Cross-Validation of Recent Satellite and Ground-Based Measurements of Ozone and Water Vapor in the Middle Atmosphere

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CROSS-VALIDATION OF RECENT SATELLITE AND GROUND-BASED MEASUREMENTS OF OZONE AND WATER VAPOR IN THE MIDDLE ATMOSPHERE

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ABSTRACT

Validation of space-based measurements of the atmosphere can be performed by means of long-term data sets from ground stations of the Network for the Detection of Atmospheric Composition Change NDACC (formerly NDSC). We derive the difference profiles of the satellite experiments ENVISAT/MIPAS, Aura/MLS, ACE/FTS, Meteor-3M/SAGE III, and UARS/HALOE with respect to the ground-based microwave radiometers SOMORA and MIAWARA monitoring the volume mixing ratios of ozone and water vapor in the middle atmosphere over Payerne and Bern in Switzerland. The long-term stability of the ground stations allows a cross-validation of space-based measurements from different satellites, years, and solar zenith angles. A good agreement (relative difference $< 10\%$) has been achieved between ENVISAT/MIPAS, Aura/MLS, and SOMORA (all measuring the thermal emission of ozone). The solar occultation experiments SAGE III and ACE/FTS provide ozone values which are 30% higher compared to SOMORA at altitudes 45-60 km. In case of water vapor, a good agreement ($< 10\%$) is found between the satellite experiments ENVISAT/MIPAS, Aura/MLS, ACE/FTS, and HALOE, while the ground station MIAWARA yields water vapor mixing ratios which are $10 - 20\%$ smaller at stratospheric heights.

1 SATELLITE EXPERIMENTS AND GROUND STATIONS

1.1 A CONCEPT FOR THE CROSS-VALIDATION OF SATELLITES

Since orbit planes and operation intervals of satellites vary from time to time, the finding of coincident measurements by two or more satellites can be difficult or impossible, particularly at equatorial and mid-latitudes. The long-term observation series of a ground station can serve here as a reference, allowing the comparison of various satellite experiments as described in Fig. 1. A cross-validation of past and present satellite missions is possible by using long-term data sets of ground stations. Double differencing of satellite observations with respect to a ground station removes the contributions of diurnal, seasonal, and interannual composition changes and trends. Ideally, double differencing will provide the difference of the systematic errors, $(e_A - e_B)$, of the satellite experiments A and B:

$$\begin{aligned} O(X_A(t_1), X_B(t_2)) &:= [X_A(t_1) - X_G(t_1)] - [X_B(t_2) - X_G(t_2)] \qquad (1) \\ &= [(X_{\mathrm{true}}(t_1) + e_A) - (X_{\mathrm{true}}(t_1) + e_G)] - [(X_{\mathrm{true}}(t_2) + e_B) - (X_{\mathrm{true}}(t_2) + e_G)] \\ &= e_A - e_B, \end{aligned}$$

if the systematic error e_G of the ground station is constant (symbols are explained in Fig. 1).

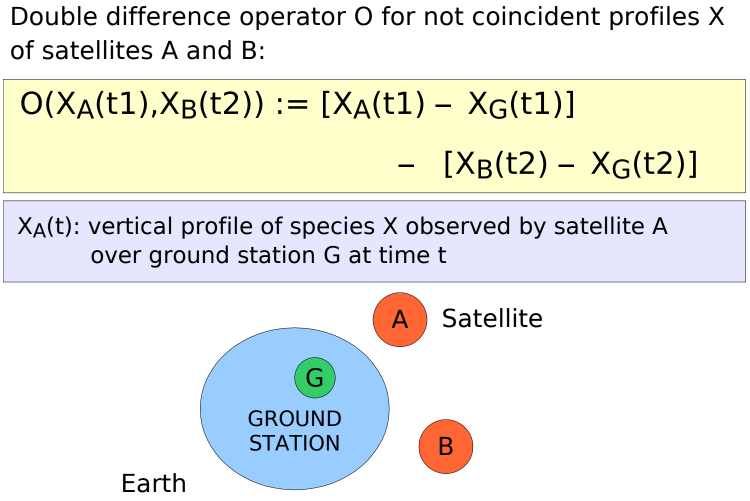

Figure 1: Cross-validation of not coincident observations of satellites **A** and **B** by means of a ground station **G**.

1.2 GROUND STATIONS

1.2.1 SOMORA

The stratospheric ozone monitoring radiometer (SOMORA) monitors the thermal emission of ozone at 142.175 GHz. SOMORA has been developed at the Institute of Applied Physics, University Bern. The instrument was first put into operation on January 1, 2000 and was operated in Bern (46.95 N, 7.44 E) until May 2002. In June 2002, the instrument was moved to Payerne (46.82 N, 6.95 E) where its operation has been taken over by MeteoSwiss. SOMORA contributes primary data to the Network for Detection of Atmospheric Composition Change (NDACC).

The vertical distribution of ozone is retrieved from the recorded pressure-broadened ozone emission spectra by means of the optimal estimation method [1]. SOMORA retrieves O_3 volume mixing ratio with less than 20% a priori contribution in the 25 to 55 km altitude range, with a vertical resolution of 8-10 km, and a time resolution (spectra integration time) of ∼30 min. More details concerning the instrument design, data retrieval, and intercomparison can be found in [2] and [3].

Table 1: Characteristics of the ground stations

Ground station	Data interval	Measurement technique	Observation target	Retrieval target	Altitude range	Vertical resolution	Time resolution
MIAWARA 46.95 N, 7.44 E	since Dec 2002	radiometer with AOS[1]	22.235 GHz emission	H_2O VMR profile	20-60km	10km	4h
SOMORA 46.82 N, 6.95 E	since Jan 2000	radiometer with AOS	142.175 GHz emission	O_3 VMR profile	20-60km	10km	30min

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[1] MIAWARA has in addition a narrowband chirp transform spectrometer (CTS) for measurement of water vapor at altitudes 50-75 km. The CTS data are not used in the present study.

1.2.2 MIAWARA

The middle atmospheric water vapor radiometer (MIAWARA) monitors the thermal emission of water vapor at 22.235 GHz. MIAWARA has been developed at the Institute of Applied Physics, University Bern. The instrument was first put into operation in April, 2000. In the present study, spectra of MIAWARA's acousto-optical broadband spectrometer (AOS) are used, as observed at Bern (46.95 N, 7.44 E) since December 2002. The averaging kernels and the *a priori contribution* profiles of the retrievals of MIAWARA and SOMORA are depicted in Fig. 2. MIAWARA contributes primary data to the Network for Detection of Atmospheric Composition Change (NDACC). More details concerning the instrument design, data retrieval, and intercomparison can be found in [4] and [5]. The main characteristics of the ground stations MIAWARA and SOMORA are summarized in Table 1.

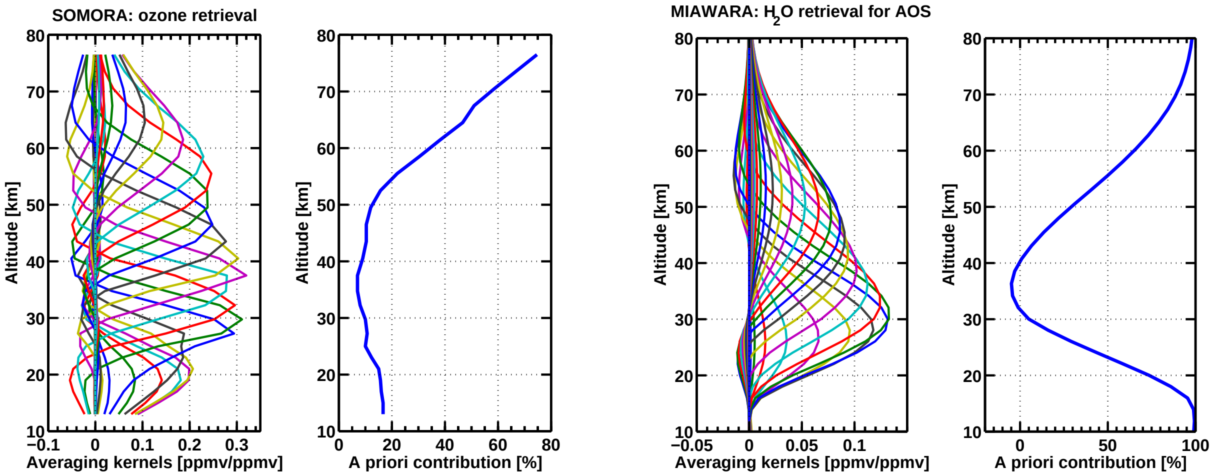

Figure 2: Averaging kernels (matrix columns) and a priori contribution of SOMORA and MIAWARA (November 2005).

Table 2: Characteristics of the satellite experiments (relevant for this study)

Satellite Experiment	Orbit	Data interval(1)	Measurement technique	Observation target	Retrieval target	Altitude range	Resolution $\Delta h,\ \Delta t$	Retrieval version
Aura MLS	$i = 98°$ $h = 705$km	Aug2004- Mar2006	radiometer, limb scan	190, 240 GHz emission	H_2O, O_3 VMR	15-60km	3km 25s(2)	v01.51
ENVISAT MIPAS	$i = 98.5°$ $h = 800$km	Aug2002- Mar2004	interferometer, limb scan	infrared emission	H_2O, O_3 VMR	15-60km	3km 80s(2)	V30-H2O-11(3) V30-O3-08(3)
ACE FTS	$i = 74°$ $h = 650$km	Feb2002- Jul2004	solar occultation	infrared absorption	H_2O, O_3 VMR	20-60km	3-4km 1min(4)	V2.2 (H_2O) V2.2up (O_3)
Meteor-3M SAGE III	$i = 99.6°$ $h = 1000$km	May2003- Aug2003	solar occultation	UV/visible absorption	O_3 VMR	20-60km	1.5-2km <2-3min(4)	Polyakov, 2006 [6]
UARS HALOE	$i = 57°$ $h = 580$km	Dec2002- Feb2005	solar occultation	infrared absorption	H_2O VMR	20-80km	1.6km <2-3min(4)	V19

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(1) Available data from this time interval are taken in the present validation study. Operation of most satellites is going on.
(2) Average time distance between two vertical profiles (sampling time of profiles).
(3) Retrieval of IMK FZ Karlsruhe [7, 8].
(4) This is the measurement time of a vertical profile. The sampling time of profiles is around (orbit revolution time / 2).

1.3 SATELLITE EXPERIMENTS

Some of the characteristics of the selected satellite experiments are given in Table 2. It is evident that the data intervals are quite different. At equatorial and mid-latitudes, the profiles of the solar occultation experiments HALOE, SAGE III, and ACE/FTS are always at different solar local times compared to ENVISAT/MIPAS and

Aura/MLS. Double differencing by means of ground-station data (Fig. 1) allows the comparison of satellite data which are not coincident and compensates for the bias that can be induced by diurnal variations of a species.

1.4 CRITERIA FOR COINCIDENCE AND AVERAGING KERNEL SMOOTHING

Coincidence shall be fulfilled when the sounding volumes of the satellite and the ground station have a horizontal distance $d < 800$ km. The time difference Δt of both measurements is chosen as < 1 hour for the ozone measurements and < 3 hours for the water vapor measurements.

Since the vertical resolution of the satellite limb soundings is better than the resolution of SOMORA and MIAWARA, we apply averaging kernel smoothing to the profiles of the satellite

$$X_{satellite,low} = X_{apriori,ground} + \mathbf{A}_{ground} \left(X_{satellite,high} - X_{apriori,ground} \right). \qquad (2)$$

$\mathbf{A}_{ground}$ is the averaging kernel matrix of the ground-based radiometer and $X_{apriori,ground}$ is the a priori profile. $X_{satellite,low}$ is the smoothed profile of the satellite measurement, adjusted to the vertical resolution of the ground-based measurement. The application of averaging kernel smoothing for the comparison of profiles with different altitude resolutions has been introduced and described by [9].

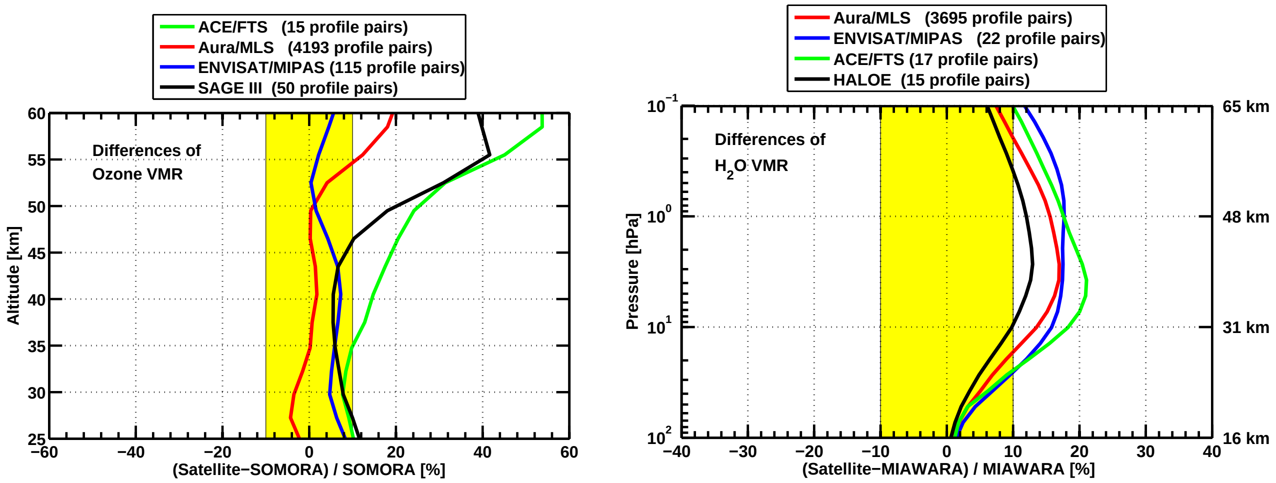

Figure 3: Left: Mean differences of the observed O_3 volume mixing ratios with respect to the ground station SOMORA in Payerne. Right: Mean differences of the observed H_2O volume mixing ratios with respect to the ground station MIAWARA in Bern. The yellow color indicates the area where the differences are within ±10%.

2 RESULTS OF THE CROSS-VALIDATION

2.1 OZONE VOLUME MIXING RATIO

The mean difference profiles of ACE/FTS, Aura/MLS, ENVISAT/MIPAS, and SAGE III are shown with respect to the ground station SOMORA in Fig. 3. The number of profile pairs is given in the figure legend. For ACE/FTS, only 15 profile pairs (coincident observations of ACE/FTS and SOMORA) have been found, and so there is only a low statistical significance for the ACE/FTS difference profile. Nevertheless, a good agreement is found between all satellite experiments and the ground stations below altitudes < 45 km. In fact, the satellite experiments themselves have relative differences $< 15\%$ at altitudes < 45 km. Beyond 45 km altitude, the solar occultation experiments SAGE III and ACE/FTS observe higher ozone values than the emission sounders SOMORA, ENVISAT/MIPAS, and Aura/MLS.

2.2 WATER VAPOR VOLUME MIXING RATIO

The mean difference profiles of ACE/FTS, Aura/MLS, ENVISAT/MIPAS, and HALOE are shown with respect to the ground station MIAWARA in Fig. 3. The number of profile pairs is given in the figure legend. A good agreement is found between all satellite experiments at all altitudes. We do not show the double difference profiles according to Fig. 1 but it is easily seen that the differences between the difference profiles are always $< 10\%$. There seems to be a systematic (dry) bias of the H_2O data from the ground station MIAWARA.

2.3 ENVISAT/MIPAS and Aura/MLS

At the moment, the available data series of ENVISAT/MIPAS stops in March 2004 while the Aura/MLS data series begins in August 2004 (Table 2). A direct cross-validation of both satellite experiments is not possible but we can apply the double differencing method (Fig. 1). The differences of both satellite experiments with respect to the ground stations SOMORA and MIAWARA have been shown in Fig.3. The difference of these differences (double difference) is depicted in Fig.4 for the measurements of the ozone and water vapor volume mixing ratios. The dashed lines indicate the error e of the average

$$e = \sqrt{\frac{\sigma^2_{mipas-ground}}{n_{mipas}} + \frac{\sigma^2_{mls-ground}}{n_{mls}}}, \tag{3}$$

where σ the standard deviation, n the number of the profiles, and *ground* the name of the ground station is (either MIAWARA or SOMORA). A good agreement is obtained for the ozone measurements of MIPAS and MLS: the difference of both experiments are mostly around 5%. An excellent agreement is achieved for the water vapor measurements: the difference of the systematic errors of MIPAS and MLS is $< 4\%$.

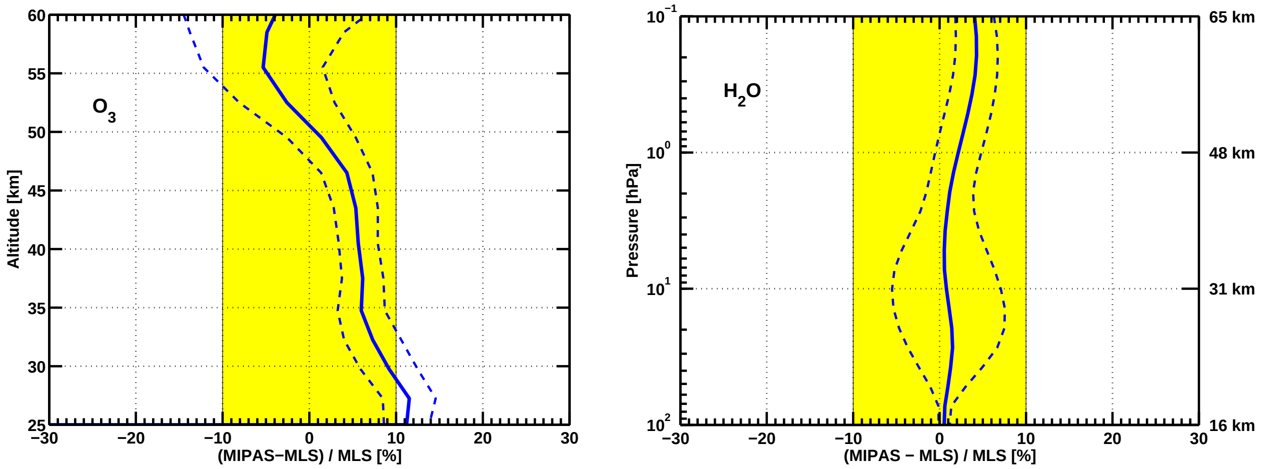

Figure 4: Relative differences of O_3 and H_2O VMR measurements of ENVISAT/MIPAS and Aura/MLS (obtained after double differencing with respect to the ground stations SOMORA and MIAWARA).

3 CONCLUSIONS

The double differencing method (Fig. 1) allows the cross-validation of satellite data by means of long-term data sets of ground stations, particularly when no coincidence is found among the satellite experiments. We tested this method with data from the satellite experiments ACE/FTS, Aura/MLS, ENVISAT/MIPAS, SAGE III, HALOE, and the ground-based radiometers SOMORA and MIAWARA in Switzerland. The ozone measurements of the selected satellite experiments agree within 15% at altitudes below 45 km. Beyond 45 km altitude, the solar occultation experiments SAGE III and ACE/FTS observe around 30% higher ozone values than the other instruments. The water vapor measurements of the selected satellite experiments are within 10% at altitudes from 20-65 km. An excellent agreement is achieved for the water vapor measurements of

ENVISAT/MIPAS and Aura/MLS: the difference of their systematic errors is $< 4\%$.

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