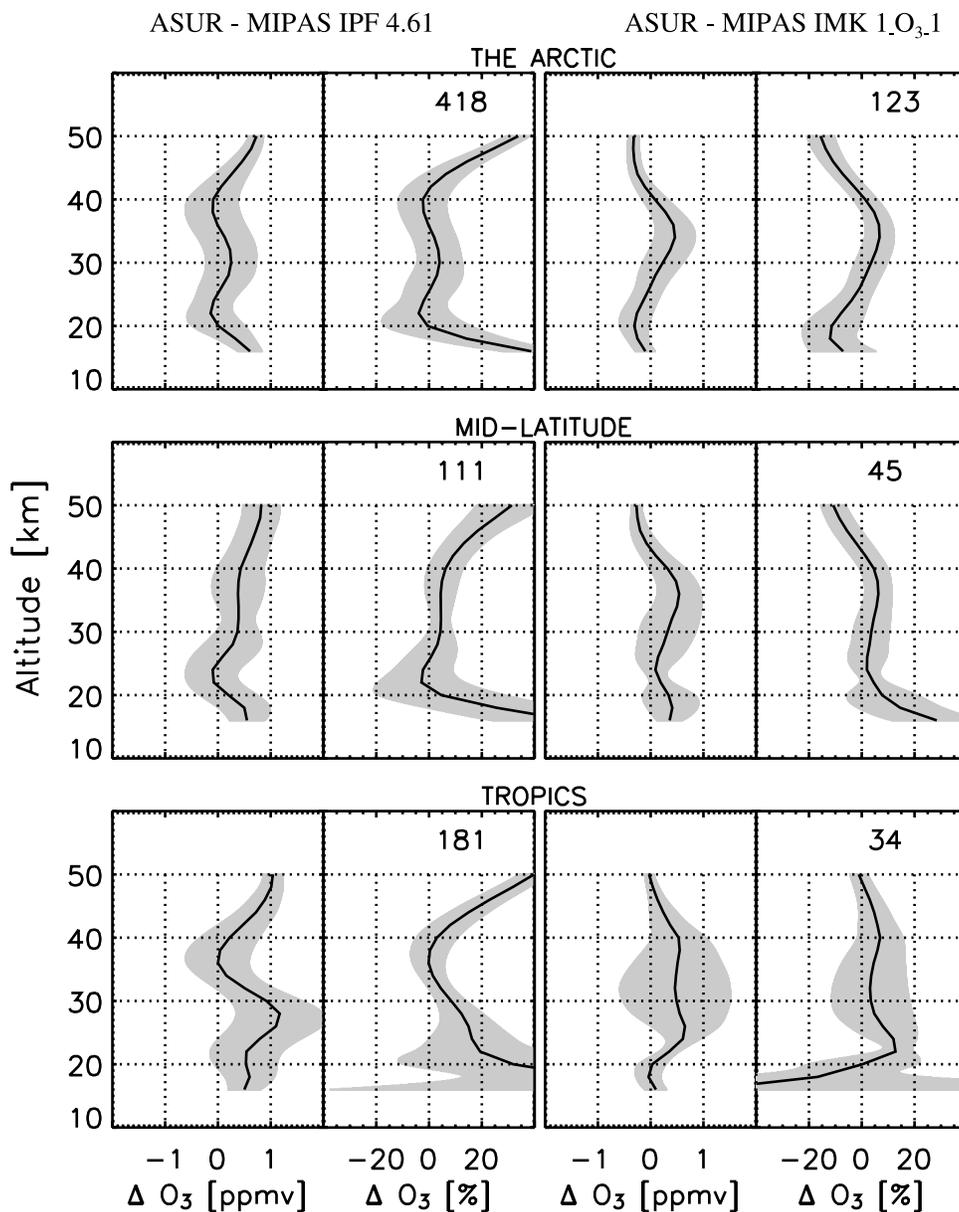


Figure 7. Same as Figure 5, but for ASUR and MIPAS.

Scientifique Odin (CTSO) [Urban *et al.*, 2005b]. The a priori influence is negligible within the measurement range. The altitude range of SMR ozone profiles is  $\sim 17$  to  $\sim 45$  km (21–45 km in the tropics), and the vertical resolution is about  $\sim 2.5$  km with a single-scan noise (precision) in the order of 0.25–1.5 ppmv (20–25%). The estimated systematic error of 501.5 GHz ozone measurements is less than 0.4 ppm at 25–50 km and less than 0.75 ppm below 25 km [Urban *et al.*, 2005b].

[38] The colocated data from 11 ASUR flights during SCIAVALUE are used for this assessment. The vertical range of the selected SMR profiles for the analysis is 21–45 km (23–45 km in the tropics). Since the SMR profiles are slightly noisy, the averaging of the profiles was necessary to get a reasonable low-noise profile. The SMR profiles were therefore averaged to the location of

the nearest ASUR measurements over a  $7.5^\circ$  latitude  $\times$   $7.5^\circ$  longitude area. The number of averaged profiles varies from 3 to 11, depending on availability of SMR measurements for the individual ASUR measurements. The coordinates were also averaged along with the profiles in order to obtain the mean positions of the averaged SMR profiles. The averaged profiles were then convolved with the ASUR averaging kernels to account for the lower vertical resolution of the ASUR ozone profile measurements. Examples of the individual profile comparisons at low, mid, and high latitudes are shown in Figure 10.

## 9.2. Results

[39] Figure 11 shows the statistical analysis of the ASUR and SMR ozone profiles with 20 tropical, 30

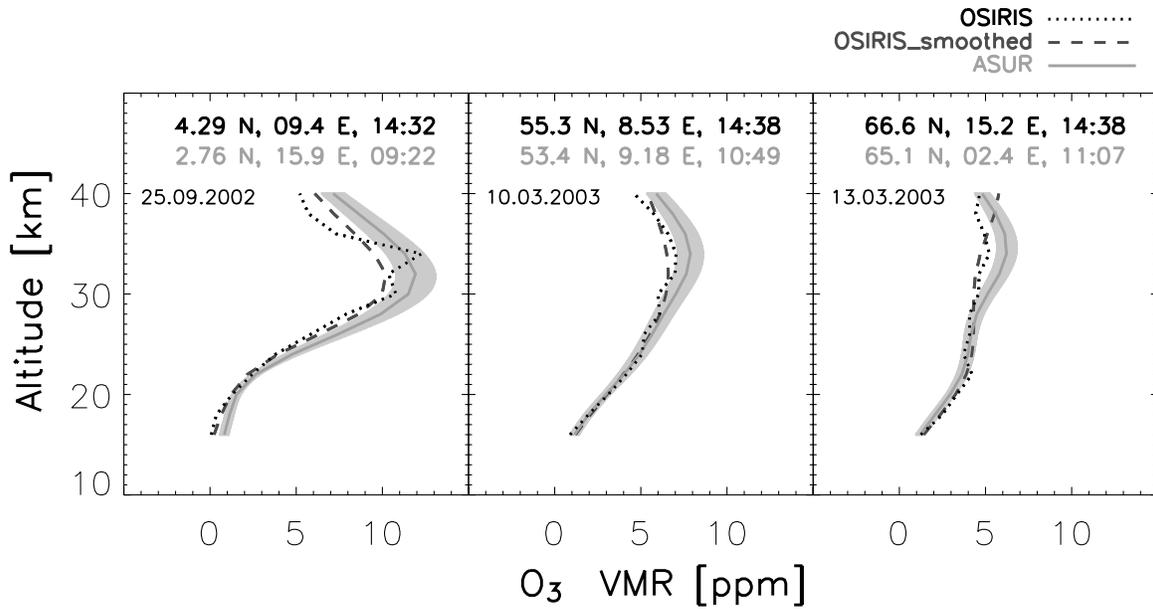


Figure 8. Same as Figure 4, but for OSIRIS.

midlatitude, and 53 high-latitude colocated measurements. A very good agreement is found in the tropics at 26–36 km, where the differences are within 5%. Above 35 km, the deviation is slightly higher and

increases up to +35% around ~45 km. The deviation at middle and high latitudes is within ±15% between ~25 and 35 km. On average, the ASUR-SMR difference is relatively small (±10%) at 25–35 km, with the differ-

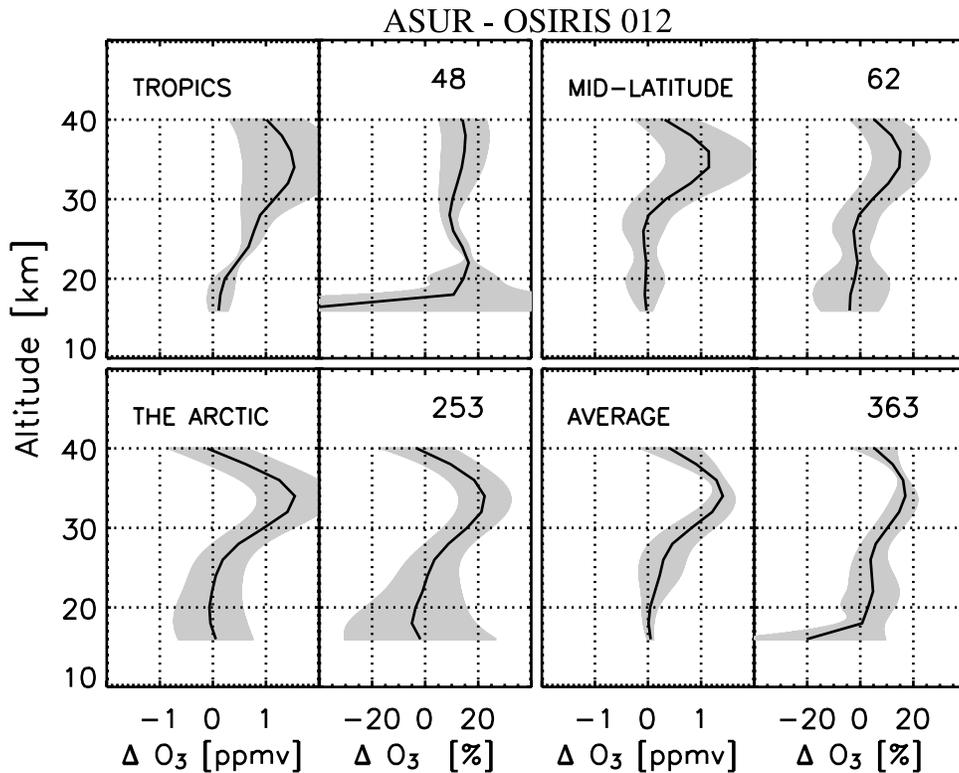
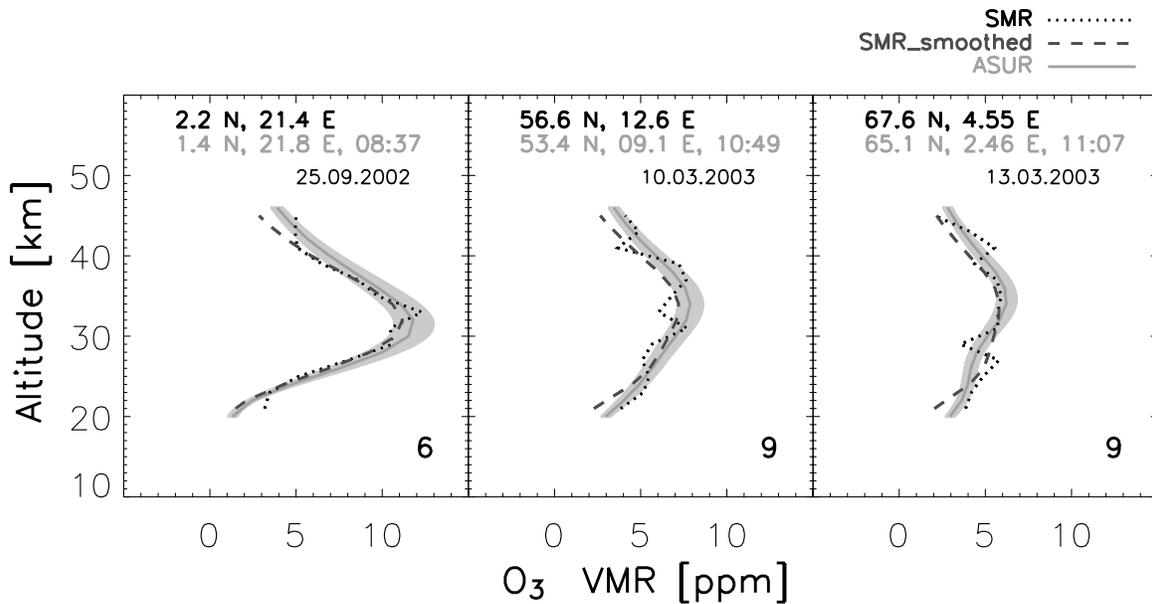


Figure 9. The absolute ( $\Delta$  = ASUR-OSIRIS ozone VMR in parts per million) and percentage ( $\Delta$  VMR in percent) differences between the ASUR and the OSIRIS ozone profiles in the tropics (top left), the midlatitude (top right), the Arctic (bottom left), and the average of all these latitude sections (bottom right). The thick black line indicates the mean  $\Delta$  profile at each section, and the shaded area represents the standard deviation from the mean profile. The number of averaged  $\Delta$  profiles at each climatic region is also noted in the plots.



**Figure 10.** Same as Figure 4, but for SMR. The number of SMR profiles averaged for each coordinate is shown with the numbers noted on the right bottom of the plots.

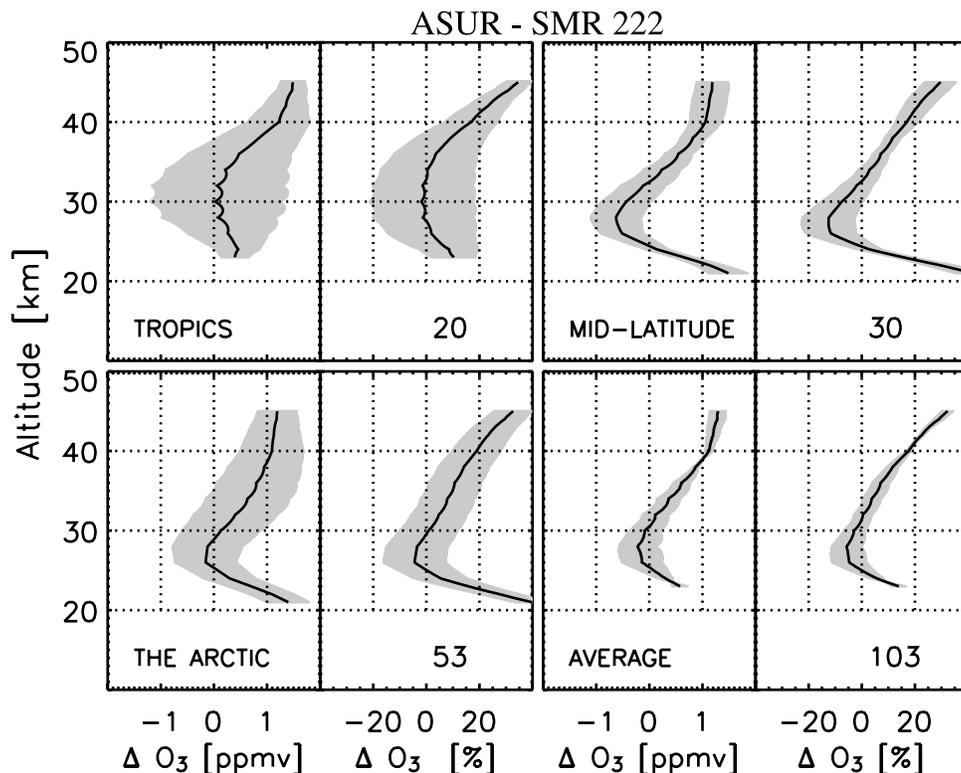
ences increasing above that kilometer range (e.g., 32% at ~45 km).

**10. Discussion**

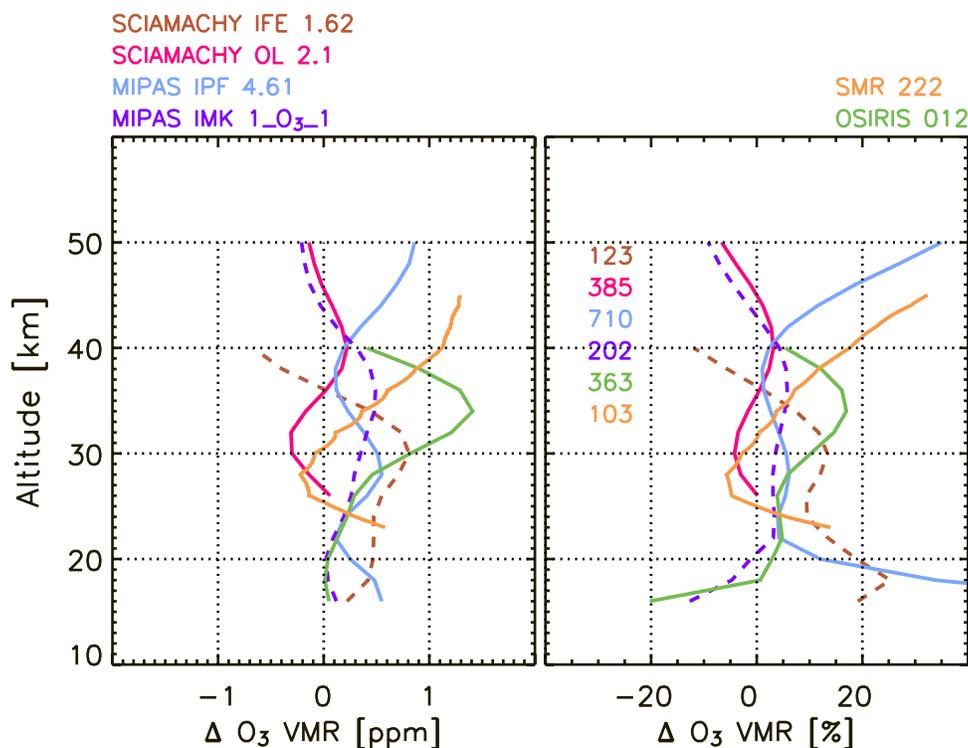
**10.1. Differences in the ASUR and Satellite Ozone Profiles**

[40] Figure 12 illustrates the mean deviation between the ASUR and the satellite ozone measurements. The

ASUR-SCIAMACHY difference is within 30% between 20 and 40 km. In the lower stratosphere, though the absolute difference is reasonable (in the order of 0.5–1.0 ppm), the difference in percentage is slightly higher. This can be due to the relatively higher VMRs in the ASUR profiles against the “near-zero” values in the SCIAMACHY profiles. There are some systematic differences between the operational and the scientific products from SCIAMACHY and MIPAS. The OL and IFE profiles show opposite behavior in the middle and



**Figure 11.** Same as Figure 9, but for ASUR and SMR.



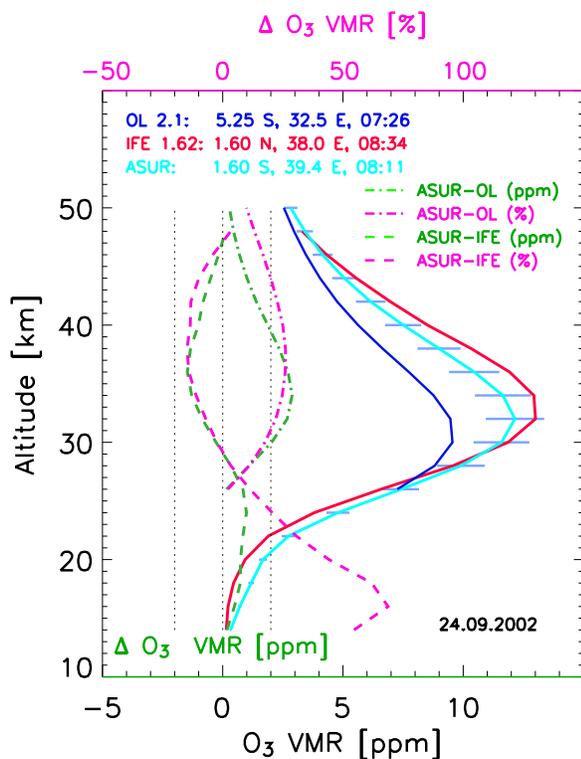
**Figure 12.** The average difference in ozone between the ASUR and the satellite sensors for all latitude bands. The curves represent the difference  $\Delta$  ozone = ASUR—the satellite sensor ozone in absolute (left) and percentage (right) scales. The number of averaged  $\Delta$  profiles for each sensor is also shown.

upper stratosphere. Comparing the scientific (IMK) and operational (IPF) products, the ASUR-MIPAS difference is within 6% at 20–40 km. Unlike the SCIAMACHY products, both MIPAS products show a common trend between 23 and 43 km and are in good agreement with the ASUR ozone. Outside this altitude bound, the trend of the  $\Delta$  profiles is just opposite to each other, for which the ASUR-IPF profile shows higher deviation. It must be noted that MIPAS IPF 4.61 is based on spectra version IPF 4.62 while MIPAS IMK v1-O<sub>3</sub>-1 is retrieved from spectra version IPF < 4.57. Therefore it may not be desirable to compare the MIPAS profiles (IPF and IMK) directly with each other. The difference between ASUR and SMR is  $\pm 5\%$  between 24 and 35 km. The OSIRIS data, however, show slightly larger (about 17%) deviation at the altitude of ozone maximum. Nonetheless, the lower stratospheric difference (18–25 km) with OSIRIS is mostly within 5% above 18 km. Hence the assessment shows that the differences between the ASUR and the satellite ozone are within 17% at 20–40 km, which is a good agreement. These values are also similar to those shown by previous comparison studies with various measurements (the SCIAMACHY data version used is different here) for the respective satellite sensors [Blumenstock *et al.*, 2004; Bracher *et al.*, 2004a, 2004b; Kerridge *et al.*, 2004; Petelina *et al.*, 2004, 2005; Bracher *et al.*, 2005; Wang *et al.*, 2005; Brochi and Pommereau, 2005; Glatthor *et al.*, 2006].

## 10.2. Comparison Among the Satellite Sensors

[41] The cross comparisons also give an opportunity to assess the satellite ozone themselves even though the differences are calculated with the ASUR ozone since, as stated

in section 1, ASUR can act as a transfer standard when two sensors are not viewing the exact atmosphere. As it is not a direct comparison between the satellite measurements, this quantitative assessment of the profiles should be taken in qualitative terms only. Figure 12 shows that the agreement between the SCIAMACHY  $\Delta$  profiles is within 10% and exhibits no common pattern. However, the MIPAS  $\Delta$  profiles show a very good agreement (difference is within 5%) at 26–42 km and deviate away outside this altitude limit. The analysis shows that the MIPAS and SCIAMACHY OL profiles have relatively smaller deviations (0.5 ppm or 5%) between 26 and 40 km, and thus the profiles show a very good agreement. A recent study by Bracher *et al.* [2005] showed that the agreement between the IFE and the IMK profiles is within 15% at 22–40 km. It is remarkable that these comparisons also yield a very similar statistics. The OSIRIS and IFE profiles show a low bias (at 28–38 km for OSIRIS and at 18–35 km for IFE) in the middle stratosphere as compared to the MIPAS (both IMK and IPF), SMR, and SCIAMACHY OL profiles. A good agreement is found among the SMR, MIPAS (both IMK and IPF), and SCIAMACHY OL profiles between 24 and 38 km. The OL and SMR profiles show a high bias at the ozone peak altitudes too. The differences found among these sensors at 20–40 km are generally in agreement with the deviations found in previous comparisons with other instruments (SCIAMACHY data version is different here) for the respective sensors [Blumenstock *et al.*, 2004; Bracher *et al.*, 2004a, 2004b; Kerridge *et al.*, 2004; Petelina *et al.*, 2004, 2005; Bracher *et al.*, 2005; Brinksma *et al.*, 2005; Glatthor *et al.*, 2005; Segers *et al.*, 2005; Wang *et al.*,



**Figure 13.** The comparison between ASUR-OL and ASUR-IFE profiles in the tropics. The SCIAMACHY profiles show an altitude shift that makes the characteristic  $\Delta$  profiles.

2005; Brochi and Pommereau, 2005]. Above 40 and below 20 km, there is hardly any consensus among the sensors although there are some similarities among some average profiles (shown in Figure 12), which leaves a cautionary note on using different satellite data sets together for a single purpose like trend analysis studies at these sensitive altitude regions. The possible causes for the differences are discussed in the following section.

### 10.3. Reasons for the Deviations

#### 10.3.1. ASUR-SCIAMACHY OL 2.1

[42] Even though the agreement between ASUR and OL is very good, there are some issues related to the OL data to be discussed. According to Brinksma *et al.* [2005], 20% of the OL v2.4/2.5 data north of 15°S have unrealistic ozone values. Furthermore, there are considerable influences of a priori information on the retrievals. A previous work by Bracher *et al.* [2004a] showed that the OL v2.1 products agree with the HALOE and SAGE-III ozone within 10–15%. The middle and upper stratospheric difference in ASUR-OL is also in the same range.

#### 10.3.2. ASUR-SCIAMACHY IFE 1.62

[43] The IFE 1.60/1.61 profiles show a low bias of 10–15% at 20–35 km for unknown reasons compared to the HALOE, SAGE II and III, global ozone monitoring by occultation of stars (GOMOS), MIPAS, lidars, and sonde ozone measurements (Rozanov *et al.*, 2003; Bracher *et al.*, 2004a, 2004b; Brinksma *et al.*, 2005; Palm *et al.*, 2005; Segers *et al.*, 2005; Wang *et al.*, 2005). The IFE 1.61 profile appeared to be biased low by 6–7% in the tropical lower

stratosphere [Brochi and Pommereau, 2005] too. The negative bias was apparent even after shifting the profiles by 1–2 km to account for the altitude shift in the IFE profiles [Brinksma *et al.*, 2005]. This analysis also reveals a similar bias in the IFE 1.62 profiles. Previous versions of IFE profiles have a downward altitude shift of up to 3 km [Bracher *et al.*, 2004a; Kuttippurath *et al.*, 2004; Bracher *et al.*, 2005; Brinksma *et al.*, 2005; Palm *et al.*, 2005; Segers *et al.*, 2005; von Savigny *et al.*, 2005a, 2005b]. The IFE 1.62 profiles too have an altitude offset of up to 1.0 km after correcting with the TRUE knee, in the tropics in particular. For instance, Figure 13 demonstrates the effect of an altitude offset in the SCIAMACHY OL and IFE  $\Delta$  profile shapes. The  $\Delta$  profiles also illustrate the sensitivity and influence of the lower stratospheric measurements in the statistical analysis, where the absolute difference (in parts per million) is very small although the difference in terms of percentage is even up to 70%. The particular elongated s-shape is very apparent in both  $\Delta$  (in parts per million and in percent) profiles. The altitude shift in the profiles hence makes a shift in the altitude of ozone maximum and, therefore, a relatively large difference in shape of the  $\Delta$  profiles. The IFE retrievals use only two orders of scattering terms as they neglect the higher orders because of their smaller contribution [von Savigny *et al.*, 2005a, 2005b]. Ignoring the scattering terms still gives rise to 1–2% errors in retrieved quantities except below the altitudes of ozone maximum where the gradient is relatively large [von Savigny *et al.*, 2005a, 2005b].

#### 10.3.3. ASUR-MIPAS IPF 4.61

[44] The MIPAS profiles exhibit a good agreement with the ASUR profiles. The satellite retrievals, however, show a low bias of up to 7% between 22 and 44 km with respect to the ASUR ozone. In a previous comparison with HALOE and SAGE II, it showed mean differences of 5–15 and 7–15%, respectively, at 50–0.5 hPa [Kerridge *et al.*, 2004]. The cross comparison of Envisat instruments showed that the IPF profiles are biased low with IFE 1.6 and GOMOS (GOPR 6.0a) by 15 and 5%, respectively, between 21 and 40 km [Bracher *et al.*, 2004b]. A detailed comparison with ground-based Network for the Detection of Stratospheric Change instruments (FTIR spectrometers, lidars, ozone-sondes, and microwave radiometers) with IPF 4.61 showed an agreement within 10% [Blumenstock *et al.*, 2004]. So the differences in the ASUR-IPF are also in the same range as found in the previous comparisons. The comparisons also showed an altitude shift in the IPF profiles due to a drift in MIPAS instrumental pointing [e.g., Blumenstock *et al.*, 2004]. A recent study by Brochi and Pommereau [2005] showed that the IPF data are biased high by 0.6–7.1% in the tropical lower stratosphere at 20–26 km compared to Système D'Analyse par Observations Zénithales ozone profiles. Below 20 km, the differences are slightly larger and are up to 14%, which are found in ASUR-IPF too. Although the lower stratospheric low bias is evident, the middle and upper stratospheric high bias is not observed in the ASUR-IPF comparisons. Instead of the high bias above 30 km, a smaller deviation with the similar profile shape (as found in the aforesaid work) is found in this comparison. Hence the shape of the  $\Delta$  profiles found from other analyses is kept in these comparisons as well, which is a particular feature of the IPF 4.61 retrievals.

#### 10.3.4. ASUR-MIPAS IMK 1.0

[45] The agreement between ASUR and IMK profiles is very good, and the difference is mostly within 5% at 20–42 km. According to Wang *et al.* [2005], the global mean difference of IMK 1-O3-1 ozone with HALOE and SMR profile is within 0.1–0.3 ppm, where the deviation in the tropics is even larger—up to 0.6 ppm (4–6%) at 25–30 km. So the positive bias in ASUR-IMK is consistent with the findings of Wang *et al.* [2005].

#### 10.3.5. ASUR-OSIRIS

[46] The deviation with OSIRIS is the largest among the satellite sensors in the middle stratosphere. The maximum deviation is found at the altitude of ozone maximum as well. Recent intercomparisons showed that, between 15 and 32 km, the OSIRIS-polar ozone and aerosol measurement-III ozone difference is between 5 and 10%, and the OSIRIS-sonde ozone difference is 5–7% [von Savigny *et al.*, 2003; Petelina *et al.*, 2004]. Relatively large difference is observed below 15 km and above 32 km, about 25–30%, which is consistent with error analyses of the OSIRIS retrievals. That is, the OSIRIS retrieval is less sensitive below 15 km due to larger optical depth and above 32 km due to smaller ozone densities. Furthermore, the OSIRIS profiles have a downward altitude shift of about 1.0 km during April–July 2002 and March–June 2003 periods due to incorrect altitude registration of the Odin satellite. The OSIRIS ozone comparison with other instruments showed a poor agreement, and the differences were found up to 30% during this particular period [Petelina *et al.*, 2004]. Since ASUR data also cover March 2003, there is a possibility to have an influence of this altitude shift in the analysis as the difference is up to 17% at ozone maximum altitudes. Nevertheless, the low bias at 30–40 km is apparent even after shifting the altitude by 1.0 km (not shown here) for unknown reasons.

#### 10.3.6. ASUR-SMR

[47] The agreement between SMR and ASUR ozone retrievals is within the combined estimated systematic errors of the SMR and ASUR instruments below 35 km. As discussed earlier, the lack of sufficient number of profiles near the ASUR measurement points for averaging the SMR profiles to get a low-noise profile might be a reason for the differences. It should be mentioned that the noise in the profiles hardly contributes to any systematic differences although that could contribute to the total deviations.

#### 10.3.7. Pointing Problem

[48] The altitude shift due to the imprecise knowledge of altitude registration of Envisat and Odin satellites has been identified in SCIAMACHY, MIPAS, and OSIRIS ozone profiles [Blumenstock *et al.*, 2004; Kerridge *et al.*, 2004; Kuttippurath *et al.*, 2004; Petelina *et al.*, 2004; Brinksma *et al.*, 2005; Brochi and Pommereau, 2005]. However, the IMK profiles have a pointing precision better than 150 m, while the pointing retrieval for IPF is performed in pressure coordinates only. The altitude in ASUR profiles is derived from pressure-temperature-altitude relation from synoptic meteorological profiles taken from the Climate Prediction Center (CPC) of NCEP, which were interpolated to the ASUR measurement points. In order to test the altitude shifts in the retrieved profiles, shifted altitudes in the ASUR ozone a priori profiles were applied. However, no shift in the altitude of maximum VMR was observed in the resultant

profiles. Sensitivity tests with meteorological data other than CPC profiles did not retrieve any shift in the ozone peak altitudes as compared to the control run retrievals as well. So there are very limited possibilities to have a shift in the altitude of ASUR ozone profiles.

#### 10.3.8. Other Reasons

[49] A difference in the ozone values (ASUR satellite ozone profiles) was still observed even after correcting for the altitude offset in the satellite retrievals [e.g., Brinksma *et al.*, 2005; Brochi and Pommereau, 2005]. So it is obvious that the altitude shift is not the sole reason for the differences between the satellite ozone profiles and that of ASUR. Apart from the possibilities of the deviations discussed above, other plausible causes can be atmospheric variations due to spatial and temporal differences during the measurements performed between ASUR and the satellite sensors. A limb profile is an average of the measurement over a few kilometers in a few minutes (as discussed in section 5, paragraph 2). The applied criterion again imposes another averaging over a few hundred kilometers ( $\pm 1000$  km here) in a few hours ( $\pm 6$  or  $\pm 8$  hrs). This could be a reason for the uncertainties in the atmospheric variations.

#### 10.3.9. Altitude Range of Comparisons

[50] Retrieval of constituent profiles from space-borne sensors are very difficult in the upper troposphere-lower stratosphere (UTLS) region because of the complexity of the region (e.g., strong horizontal and vertical gradients in the temperature and trace gas distributions, gaps in understanding the heating rates and vertical transport in the tropics, presence of high-altitude clouds, assumption of spherically symmetric atmosphere in the conventional retrieval method, etc.). Therefore most satellite retrievals show comparatively large uncertainties and, hence, wider error bars in the UTLS region. The initial error estimation of the sensors has been mostly carried out down to 20 km only, tropics in particular (e.g., MIPAS, SCIAMACHY, and SMR). Similarly, the uncertainties/differences in the upper stratosphere-mesosphere region is also relatively high for almost all sensors (e.g., SCIAMACHY IFE, OSIRIS, and SMR). Therefore it would be more appropriate to consider an altitude region between 20 and 40 km for this intercomparison to make a meaningful conclusion, where most sensors have reasonable retrievals and relatively very good accuracy.

## 11. Conclusions

[51] The SCIAMACHY, MIPAS, OSIRIS, and SMR ozone profiles are compared with ASUR measurements gathered during the SCIAVALUE and EuPLEx campaigns. The comparison criterion, the ASUR measurements that were carried out within  $\pm 1000$  km in  $\pm 6$  hrs of the satellite observations, was common to all data sets except for OSIRIS, where the measurements were selected within  $\pm 8$  hrs. The analyses reveal that, irrespective of the latitude sections, the difference between the ASUR and satellite sensor ozone is within 17% at 20–40 km, which is a promising result. Since the upper and lower stratospheric ozone mixing ratios are rather low, small absolute deviations result in large differences in  $\Delta$  (in percent) profiles. The assessment shows the following deviation values:  $-4$  to  $+8\%$  for ASUR-SCIAMACHY (operational product, v2.1), within  $\pm 15\%$  for

ASUR-SCIAMACHY (scientific product, v1.62), up to +6% for ASUR-MIPAS (operational product v4.61) and ASUR-MIPAS (scientific product v1-O<sub>3</sub>-1), up to 17% for ASUR-OSIRIS (v012), and -6 to 17% for ASUR-SMR (CTSO v222) between 20 and 40 km depending on altitude. Therefore this quantitative information has to be taken into account when using the satellite ozone for various scientific studies.

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