GEOPHYSICAL CONSISTENCY OF ENVISAT OZONE PROFILE DATA WITH GLOBAL ATMOSPHERE WATCH POLE-TO-POLE NETWORK MEASUREMENTS

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ABSTRACT

The vertical distribution of atmospheric ozone is monitored by three Envisat ozone profilers, Global Ozone Monitoring by Occultation of Stars (GOMOS), Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), and SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY). We present here the outcome of a large-scale ground-based validation of the latest versions of the Envisat ozone profile data. The latter are confronted qualitatively and quantitatively to ground-based observations collected from ozonesonde, lidar, and microwave radiometer stations performing network operation as part of WMO's Global Atmosphere Watch programme. Envisat ozone profile data are investigated from pole to pole and from the ground up to the lower mesosphere. The study concludes to a reasonable quality and consistency of Envisat profiles when adequate data selection and vertical ranges are envisaged. Seasonal variations, altitude registration issues and error budgets are further investigated.

1. INTRODUCTION

The atmospheric chemistry payload of ESA's environmental satellite Envisat includes three instruments monitoring the vertical distribution of atmospheric ozone on the global scale: Global Ozone Monitoring by Occultation of Stars (GOMOS), Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), and SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY). Although operating from the same orbiting platform, the three instruments rely on substantially different remote sounding techniques and strategies, leading to different perceptions of the ozone profile. Following the recommendations drawn after a first validation exercise conducted during the commissioning phase in 2002 [1, 2] and a main validation carried out in 2004-2005 [3, 4], retrieval algorithms of the three Envisat ozone profilers have been upgraded. The entire GOMOS data record has been reprocessed with the prototype processor version 6.0f and its operational implementation IPF 5.0. The entire MIPAS data record acquired in full resolution mode is available in version IPF 4.61- 4.62. The development of adapted processors for the analysis of MIPAS spectra acquired in Reduced Resolution mode is near completion. Data have not been available for the present study. For the first time, the Off-line processor (version 3.0) of SCIAMACHY has generated limb ozone profile data suitable for validation, although for a limited subset of orbits.

In 2004, we reported (at the Envisat Symposium in Salzburg) an integrated characterisation of Envisat ozone profile data using ground-based network data [3]. This paper updates this work with the latest versions of the Envisat ozone profile data.

2. CORRELATIVE MEASUREMENTS

Three instruments measuring the vertical distribution of ozone and relying on different techniques constitute the backbone of ground-based ozone profile monitoring: ozonesonde, lidar and microwave radiometer.

Electrochemical cell (ECC) ozonesondes are launched more or less regularly on board of small meteorological balloons at a variety of stations from pole to pole. They yield the vertical distribution of ozone volume mixing ratio (VMR) from the ground up to burst point, the latter occurring typically around 30 km. Ozone VMR recorded at a typical vertical resolution of 100-150 m is converted into ozone number density using pressure and temperature data recorded onboard the same balloon [5]. Error on the ozone profile of ozonesonde depends of a large number of parameters. For ECC sonde important parameters are: the manufacturer of the sonde (SPC or EnSci), the percentage of the sensing solution used in the electrochemical cell and the type of correction applied for pump efficiency. Unfortunately, this information is not always given or well identified in the data files. However, as shown during the JOSIE chamber comparison [6], if ozonesondes are operated in a specific way, a similar level of precision and accuracy is achievable from the different sondes types. Typical error estimates are : systematic error from 3% (0-20km) to 5% (20-35km); precision from 5% (0-20km) to 7% (20-35km).

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Differential absorption ozone lidar (DIAL) systems provide the vertical distribution of night-time ozone number density at altitudes between 8-15 km and 45-50 km, depending on the cloud cover and other measurement conditions. The typical integration time of an ozone measurement in the whole stratosphere is 4 hours. Typical vertical resolution ranges from 300 m up to 3 km depending on the altitude. The accuracy of the lidar ozone profile depends on the duration of the measurement and on the vertical resolution chosen to process the data. Individual errors bars are given in each ozone file. Typical accuracy estimates range from 3 to 7% from 15 to 40km. At 40-45km and above, due to the rapid decrease in signal to noise ratio, the error bars increase and significant bias reaching 10% may exist [7].

Millimetre wave radiometers (MWR) operate night and day, providing ozone VMR integrated over typically 2 hours (a few stations provide shorter integration time) from 20-25 to 70km, with a vertical resolution of 8 to12 km. Ozone VMR is converted into number density using ECMWF or NCEP meteorological analyses of pressure and temperature. The individual errors bars are given in each ozone file. Typical accuracy ranges from 5% at 20km to 20% at 70km where the information content is smaller leaving a larger weight to a priori constraints [8]. Its low vertical resolution poses additional problems for comparisons, for which dedicated methods have been developed [9].

Most of ozone profilers perform network operation in the framework of international structures like the Network for the Detection of Atmospheric Composition Change (NDACC, formerly the NDSC) and the World Ozone and Ultraviolet radiation Data Center (WOUDC), two major components of WMO's Global Atmospheric Watch programme (GAW).

We have found collocation with Envisat measurement at 39 ozonesonde stations, 8 lidar and 7 microwave radiometer between July 2002 and now (See Tab. 1 for a list). They form a robust set of independent and of well-known quality correlative measurements. Their complementary altitude ranges offer a ground to mesosphere access to the ozone vertical distribution and the variety of stations with different geo-location ensures a quasi pole to pole coverage. We use them as a common reference to characterise the absolute and relative consistency of the three different Envisat perceptions of atmospheric ozone vertical distribution.

3. VALIDATION METHODOLOGY

The correlative data and MIPAS data record (respectively GOMOS and SCIAMACHY) ozone profiles have been processed to select collocated pairs of profiles. A collocation criteria was chosen as the best compromise between a sufficient amount of comparison points and a sufficient collocation of the probed air masses. A maximum distance of 500km from station to Envisat profile tangent point and a maximum time difference of 6 hours seem to work properly although not optimally. This time coincidence criteria can be reduced to a maximum 2 hour to 15 min for microwave radiometer instruments that have shorter integration time. Stronger criteria result in insufficient amounts of comparison points, especially in the Southern Hemisphere and for SCIAMACHY. Errors in the comparisons due to non-perfect coincidence are illustrated here in details for MIPAS correlative studies.

The correlative analysis of Envisat ozone profile data starts with visual and statistical studies of the differences with correlative ozone profile data. The time series of ozone partial columns and of ozone profile over their full altitude/pressure range are analysed. The objective is to identify global features and trends. From the analysis of times series, time periods with homogeneous results, from which statistical values may be deduced and are meaningful, are identified. In a second step, the vertical structure of the differences is analysed within these time periods where statistical analysis is relevant.

4. MIPAS

4.1. Error Budget of the Comparison

Instead of comparing the observed relative differences with errors bars of the measurements, they should be compared to the error budget of the comparison. As the documentation about operational retrievals and related errors is detailed both for MIPAS and ground-based data, we have been able to compute the total error budget for comparison. To transpose this work to GOMOS and SCIAMACHY, more detailed information than actually available is required

Using the formalism adopted by Rodgers [10], the comparison error budget can be expressed in terms of different covariance contributions:

$$\begin{aligned} S_{MN} &= S_M + S_N \\ &+ (A_M - A_N) S_V (A_M - A_N)^T \\ &+ (A_M - A_N) S_H (A_M - A_N)^T \\ &+ S_{\Delta O_3} \\ &+ \ldots \end{aligned}$$

with:

- S_{MN} = total error covariance of the MIPAS/ NDACC comparison
- S_M = MIPAS error (measurement and retrieval)
- S_N = correlative instrument error (measurement and retrieval)
- A_M = MIPAS averaging kernels
- A_N = correlative instrument averaging kernels

Table 1. List of contributing ground-based instruments. ^{s} are ozonesonde and lidar stations where collocations with SCIAMACHY limb profile data have been found.

OZONESONDE

Station	***Location***	***Latitude***	***Longitude***	***Institute***
Alert	Canada	82.5	-62.33	MSC
Eureka	Canada	80.05	-86.42	MSC
Ny-Alesund	Svalbard	78.91	11.88	AWI
Thule	Greenland	76.51	-68.76	DMI
Resolute	Canada	74.72	-94.98	MSC
Scoresbysund	Greenland	70.48	-21.97	DMI
Esrange	Sweden	67.88	21.06	NIES
Sodankylä^s	Finland	67.37	26.67	FMI
Keflavik	Iceland	63.97	-22.6	INTA
Orlandet	Norway	63.42	9.24	NILU
Jokioinen	Finland	60.82	23.48	FMI
Churchill	Canada	58.75	-94.07	MSC
Edmonton^s	Canada	53.55	-114.1	MSC
Goose Bay	Canada	53.32	-60.38	MSC
Legionowo^s	Poland	52.4	20.97	INWM
Debilt^s	Netherlands	52.1	5.18	KNMI
Valentia	Ireland	51.93	-10.25	ME
Uccle^s	Belgium	50.8	4.35	KMI
Praha^s	Czech Republic	50.02	14.45	CHMI
Hohenpeissenberg^s	Germany	47.8	11.02	DWD
Payerne^s	Swiss Alps	46.49	6.57	MCH
Tsukuba^s	Japan	36.05	140.13	JMA
Paramaribo^s	Surinam	5.81	-55.21	KNMI
San Cristobal	Galapagos	-0.92	-89.6	NOAA
Nairobi	Kenya	-1.27	36.8	MCH
Malindi	Kenya	-2.99	40.19	RPSM
Natal	Brazil	-5.42	-35.38	INPE
Watukosek	Java	-7.5	112.6	JAXA
Ascension Island	Congo	-7.98	-14.42	NASA
Tutuila	Samoa	-14.23	-170.56	NOAA
Fiji	Fiji	-18.13	178.42	NOAA
Saint-Denis	Reunion	-21.06	55.47	CNRS
Irene	South Africa	-25.25	28.18	SAWS
Lauder^s	New Zealand	-45.03	169.68	NIWA
Marambio	Antarctica	-64.28	-56.72	INTA
Dumontd'Urville	Antarctica	-66.67	140.01	CNRS
Syowa	Antarctica	-69	39.58	JMA
Neumayer	Antarctica	-70.65	-8.25	AWI
Belgrano	Antarctica	-77.87	-34.63	INTA

LIDAR

Station	***Location***	***Latitude***	***Longitude***	***Institute***
Ny-Alesund	Svalbard	78.91	11.88	AWI
Andoya^s	Norway	69.28	16.02	NILU
Hohenpeissenberg^s	Germany	47.8	11.02	DWD
Haute Provence^s	French Alps	43.94	5.71	CNRS
Tsukuba	Japan	36.05	140.13	NIES
Table Mountain^s	California	34.23	-117.41	JPL
Mauna Loa^s	Hawaii	19.54	-155.58	JPL
Lauder^s	New Zealand	-45.03	169.68	RIVM

MICROWAVE RADIOMETER

Station	***Location***	***Latitude***	***Longitude***	***Institute***
Ny-Alesund	Svalbard	78.91	11.88	IFE
Kiruna	Sweden	67.84	21.06	IMK
Bremen	Germany	53.11	8.86	IFE
Zugspitze	German Alps	47.42	11.98	IMK
Payerne	Swiss Alps	46.49	6.57	MCH
Mauna Loa	Hawaii	19.54	-155.58	UMAS
Lauder	New Zealand	-45.03	169.68	UMAS

- S_V = atmospheric variability covariance (vertical)
- S_H = atmospheric variability covariance (horizontal)
- $S_{\Delta O3}$ = ozone difference between actual air masses
- ... = all other errors

MIPAS [11] and ground-based instrument [6, 7, 8] error budgets are described in the literature. Ideally, they are the error bars that comparison results (MIPAS/ground differences) should fit within if the compared air masses were perfectly coincident. Smoothing and collocation differences increase the comparison error. In our study, we estimate separately errors due to those differences in horizontal and vertical resolution and to difference in geolocation. The full description of this experimental method falls beyond the scope of this paper. More details could be found in [12] and [13].

4.2. Time Series

MIPAS full resolution ozone profiles processed with software version 4.61 and 4.62 (off line) were compared with data from three different ground-based techniques. As there is still an error in tangent altitude registration, MIPAS profiles have been studied versus pressure.

Comparison results vary significantly between the lower stratosphere (LS), where dynamics and chemistry interfere, and the higher stratosphere (HS) dominated at first order by photochemistry. They have been classified according to the behaviour that they reflect. In the LS the ozone profile is highly dependent both on tropospheric dynamics (ex : direct link with tropospause height) and on stratospheric dynamics. Consequently, the comparison results can be grouped around the major synoptic and regional systems and the systems linked to stratospheric transport. As dynamical influences from the troposphere tend to vanish at higher altitudes, we move from large synoptic groups to a more zonal behaviour and we can group more stations. In the middle and high stratosphere, zonal symmetry becomes dominant and comparisons results follow this behaviour. Deviations from zonal symmetry nevertheless exist and must be taken into account.

An example of the time series analysis is shown on Fig. 1. This plot depicts relative differences between MIPAS partial columns and correlative data influenced by the Northern Atlantic system in 2003.

For each collocated pair of profiles, the relative difference between MIPAS and correlative ozone partial columns is shown (black bullets). Grey rectangles depict statistical values (mean $\pm 1\sigma$ standard deviation) associated with the comparisons. Different contributions to the total error budget are shown separately. The red lines depict the upper limit for the uncertainties associated with differences in smoothing of horizontal inhomogeneity. The blue lines

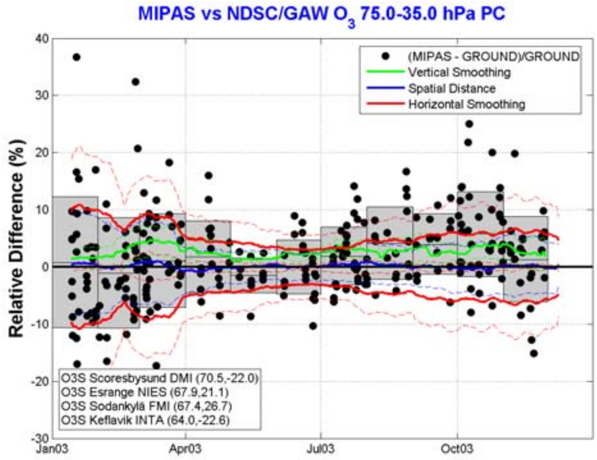

Figure 1. Time series of MIPAS 75-35 hPa ozone partial columns percentage relative differences with coincident ozonesondes measurements at Northern Atlantic stations. Individual comparisons and monthly statistics. Vertical and horizontal smoothing and spatial distance error budget contribution are depicted.

depict non-perfect collocation systematic (plain) and random (dashed) error contributions. The green lines depict difference in vertical smoothing systematic (plain) and random (dashed) error contributions.

This example show that the standard deviation of the comparisons fits well within error contribution due to difference in MIPAS/ozonesonde horizontal smoothing. The mean positive difference between MIPAS and correlative partial columns is of the order of magnitude of the MIPAS vertical smoothing effect. The spatial distance effect is smaller and dominated by the two other effects.

Based on the results from the time series of O3 partial column differences, we have identified time periods where the agreement has a constant behaviour, and thus allows us to derive meaningful statistics. At Arctic, Northern and Southern middle latitudes, we have separated the results between "winter" (1 October to 31 March) and "summer" (1 April to 30 September). At tropical and equatorial stations, the weak seasonal variation allows us to draw annual plots. At Antarctic stations we can separate results between "ozone hole" (21 August to 15 October) and "normal ozone" periods (16 October to 20 August).

4.3. Vertical and Meridian Structures

Fig. 2 shows corresponding vertical statistics results for the "winter" time period at Northern Atlantic stations. The plot shows, for each collocated pair of profiles, the relative difference between MIPAS and correlative measurements (grey lines). The high-resolution correlative measurements have been previously convolved with MIPAS averaging kernels and first-guess profile, following Rodgers equation in order to reduce effect of vertical

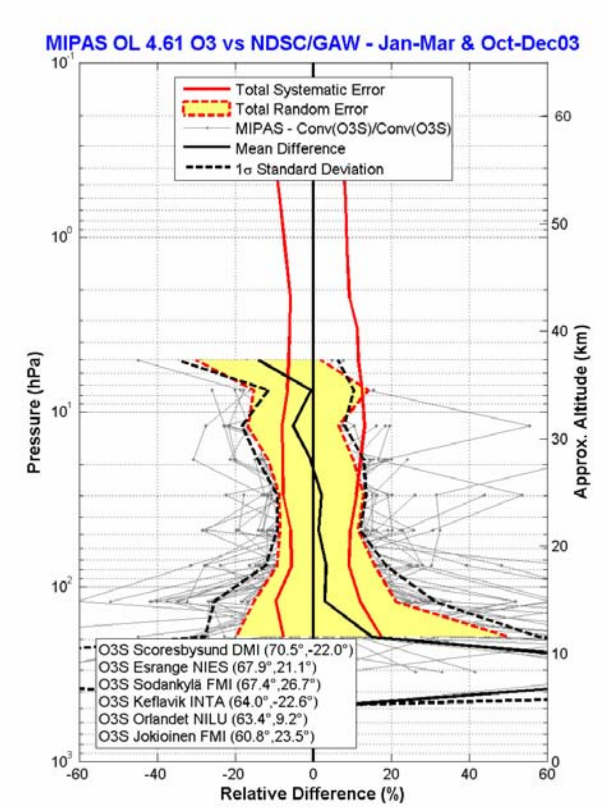

Figure 2. Percentage relative differences with coincident ozonesondes measurements at Northern Atlantic stations versus pressure, for the "Winter" time period. Individual comparisons, mean and standard deviation and corresponding random and systematic total error budget of the comparison are depicted.

smoothing differences. Black lines depict statistical values (mean and 1σ standard deviation) associated with the comparisons. Red lines depict the limits for the total systematic error of the comparison. The mean difference between MIPAS and ground station data should be compared to these lines. The total systematic error of the comparison is calculated as the sum of MIPAS systematic error and the systematic bias due to non-perfect collocation (spatial distance). The yellow block delimited by dashed red lines depicts the total random error of the comparison. This value should be compared with the 1σ standard deviation of the differences. This total random error of the comparison is calculated as the quadratic sum of MIPAS random error, ground-based random error, random contribution of spatial distance and LOS inhomogeneity.

In general MIPAS ozone profiles show a good agreement with correlative data and the mean differences fall within the systematic error budget, except in the following cases. MIPAS reports larger ozone concentration than the ground based-instruments: (a) in the lower stratosphere at stations from Northern and Southern mid latitudes, Equator and Tropics; (b) in the middle stratosphere over stations at the Equator, in the Tropic of Capricorn, and in Antarctica during ozone hole events; (c) at altitudes higher than 40km, MIPAS ozone profiles underestimate correlative observations in Hawaii.

These validation results are summarised in Fig.3, that reports mean relative differences for the two considered time periods of 2003 versus latitude. Results for all stations have been averaged within bin of 5˚of latitude. MIPAS overestimation of the ozone concentration in the lower stratosphere of the inter-tropical zone is clearly viewed. Below the tropopause more scattered results are obtained. Weight of MIPAS overestimation of the ozone amount during ozone hole period is also observed in the "January-March and October-December" Antarctica results. For other geophysical states, the mean agreement between MIPAS and correlative instruments usually fall within the 10% level and often better.

5. GOMOS

5.1. Limb Illumination States

Previous versions of GOMOS retrieved profile were strongly affected by the brightness of the limb in which the star occults. Bright limb occultations gave poor results, and only dark limb occultations were suitable for validation and scientific usage. Data measured under twilight condition were questionable. We will verify if it is still the case for the GOMOS data set reprocessed with GOPR 6.0f.

Fig. 4 and Fig. 5 show GOMOS ozone profile data records plotted versus altitude and solar zenith angle (SZA) around the NDACC/Arctic station of Ny-Ålesund and the NDACC/New Zealand station of Lauder, respectively. These plots show clearly that GOMOS ozone profiles retrieved under bright limb condition still give unrealistic results. When SZA is larger than 100˚, the ozone profile seems suitable showing the ozone layer with ozone maximum values of about 6.10^{12} molecule cm^{-2}, that correspond to standard ozone concentration at these altitudes. During twilight, for SZA between 90˚and 100˚, a specific pattern appears at high latitudes. In the upper layers that are already in the dark, GOMOS retrieve standard ozone concentration levels; while in the lower altitude layers unrealistic ozone values still appear. The altitude of the transition between realistic and unrealistic ozone concentrations varies with SZA between 90˚and about 100˚, while the Sun is setting. Due to the orbital configuration of ENVISAT and the limited azimuthal range of allowed occultations (-10.8˚to 90.8˚reduced to -5˚to +20˚, after 2005 instrument anomaly) these twilight configuration happen mostly at high latitudes, at lower latitudes the transition is sharper. We also remark that below about 15km, spots of large positive or even negative ozone densities are retrieved by GOMOS, also under dark limb conditions.

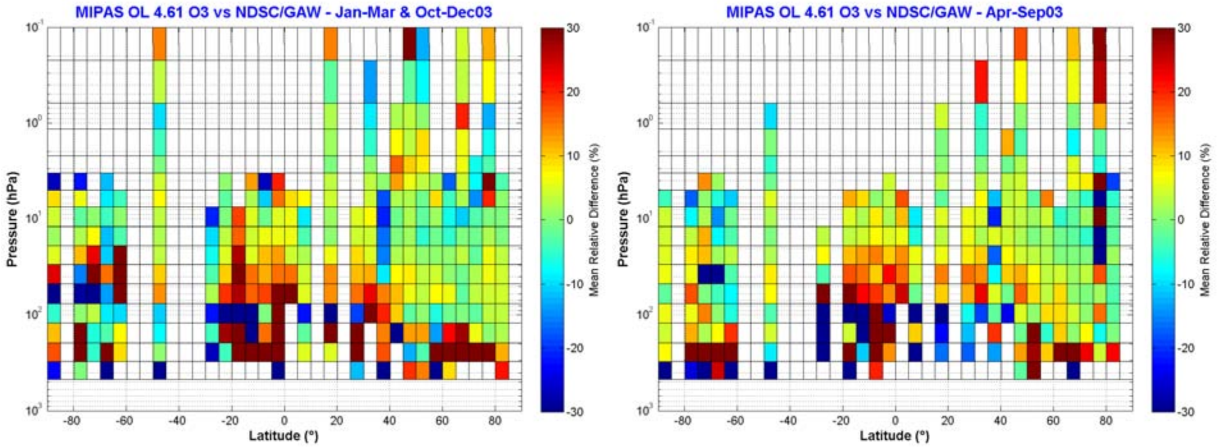

Figure 3. Mean relative difference between MIPAS and correlative ozone concentration versus pressure and latitude. Data from January to March and October to December 2003 (left) and from April to September 2003 (right).

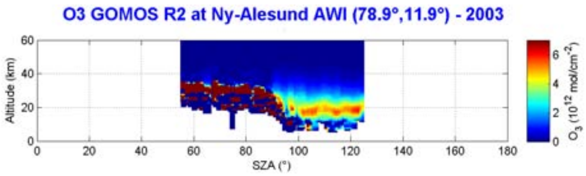

Figure 4. GOMOS ozone number densities over the NDACC/Arctic station of Ny-Ålesund, as a function of altitude and solar zenith angle (SZA) for 2003.

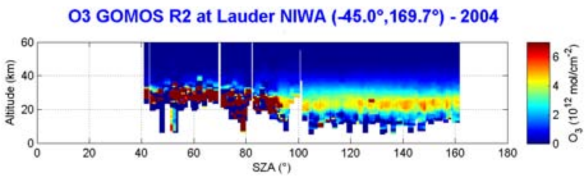

Figure 5. Same as Fig. 4 but around the NDACC/New Zealand station of Lauder and for 2004.

For the rest of this analysis, only data measured under dark limb condition, for SZA larger than 100˚have been selected. They represent about 45% of the profiles suitable for validation.

5.2. Time Series

Three examples of individual stations time series are shown in Fig. 6, Fig. 7 and Fig. 8, illustrating comparisons with ozonesonde and lidar data at Northern high, middle and tropical latitudes. The figures present the relative difference between GOMOS and correlative instruments.

In the stratosphere, between 15-20 and 50 km, comparisons show a good agreement between GOMOS and correlative data. Mean differences are lower than 10% and even better. Below 15-20km, larger differences are observed. This conclusion confirms results from the direct

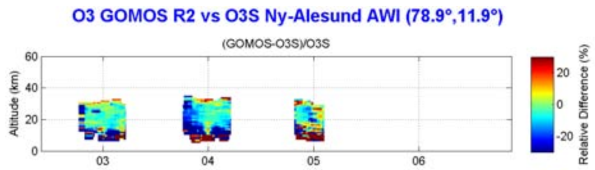

Figure 6. Time series of the percentage relative difference between GOMOS and The NDACC/Arctic station of Ny-Ålesund ozonesonde ozone profiles versus altitude. A three month running mean has been applied.

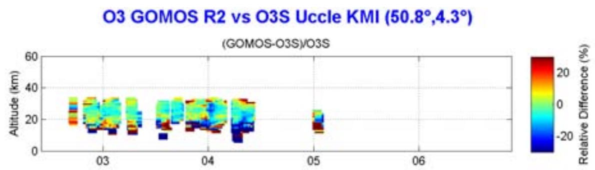

Figure 7. Same as Fig. 6 but with Belgian NDACC station of Uccle ozonesonde data.

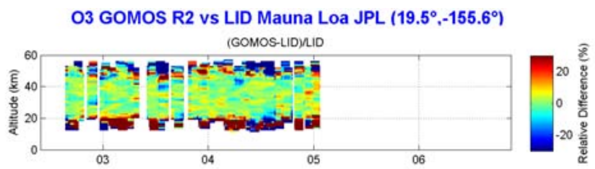

Figure 8. Same as Fig. 6 but with the NDACC/Hawaii of Mauna Loa lidar data.

ozone analysis, where large positive and negative ozone value where observed below this limit. GOMOS retrieve good ozone values to an altitude of about 15km at high latitudes while in the inter-tropical zone large differences appear already below 20km. Above 50km, comparisons with lidar and microwave radiometer show that GOMOS ozone concentrations are lower than the correlative values by more than 20%. Part of this difference could be attributed to increasing lidar error bars and microwave radiometer a-priori information content above 50km. Besides, GOMOS-related problems cannot be ruled out especially if we consider the better agreement obtained with MIPAS at such altitudes.

At high latitudes GOMOS show lower ozone values than the correlative ozonesonde near the terminator and in the bottom part of the profile. This feature may be linked to limb illumination condition issue as the Sun keeps close to the horizon at these latitudes and time periods and bright limb problems begin to appear.

5.3. Vertical Structures

The time series do not show any evident time dependences of the relative differences. The absence of time structure allows drawing annual statistics of the agreement between GOMOS and correlative data. A few examples of these vertically resolved statistics for year 2004 are shown on Fig 9 and Fig.10. This analysis confirms the results from time series study. GOMOS agree well with the correlative instrument between 15-20 and 50km. Larger mean difference are obtained above and below this altitude range. Similar results are obtained at other ground-based stations and other time periods.

6. SCIAMACHY

A reduced data set of SCIAMACHY ozone limb profile has been retrieved at DLR with off-line processor version 3.0. This set is limited and it reduces the number of ground based stations where coincidences can be found to: 11 ozonesonde and 6 lidar stations, see Tab. 1 for a list.

Previous versions of ESA operational SCIAMACHY ozone limb profile profiles, as well as preliminary SCIAMACHY ozone limb profiles retrieved at University of Bremen, have demonstrated an altitude shift problem [14, 3]. A problem exists with the accuracy of the limb pointing information in the Level 0 (and then in Level 1) data sets. The pointing errors were found to be caused by an incorrect knowledge of the satellite position.

A study of the resulting altitude shift for these preliminary versions of SCIAMACHY ozone profiles concluded to a mean shift of 1.5km varying with longitude and latitude. On-board orbit propagator is updated twice a day, always roughly at the same geographical locations : (i)

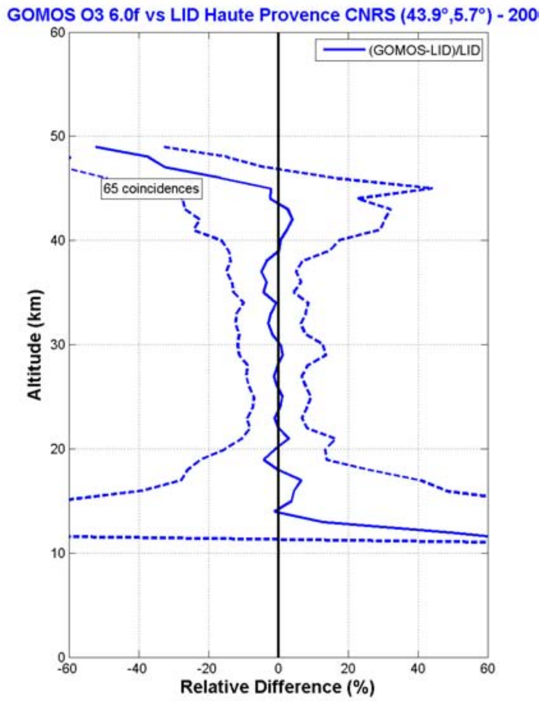

Figure 9. Mean relative difference and standard deviation of comparisons between GOMOS and the NDACC/Alpine station of Haute Provence lidar ozone profile as a function of altitude for 2004.

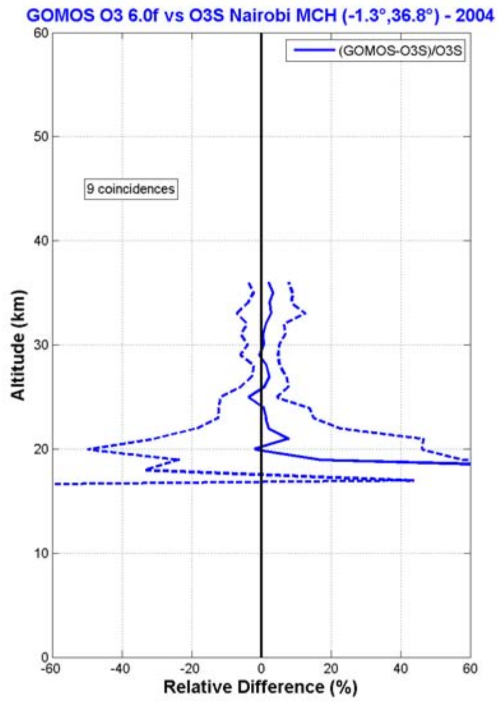

Figure 10. Same as Fig. 9 but with Kenyan NDACC station of Nairobi ozonesondes data.

around 60˚- 70˚W between approximately 20˚N and the equator, i.e., the Caribbean and/or the northern part of South America; and (ii) around 100˚E and 45˚S, i.e., south-west of Australia. Just after this sudden update of the on-board orbit model, the limb pointing appears to be more accurate and then deviates slowly from the nominal pointing.

Corrections for this pointing error have been implemented to correct the problem. First, an upgrade of the on-board orbit propagator was implemented in December 2003. Further corrections in the retrievals algorithm are supposed to correct the remaining shift.

6.1. Individual Ozone Profile Comparisons

New SCIAMACHY 3.0 ozone limb profiles should be accurate enough for validation, with a reduced altitude pointing shift. Fig.11 shows an example of retrieved SCIAMACHY ozone profile and coincident ozonesonde profile at the NDACC/Alpine station of Payerne. SCIAMACHY averaging kernel matrix and a priori data are part of the product files. Ozonesonde and lidar ozone profiles have been convolved with SCIAMACHY averaging kernel matrix and a priori data, the corresponding smoothed correlative profile is also shown on the plots.

No obvious altitude shift between the profiles appears. This example represents the majority of the analysed pairs of coincidence at middle and high norhtern latitudes. However, in a few cases SCIAMACHY seems to be shifted downward compared to coincident ground-based profiles (while known altitude pointing error is a shifted upward of SCIAMACHY ozone profiles). One of this cases is illustrated in Fig.12 with collocated SCIAMACHY and the NDACC/Alpine station of Hohenpeißenberg lidar ozone profiles.

At lower latitudes, in the inter-tropical zone, SCIAMACHY ozone profiles show a remaining positive altitude shift compared to ground-based ozonesondes and lidars. The maximum shifted is observed at the equatorial NDACC stations of Paramaribo as illustrated in Fig. 13

Individual comparisons were plotted for pairs of coincident profiles at all considered stations. This analysis reveals that SCIAMACHY gives lower ozone concentration at the altitude of the ozone maximum. This behaviour seems to be more marked at Paramaribo station in the equatorial latitude range. The relative agreement between SCIAMACHY and coincident correlative data will be studied in more details hereafter, but we will first investigate the altitude shift issue.

6.2. Altitude Shift

In order to analyse in detail the altitude shift issue, we have applied the method of cross-correlation to this new SCIAMACHY data set. This method has been developed

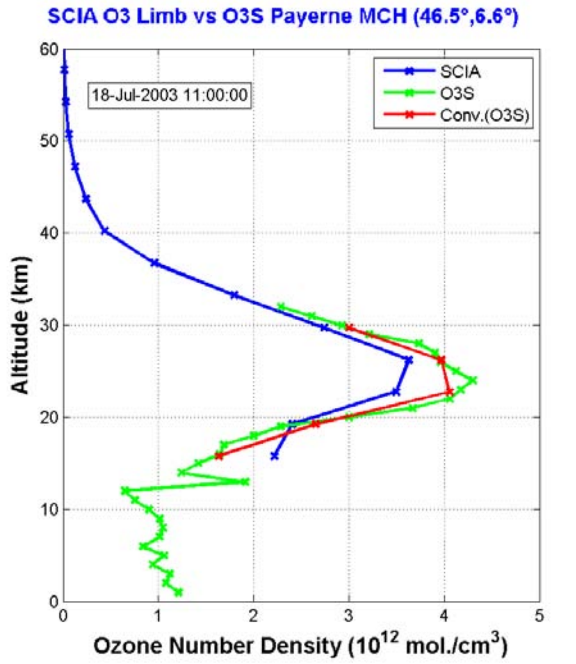

Figure 11. SCIAMACHY ozone profile plotted versus altitude and coincident ozonesonde profile measured at the NDACC/Alpine station of Payerne. Corresponding correlative profile smoothed to the SCIAMACHY vertical perception using averaging kernel matrix and a priori information.

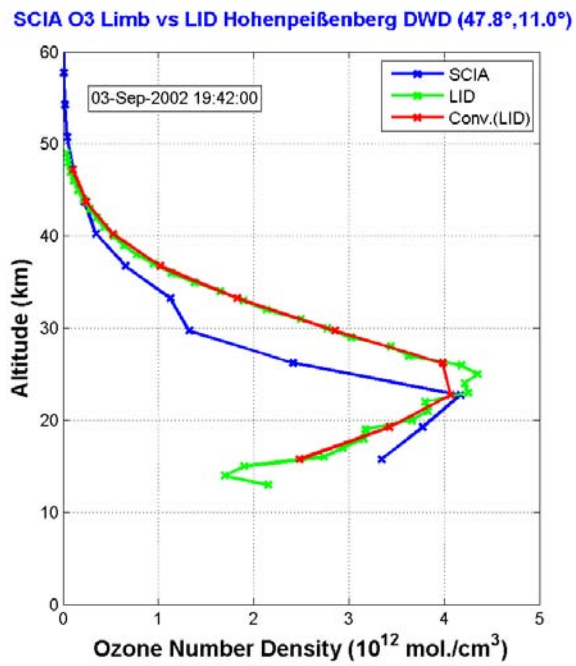

Figure 12. Same as Fig. 11 but for SCIAMACHY and the NDACC/Alpine station of Hohenpeißenberg lidar coincident ozone profiles.

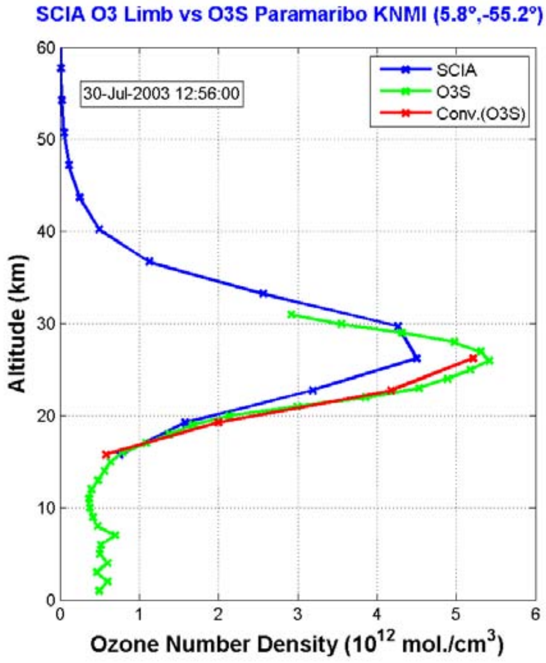

Figure 13. Same as Fig. 11 but for SCIAMACHY and the equatorial NDACC station of Paramaribo ozonesonde coincident ozone profiles.

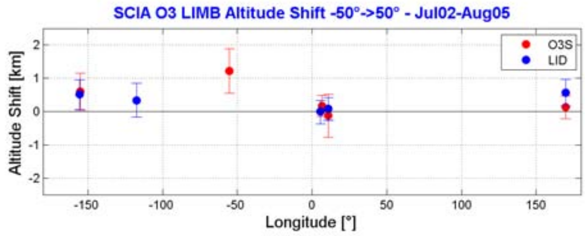

Figure 14. Mean altitude shifts between SCIAMACHY limb ozone profiles and coincident correlative data plotted according to longitude. Stations located between 50˚S and 50˚N of latitude have been selected.

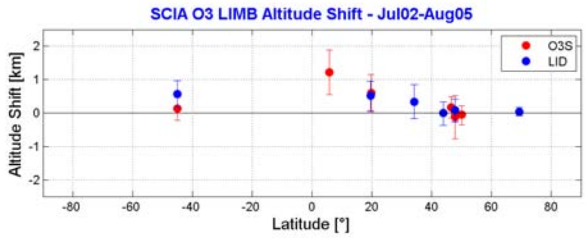

Figure 15. Mean altitude shifts between SCIAMACHY limb ozone profiles and coincident correlative data plotted according to latitude.

and successfully used to study SCIAMACHY pointing error effects previously [3]. The satellite profiles are compared with high resolution and of well known altitude pointing ozone profile given by ozonesonde and lidar instruments. The cross correlation function is given by:

$$Corr(f, g)(x) = \int f(y)g(x + y)dy \qquad (1)$$

where f and g represent the two ozone profiles to be compared and x the altitude. The altitude shift between the two functions is given by abscissa of the maximum of the cross correlation.

Mean altitude shifts, at all stations located between 50˚S and 50˚N of latitude have been calculated. Results are plotted in Fig.14. Previous version of SCHIAMACHY profile had shown dependences of the mean shift versus longitude, due to updates of the on-board orbit propagator at two permanent locations (Carribean and Australia), consequently, we have investigated the zonal variation of the shift.

The mean altitude shift is strongly reduced compared to the previous version, with a mean value lower than 1km and stations where it is quasi null. We should remark that this method has a resolution limited to the resolution of the correlative profile and is not precise enough to detect shifts smaller than a few hundred meters. The amount of available SCIAMACHY profiles is limited and does not allow drawing global statistics. One point of 1km mean shift appear at -50˚of longitude, this could be a remaining effect of the Caribbean update of the on-board orbit propagator. However, due to the low number of processed profile it is difficult to conclude and no evident longitudinal dependency of the altitude shift could be confirmed. We have also studied meridian dependency of the SCIAMACHY altitude shift. Mean shifts at all stations plotted according to latitude are shown on Fig.15.

This plot makes appear an increase of the altitude shift for stations located in the inter-tropical zone. The mean altitude shift is negligible at northern middle latitude stations in Europe and increase up to 1km when going down to equator. This behaviour is observed in the northern hemisphere. Due to the lack of coincidence in the southern hemisphere it was impossible to see if a similar pattern exists.

In principle, the off-line 3.0 processor includes a pointing error correction that should reduce the altitude shift significantly. This is what we observe. However our study highlights also a persistent altitude shift which exhibits a clear meridian structure. Further validation studies should discriminate possible contributions of the limb profile retrieval algorithm adding to Envisat pointing errors. Although some remaining features are still present, profile are suitable for a preliminary validation especially over Europe where remaining shift is quasi null.

6.3. Time Series

As for MIPAS and GOMOS we have computed time series of the relative difference between SCIAMACHY and correlative ozonesonde and lidar profiles. Ozonesonde and lidar high resolution profiles are convolved with SCIAMACHY averaging kernel matrix and a priori data. Results are illustrated in Fig.16 and Fig.17 with comparisons at the NDACC/Alpine station of Payerne and at the NDACC/Hawaii station of Mauna Loa. SCIAMACHY ozone profiles show an agreement within 10% with ozonesonde and lidar data. They are generally lower than the correlative ozone profile by -10% in the altitude range of the ozone maximum. This confirms conclusion drawn from individual comparisons. Comparisons with lidar data also show negative differences of -10% at 40km of altitude. No evident time structure was found, but here again the few number of coincidence limit the analysis. Similar results are obtained at other middle latitude stations and in the Southern Hemisphere.

Results at the equatorial NDACC station of Paramaribo are shown at Fig.18. Here the negative differences observed are larger, up to -20%, and may be partly due to remaining altitude shift problem.

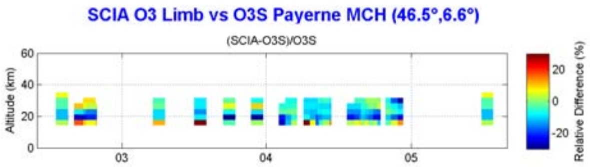

Figure 16. Time series of percentage relative differences between SCIAMACHY and the NDACC/Alpine station of Payerne ozonesonde ozone profiles versus altitude. A three month running mean has been applied.

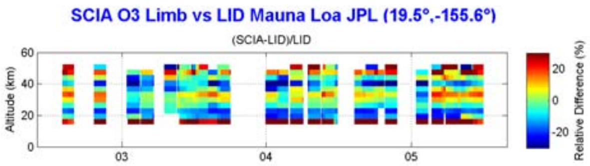

Figure 17. Same as Fig. 16 but with the NDACC/Hawaii station of Mauna Loa lidar data.

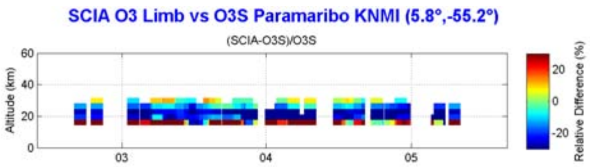

Figure 18. Same as Fig. 16 but with the equatorial NDACC station of Paramaribo ozonesonde data.

6.4. Vertical Structures

Similar to what has been done for MIPAS and GOMOS, we have computed vertical statistics for homogenous time period. Due to the few number of retrieved SCIAMACHY profile, we have computed annual statistics to have a sufficient number of coincidences. Comparisons have been made with and without convolving correlative ozone profile with SCIAMACHY averaging kernel matrix and a priori data. The difference gives an estimate of the smoothing error associated with the SCIAMACHY data. Mean (plain line) and standard deviation (dashed) are depicted for the two cases. Results at the NDACC/Alpine station of Payerne in 2005, at the equatorial NDACC station of Paramaribo in 2003 and at the NDACC/New Zealand station of Lauder in 2004 are shown on Fig. 19, Fig. 20 and Fig. 21 and illustrate well the general behaviour observed. In general, the mean relative difference between SCIAMACHY and ozonesonde and lidar correlative ozone profiles fits within the $\pm 10\%$ level, except in the following cases: (a) SCIAMACHY reports lower ozone concentration at altitude of the ozone maximum, from about 15 to 25km. (b) SCIAMACHY reports lower ozone concentration than lidars at 40km of altitude. (c) at the Paramaribo equatorial station, the underestimation of the ozone maximum is more marked and could be due to remaining altitude shift problems. Additional orbits overpassing low latitude stations located before and after the on-board orbit propagator update might helps to confirm this finding.

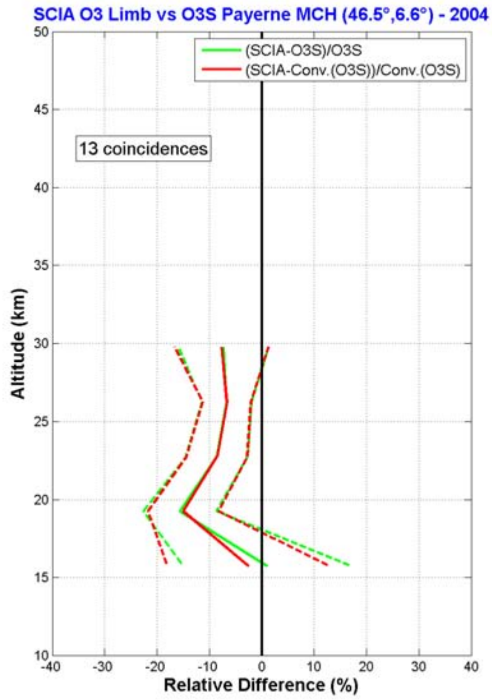

Figure 19. Mean relative difference and standard deviation of comparisons between SCIAMACHY and the NDACC/Alpine station of Payerne ozonesonde ozone profile as a function of altitude for year 2004. Corresponding statistic for comparisons with correlative data smoothed to the SCIAMACHY vertical resolution using Averaging kernel matrix and a priori data.

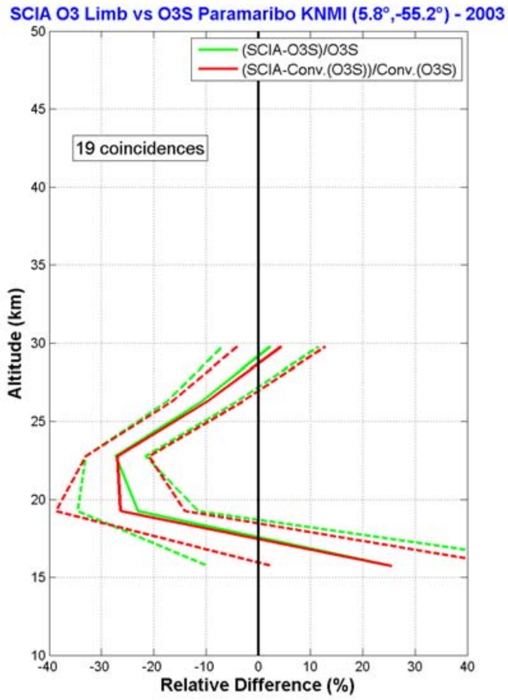

Figure 20. Same as Fig. 19 but with the equatorial NDACC Paramaribo station ozonesondes data in 2003.

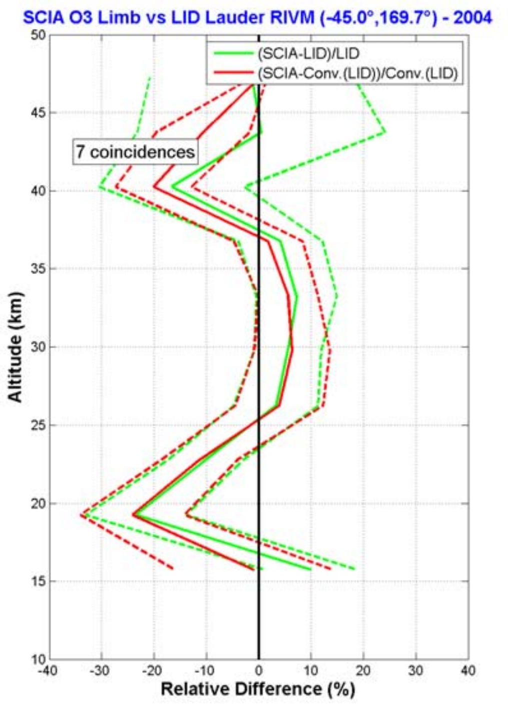

Figure 21. Same as Fig. 19 but with the NDACC/New Zealand station of Lauder lidar data in 2004.

7. CONCLUSION

Independent ground-based measurement techniques have been used to validate ozone profile data reported by the three Envisat ozone profilers, GOMOS, MIPAS and SCIAMACHY. Correlative profiles measured by ozonesonde, lidar and microwave radiometry in the framework of GAW/NDACC ground-based networks have been used as a common reference of well known quality. The different geo-locations of the ground-based stations and the different altitude range covered by the three techniques allow pseudo-global investigations.

As detailed documentation about operational retrievals and related errors is available both for MIPAS and ground-based data, we have been able to calculate the total error budget of the comparisons. Horizontal ozone gradient and geolocation difference contributions to the comparison error budget have been estimated experimentally. Temporal analysis of the relative differences between MIPAS and correlative data helps to identify time periods were statistical analysis is relevant. Vertically-resolved statistics computed for these time periods (mean and standard deviation) have been compared to the systematic and random components of the comparison error budget. The standard deviation of the comparisons correlates well with the estimated random error. The analysis shows that horizontal inhomogeneities captured by MIPAS air masses are the main contribution to this random error. In general MIPAS/ground mean differences fit within the systematic error budget and are within 10% level, except a few cases. MIPAS reports larger ozone values in the lower stratosphere of the inter-tropical zone and in Antarctica during the ozone hole. Below the tropopause more scattered results are obtained.

GOMOS ozone profiles are still strongly affected by the limb illumination conditions of the star occultation. Profiles retrieved in bright limb situation, for SZA smaller than 100˚, contain unrealistic ozone values. When selecting only dark limb occultations, ozone profiles agree well with the correlative data. Between 15-20km and 50km, mean differences are within the 10%level. Below 15km at high latitude and 20km in the inter-tropical zone, GOMOS ozone profiles show unrealistic large positive or even negative ozone values. Above 50km, negative differences are observed between GOMOS and correlative lidars and microwave radiometers. The time series analysis does not reveal any evident time dependence, except at high latitudes where a poorer agreement is obtained close to the terminator.

Previous versions of SCIAMACHY limb ozone profile data suffered from a know altitude pointing problem, resulting in an altitude shift of the profile. A limited data subset of SCIAMACHY limb ozone profiles have been reprocessed with a new version 3.0 of the off-line processor, including some correction for this shift. A specific study of the altitude shift reveals that it is effectively reduced with the new version. The mean altitude shift is now less than 1km and quasi null at some locations;

while it was between 1.5 and 3km for the previous versions. However, meridian and zonal dependences of the SCIAMACHY pointing error persist. Despite remaining issues, ozone profile data are suitable for a preliminary validation, especially over Europe where the remaining shift is quasi null. Time series and vertical statistics of the relative differences have been studied. The analysis reveals that SCIAMACHY underestimates the ozone maximum between 15 and 25km. This underestimation is more marked at the equatorial station of Paramaribo and could be due to remaining altitude shift problems. Further validation studies should discriminate possible contributions of the limb profile retrieval algorithm adding to Envisat pointing errors. Comparisons with lidar data also show that SCIAMACHY gives lower ozone concentration than lidars around 40km of altitude. For other altitude ranges, mean relative difference fits within the $\pm$10% level.

The three Envisat ozone profilers rely on totally different techniques. Consequently our validation methodology, although being established on the same base, has been adapted to each instrument and retrieval characteristics. Limb illumination condition is an issue for GOMOS while altitude shift of the retrieved profile is investigated for SCIAMACHY. When adequate data selection and vertical ranges are envisaged, validation results show an acceptable agreement between ground-based data and MIPAS and GOMOS ozone profiles in the stratosphere (that is the standard accessible altitude range reported in the literature for well-proven satellite ozone profilers). SCIAMACHY ozone profile still show some problems linked with altitude pointing errors.

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