GEOPHYSICAL VALIDATION OF ERS-2 GOME OZONE PRODUCTS BY MEANS OF CORRELATIVE OBSERVATIONS FROM THE NDSC

J.-C. Lambert, M. Van Roozendael, J. Granville, P. Gerard, and P.C. Simon

Belgian Institute for Space Aeronomy (IASB-BIRA), Avenue Circulaire 3, B-1180 Brussels, Belgium
phone: +32-2-373 04 68; fax: +32-2-374 84 23; lambert@bira-iasb.oma.be

J.-P. Pommereau, F. Goutail, and A. Sarkissian

Service d'Aéronomie du CNRS (CNRS/SA), BP3, F-91371 Verrières-le-Buisson Cedex, France
phone: +33-1-64 47 42 88; fax: +33-1-69 20 29 99; pommereau@aerov.jussieu.fr

ABSTRACT

The global picture of total ozone has been retrieved routinely from ERS-2 GOME radiometric data for nearly four years, with the successive versions 2.0 and 2.3 of the operational GOME Data Processor. Information on the vertical distribution of atmospheric ozone has also been derived from GOME measurements with the Full Retrieval Method. Since the beginning of the GOME operation, correlative ozone measurements have been collected from three dozen ground-based instruments associated with the Network for the Detection of Stratospheric Change (NDSC). The geophysical consistency of the GOME total ozone and its sensitivity to relevant parameters have been studied by means of independent NDSC observations from the Arctic to the Antarctic, under a variety of relevant geophysical conditions. After a short description of the capabilities of the NDSC for the validation of satellite ozone data, the present paper summarises the current conclusions about the GOME total ozone data record available at present time. A representative set of ozone profiles derived from GOME data have also been compared, at altitudes from ground to 60 km, with correlative ozone profiles measured by ozonesonde, lidar, and microwave radiometer. Preliminary results of this study are presented.

1. INTRODUCTION

The Global Ozone Monitoring Experiment (GOME) was launched in April 1995 aboard the ESA's Earth observation satellite ERS-2, into a heliosynchronous polar orbit. The instrument consists of four grating spectrometers observing, between 240 nm and 790 nm, with a resolution of 0.2 to 0.4 nm, the solar irradiance and the solar radiation backscattered at nadir by the atmosphere or the Earth surface (ESA, 1995). GOME carries on with the required continuous measurement of atmospheric ozone on the global scale and in the long term initiated with the NASA Total Ozone Mapping Spectrometer (TOMS) aboard Nimbus-7, from 1978 to 1993, and continued with a second TOMS aboard Meteor-3, from 1991 to 1994 (McPeters *et al.*, 1996). The vertical column abundance of atmospheric ozone is derived from GOME spectra using the Differential Optical Absorption Spectroscopy (DOAS). Line-of-sight column amounts, or apparent slant columns, are retrieved with an iterative least-squares procedure, fitting the observed differential optical thickness with differential absorption cross-sections derived from laboratory measurements. Slant columns are converted into vertical columns using an optical enhancement factor, or air mass factor (AMF), evaluated with a radiative transfer model assuming vertical distributions of the target absorber and of radiatively active atmospheric constituents. Height-resolved information on ozone can also be derived from GOME spectra using the Full Retrieval Method (FURM) developed at IFE/IUP (Hoogen *et al.*, 1999), based on the optimal estimation approach.

The geophysical exploitation of satellite observations requires a high level of accuracy to be verified over the lifetime of the experiment. Intensive validation studies are needed to verify that satellite data do meet the requirements of potential scientific applications. It is of prime importance to characterise the sensitivity of both the measurement and the retrieval algorithms to a variety of instrumental as well as atmospheric parameters. The consistency between sensors operating on different platforms must be studied as well. The independent calibration and validation of satellite experiments is precisely a main goal of the Network for the Detection of Stratospheric Change (NDSC). This pole-to-pole ground-based network of remote-sounding research stations has played a major role in the validation of geophysical data products from GOME. It is also expected to be a main basis for the validation of data from ENVISAT-1. Section 2 describes the capabilities of the NDSC for the validation of satellite ozone data products, as well as its involvement in the characterisation and maturation of GOME data. Section 3 summarises the current conclusions on the GOME total ozone. A preliminary study of GOME ozone profiles retrieved with the latest version of the FURM algorithm is reported in section 4.

2. OZONE VALIDATION CAPABILITIES OF THE NDSC

2.1 General description of the NDSC

The NDSC consists of about 17 sites distributed in five primary stations (Arctic, Alpine, Hawaii, New Zealand, Antarctic), and of two dozen complementary sites. It started network operation in 1991, under the auspices of the United Nations Environment Program (UNEP), the International Ozone Commission (IOC) of the International Association of Meteorology and Atmospheric Physics, and the World Meteorological Organization (WMO). Combining complementary observation techniques, each NDSC primary station provides total column measurements of ozone, nitrogen dioxide and other key constituents, such as NO_y, ClO_y or CH_4, as well as vertical distributions of ozone, temperature, water vapour, ClO and aerosols. Complementary NDSC sites are equipped with a limited number of instruments validated in the same way as those of the primary stations. High-quality observations associated with the NDSC allow accurate satellite validation studies from the Arctic to the Antarctic, under a variety of geophysical conditions. They provide also a well-controlled reference for validation studies carried out at the global scale with data from other spaceborne sensors or with results from chemical-transport models. Lambert *et al.* (1999) and Zander *et al.* (this issue) give more complete descriptions of the capabilities of the NDSC for the validation of space-based atmospheric chemistry measurements.

2.2 Capabilities for ozone vertical column amount

About 30 UV-visible spectrometers constitute the backbone of the NDSC for total ozone monitoring. The DOAS technique is applied in the Chappuis band (between 470 and 540 nm) to infer slant column amounts of ozone from twilight observations of the UV-visible sunlight scattered at zenith by the atmosphere, which are converted into vertical column amounts by means of an appropriate AMF. Total ozone is also monitored at selected NDSC sites with Dobson and Brewer ultraviolet spectrophotometers, and with about 14 Fourier transform infrared spectrometers (FTIR) which measure also the atmospheric abundance of a bunch of relevant species. Correlative studies using data from the entire Dobson and Brewer networks have proved to be valuable for investigating the performances of the TOMS sensors (e.g., Barthia et al., 1984). Among other things, this approach yields a statistically significant study of heliosynchronous satellite data, due to the good air mass coincidence and the large amount of ground-based data. The various ozone observation techniques used in the frame of the NDSC provide powerful complementary information for satellite validation, and complement the classical Dobson and Brewer approach by extending its capabilities. Direct sun total ozone measurements in the ultraviolet (Dobson, Brewer) and in the infrared (FTIR) yield a very good temporal coincidence with heliosynchronous satellite data. Given a clear sky throughout the day, direct sun observations can provide information on the short-term variation of the monitored constituents. However, under cloudy conditions, Dobson and Brewer measurements are feasible only with the less accurate zenith-sky approach, while FTIR observations are not suitable. Although Dobson and Brewer spectrophotometers are believed to provide the most accurate measurements of total ozone, their accuracy degrades at low sun elevation and at low stratospheric temperatures, preventing reliable ozone monitoring in wintertime and early springtime polar regions. On the opposite, zenith-sky DOAS observations in the visible are possible up to the polar circle throughout the year. Since they are performed always during twilight, when their sensitivity to stratospheric absorbers and their accuracy are the best, they are not sensitive to the sun elevation. Combined with their generally low sensitivity to clouds and their negligible temperature dependence, their high accuracy at large SZA makes them particularly well suited for satellite validation in polar areas. This advantage is reinforced by the similarity of the stratospheric path of the sunlight observed by ground-based zenith-sky and spaceborne nadir-viewing instruments at twilight, and their good temporal coincidence.

2.3 Capabilities for ozone vertical distribution

The backbone of the NDSC ozone profile monitoring relies on three independent techniques. Ground-based lidar soundings are performed at primary NDSC stations several times per week under clear skies. Ozone number density is measured by stratospheric lidar from 10 to 45 km with a vertical resolution of 300 m to 3 km depending on the altitude and a precision of 2 to 5%. Tropospheric lidars yield ozone profiles below 15 km of altitude. Millimetre wave radiometers can operate night and day, providing ozone volume mixing ratios integrated over typically 2 hours from 25 to 70 km, with a vertical resolution of 8 to 12 km and a corresponding accuracy of 5 to 20%. Ozonesondes are generally launched several times a month at primary stations, and sometimes almost daily at particular stations during special events. They record vertical profiles of ozone partial pressure, total pressure, and temperature from the ground up to burst point, typically 30 km, with a vertical resolution of about 100 m. Combining observations performed with the three different techniques, comparisons with satellite measurements can be carried out over the entire vertical range from the ground up to 70 km. In the altitude overlaps, redundant information acquired with independent techniques is affected by independent errors, providing a valuable consistency check. The air mass probed by space-based remote-sensing can extent horizontally from several 100 km when observed at the nadir, up to more than 1000 km when scanning the limb. Although individual lidar and microwave data are intrinsically local, they can be obtained at comparable spatial resolution when averaged over a few hours, because of horizontal transport, while individual measurements inform on the variability through the averaged air mass. The method is obviously not applicable to ozonesonde data, requiring a larger data set to get statistically significant comparison results. The various ground-based vertical resolutions allow the investigation of low-resolution profiles from nadir-viewing instruments as well as high-resolution profiles from limb-viewing and occultation experiments. If degraded to the vertical resolution of the satellite instrument by means of its averaging kernels, profile observations at high vertical resolution (ozonesonde and lidar) can be valuable in testing the satellite retrieval algorithms.

2.4 GOME validation: main achievements

Ground-based observations associated with the NDSC have contributed significantly to the characterisation and maturation of geophysical products from the ERS-2 GOME and the TOMS series (see Lambert *et al.*, 1999a, and references therein). The geophysical relevance of the GOME total ozone data product has been evaluated at every step of its maturation, from the successive developmental versions 1.x of the GOME Data Processor (GDP) to the current operational version GDP 2.3. At the end of 1995, a limited data set of 45 days processed with GDP 1.20/1.21 was investigated with data from the NDSC Alpine, Arctic and Antarctic stations and from a pole-to-pole network of SAOZ/UV-visible spectrometers associated with the NDSC (ESA, 1996). A representative subset of NDSC and SAOZ stations continued the evaluation effort within the framework of the so-called GOME Tiger Team aiming at the needed improvement of the GDP total ozone product before its public release. Since July 1996, correlative studies of the first operational version GDP 2.0 of GOME total ozone have been regularly conducted using NDSC observations. NDSC data contributed at the end of 1997 to a second Tiger Team exercise to evaluate the improvement between GDP 2.0 and 2.3 (ESA, 1998). Since January 1998, they participate to the regular monitoring of the total ozone product processed routinely with GDP 2.3. The study of both GDP 2.0 and 2.3 has been combined to that of the third and fourth TOMS ozone sensors operating aboard the Earth Probe since July 1996 and aboard the ADEOS from September 1996 through June 1997 (Lambert *et al.*, 1999a,b).

From 24 January to 31 March 1997, a set of preliminary GOME ozone vertical distributions were available in near-real time, in support to the 1997 Arctic winter campaign (Eichmann *et al.*, 1997). The geophysical relevance of those profiles was investigated with correlative ozone profiles measured by ozonesondes launched at a variety of stations in the Northern Hemisphere (Lambert *et al.*, 1997). Comparison results extended to lidar and microwave data and to longer time-series obtained with an improved version of the FURM algorithm are reported in section 4 of the present paper.

3. CHARACTERISATION OF GOME TOTAL OZONE

3.1 Methodology

Twilight measurements of the ozone vertical column amount have been collected from 19 zenith-sky UV-visible DOAS spectrometers operating at the stations listed in Table 1: (a) 15 *SAOZ* instruments (Système d'Analyse par Observation Zénithale) developed by CNRS and performing automated network operation since the late 1980s (Pommereau and Goutail, 1988) and 4 DOAS spectrometers of a similar design developed at (b) IASB (Van Roozendael *et al.*, 1995), (c) IFE (Richter *et al.*, 1998), and (d) NILU (Arlander *et al.*, 1998), respectively. Total ozone data have also been collected from 8 Dobson and Brewer operated at the NDSC/Alpine and Antarctic stations, and from the two FTIR spectrometers operated at the NDSC/Alpine site of the Jungfraujoch by the University of Liège as part of its monitoring activities initiated in the 1950s (Delbouille and Roland, 1995). For each ground-based data record, absolute and relative differences with satellite data (GOME, TOMS-EP and TOMS-AD) have been investigated systematically with respect to relevant parameters, namely the SZA and the air mass factor of the space-based measurement, the ozone column value, the tropospheric cloud cover, the possible occurrence of polar stratospheric clouds, the relative position of the polar vortex, and stratospheric temperatures. Comparisons have been carried out according to the air mass optimisation method proposed by Lambert *et al.* (1998). The known biases of the ground-based total ozone time-series (e.g., seasonal/latitudinal variation in real-time SAOZ data, or temperature dependence of the ozone absorption coefficients for the Dobson and Brewer instruments) have been taken into account.

3.2 Global consistency

The agreement is found to vary with the latitude. In the Alps, the average agreement between the GOME and ground-based total ozone falls within ±2-4%. At higher latitudes, the signature of a SZA dependent difference appears, which varies with the latitude and the season. The SZA dependence is observed in both hemispheres, however slightly more pronounced in the south, and already detectable at 50°S. The SZA dependence is found to combine with a difference of sensitivity at low ozone column values, compared to ground-based observations. This difference of sensitivity is also noticeable around the southern Tropics. The three spaceborne sensors capture similarly the spatial structure of the total ozone field. The comparison of the space- and ground-based

Table 1. Contributing ground-based stations and instruments

Station	Location	Lat.	Long.	Instrument	Institute
Ny-Ålesund	Spitsbergen	79°N	12°E	SAOZ, DOAS (2), ozonesonde	NILU, IFE, AWI
Longyearbyen	Spitsbergen	78°N	16°E	DOAS	NILU
Thulé	Eastern Greenland	77°N	69°W	SAOZ, ozonesonde	DMI
Scoresbysund	Western Greenland	70°N	22°W	SAOZ, ozonesonde	CNRS/DMI, DMI
Sodankylä	Finland	67°N	27°E	SAOZ, ozonesonde	CNRS/FMI, FMI
Salekhard	Eastern Siberia	67°N	67°E	SAOZ, ozonesonde	CNRS/CAO, CAO
Zhigansk	Western Siberia	67°N	123°E	SAOZ	CNRS/CAO
Harestua	Norway	60°N	10°E	DOAS	IASB-BIRA
Bremen	Germany	53°N	9°E	DOAS	IFE
Aberystwyth	United Kingdom	52°N	4°W	SAOZ, ozonesonde	U. Wales
Hohenpeißenberg	Germany	48°N	11°E	Dobson, Brewer, lidar, ozonesonde	DWD
Bern	Switzerland	47°N	7°E	microwave	U. Bern
Jungfraujoch	Switzerland	47°N	8°E	SAOZ, FTIR, microwave	IASB, U. Liège, U. Bern
Payerne	Switzerland	46°N	7°E	ozonesonde	SMI
Arosa	Switzerland	46°N	9°E	Dobson, Brewer	ETH-Zürich
Bordeaux	France	45°N	1°W	Dobson, microwave	U. Bordeaux
Haute Provence	France	44°N	6°E	Dobson, SAOZ, lidar, ozonesonde	U. Reims, CNRS
Tarawa	Kiribati	1°N	172°E	SAOZ	CNRS/NIWA
Saint Denis	Reunion Island	21°S	55°E	SAOZ, ozonesonde	U. Réunion, CNRS
Bauru	Brazil	22°S	48°W	SAOZ	CNRS/UNESP
Lauder	New Zealand	45°S	170°E	DOAS, lidar, microwave, sonde	NIWA
Kerguelen	Kerguelen Islands	49°S	70°E	SAOZ	CNRS
Faraday/Vernadsky	Antarctica	65°S	64°W	Dobson, SAOZ	BAS/KTSU, BAS
Dumont d'Urville	Antarctica	67°S	140°E	SAOZ, lidar, ozonesonde	CNRS
Rothera	Antarctica	68°S	68°W	SAOZ	BAS
Halley	Antarctica	76°S	27°W	Dobson	BAS

time-series leads to similar conclusions for the day-to-day variability of the ozone column, under normal conditions as well as during springtime polar ozone depletion. The quantitative comparison of time-series does not reveal any significant long-term drift.

3.3 Dispersion

After removal of the average difference, the dispersion between space- and ground-based total ozone increases from ±2-3% at middle latitudes and in the tropics, up to ±10% at high latitudes in winter and also at high SZA. It varies with the season, but does not exhibit interannual variability. A major contribution to the dispersion is related to the spatial and temporal difference in air masses probed by the spaceborne and the ground-based instruments, combined with the presence of horizontal gradients and of variability. The dispersion at high SZA also arises partly from the low sensitivity of UV nadir measurements to the lower atmosphere at low sun elevation, and partly from the uncertainty on radiative transfer modeling in the ultraviolet when SZA increases. Another important source of scatter originates in deviations of the actual ozone, pressure and temperature profiles from those in use in the retrievals. Uncertainties in the treatment of the cloud cover might play a role for both the space- and ground-based instruments. Other potential effects were investigated, such as the possible radiative effect of polar stratospheric clouds, or the impact of extremely low temperatures experienced inside the wintertime polar vortex. However, those effects are masked by the strong SZA/column dependence summarised hereafter.

3.4 Solar zenith angle dependence

The GOME SZA dependence changes with the latitude, the season, and the ozone column value. In general, the deviation of GOME from ground-based data does not exceed ±4% below 70° SZA. Beyond 70° SZA, the mean agreement is dominated by a seasonal component and can even vary from month to month, as confirmed by other studies (e.g., Hansen *et al.*, 1999a). Between 70° and 85° SZA, the mean difference remains lower than ±4% in winter, but, in summer-fall, it decreases down to 5-10%, with a minimum at 75°-80° SZA. Beyond 85° SZA, the GOME total ozone values increase compared to those measured between 70° and 85° SZA. The shape and the seasonal variation of the GOME SZA dependence are similar in both hemispheres, however slightly more pronounced in the south. The SZA/latitudinal dependence of GOME total ozone is most likely to be attributed to the inaccurate treatment of the sensitivity of the GOME AMF to the ozone profile shape, suggesting possible problems with the ozone profile climatology used in the retrieval algorithm, and the partial unsuitability of the particular spectral analysis approach of GDP when the atmosphere becomes optically thick, which is the case at large SZA in the UV spectral region where GOME total ozone is retrieved.

3.5 Difference in sensitivity

For several geophysical conditions, the relative difference is found to correlate clearly with the ozone column. During springtime ozone depletion in Antarctica, the agreement is reasonable around 300 DU, however the lowest total ozone values (100 DU up to 250 DU) are overestimated by GOME by 10 to 20% compared to SAOZ and Dobson. The difference of sensitivity is also noticeable around the southern Tropics, where GOME overestimates low SAOZ total ozone values (<260 DU) and underestimates higher values, by about 5% on average. Again, the difference of sensitivity of GOME compared to ground-based data might be related to the inaccurate treatment of the profile shape effect in the current GDP, based on monthly atmospheric profiles which cannot match the actual, highly variable atmospheric profile. The effect would be significantly reduced with the TOMS V7 algorithm since it relies on a column-resolved climatology and, in addition, uses at higher SZA radiometric measurements at the shorter wavelengths to optimise the combination of middle and high latitudes profiles.

3.6 Internal inconsistencies

A close examination of the GOME comparison time-series in the Alps reveals systematic features likely generated inside the GOME processing chain itself. Every three months, GOME data are shifted by a few percent, the sign and the amplitude of the shift depending on the season. This effect appears most clearly at the end of each year when the shift can exceed 5%. GOME total ozone also exhibits a slight drift with the time of the year. This drift is reset at the beginning of each year by the 5% shift. The three-months shifts might result from seasonal changes in the profile climatology used in the GDP, combined with an inadequate temporal interpolation of this climatology. At high latitudes, the seasonal variation of the SZA dependence might be partly connected with this effect as well.

3.7 Comparison of GDP 2.0 and GDP 2.3

Compared to the first operational version of the GOME Data Processor GDP 2.0, the new operational version GDP 2.3 includes improvements taking place at various levels of the GOME data processing chain. Nevertheless, as confirmed by the correlative study, no significant improvement is to be expected from the modifications implemented in GDP 2.3. From pole to pole, the average agreement with GDP 2.3 is found similar to that observed with GDP 2.0. Changes often are within a few percent, that is, within the accuracy level of the ground-based measurements. The column-resolved, seasonal SZA dependence of GOME at high latitudes remains with GDP 2.3. Similar investigations in the Tropics and during springtime ozone depletion in both the Arctic and the Antarctic confirm the persistence of the difference of sensitivity of GOME.

4. VALIDATION OF GOME/FURM OZONE PROFILE

4.1 Data sets

For validation purposes, a representative data set of GOME ozone profiles have been retrieved at IFE/IUP with the latest version of the FURM algorithm. FURM retrieves an estimate of ozone number density at every kilometre from the ground up to 80 km. It must be kept in mind that the real vertical resolution of an ozone profile inferred from backscattered ultraviolet radiation measurements is limited physically to about 5 to 10 km. The ground pixel is about 960 km across track x 100 km along track. The GOME validation data set processed for the reported study consists of 1578 profiles from summer 1996 through summer 1998, expected to coincide with NDSC observations collected since 1995 for GOME validation purposes as part of several ERS AO projects. Ground-based instruments contributing to the present

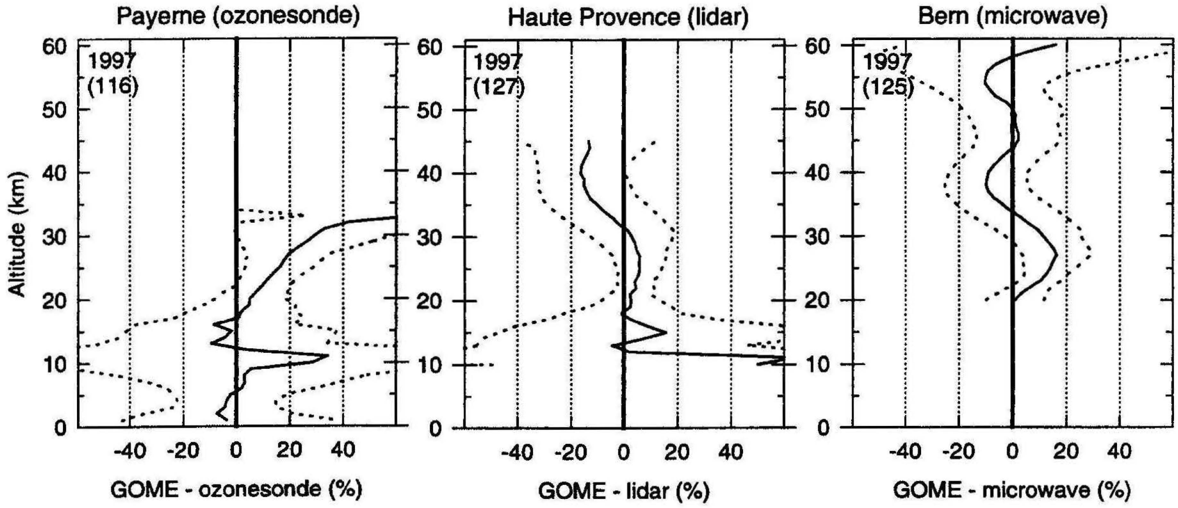

Figure 1. Mean relative difference and its standard deviation (1σ) between GOME/FURM and correlative ozone profiles measured in 1997 with independent techniques at three sites of the NDSC Alpine station. The number of coincidences is indicated.

preliminary study are listed in Table 1. They are associated mainly with the NDSC Alpine and New Zealand stations. To increase the statistical significance of the investigation in the highly variable troposphere as well as towards higher latitudes, additional ozonesonde data have been included from about 14 stations – not listed in Table 1 - contributing to large scale research campaigns supported by the European Commission, namely the Second European Stratospheric Arctic and Mid-latitude Experiment (SESAME) and the Third European Stratospheric Experiment on Ozone (THESEO). GOME and correlative profiles are selected for comparison when recorded on the same day and where corresponding to a distance between the station and the ground pixel centre within 600 km across track and 250 km along track, that is, about 8° of longitude against 2.5° of latitude at middle latitudes. The selection yields a total of 1265 coincidences. In a number of cases, a single GOME profile is compared to several correlative observations acquired by independent techniques. About 330 coincidences are found with lidar measurements from three sites of the NDSC Alpine and New Zealand stations. Lidar observations are averaged over the night and hence represent a height-resolved estimate of the ozone number density over an extended area comparable to that of the GOME ground pixel, due to horizontal transport. The time difference of about 8 hours in summer but less in winter increases the dispersion of comparison points but should not change the mean agreement. A total of 358 coincidences are found with microwave measurements at three sites of the same NDSC stations. Microwave measurements are averaged over two hours and supplied as height-resolved estimate of the ozone volume mixing ratio for the 8-12h, 12-14h, and 14-16h windows. Those time windows are sufficiently close to the GOME measurement to avoid any impact of the diurnal variation of upper stratospheric and mesospheric ozone. In addition, the temporal integration over two hours is expected to improve the spatial coincidence of the probed air masses. The conversion of volume mixing ratio into number density relies on temperature and pressure profiles derived from meteorological analyses of the NMC/NCEP below about 45 km, and climatological information of CIRA beyond. Finally, about 577 coincidences are found between ozonesonde and GOME data. High-resolution profiles from lidar and ozonesonde are integrated over the 1-km slabs of the FURM retrieval.

4.2 Preliminary results

Within their altitude range of best accuracy, a reasonable consistency is observed between comparison results obtained with the three independent ground-based techniques, as illustrated in Figure 1 at three sites of the NDSC/Alpine station. Results at northern and southern middle latitudes are in reasonable agreement as well. From the ground up to 55 km, the mean agreement generally falls within 5% to 15%, but larger individual differences are frequent, especially between 10 km and 15 km where GOME/FURM overestimates correlative data by 20% to 50%. The standard deviation (1σ) from the mean difference falls within 5% to 20%, except at the tropopause where it can reach 50%, likely due to the combination of the difference in vertical resolution, the difference in sampled air mass, and the enhanced variability of the ozone field at such altitudes. Results are consistent with those from other validation studies conducted with correlative ozonesonde or lidar data at northern latitudes (Hoogen *et al.*, 1998; Hansen *et al.*, 1999). The limited GOME data set does not allow the detection of any long-term drift of the relative difference.

The optimal estimation method requires an *a priori* knowledge of the vertical distribution of ozone which constraints the retrieval. Consequently, profiles retrieved with FURM exhibit similar vertical structures as those included in the *a priori.* To assess to which extent the information is derived from the GOME measurement itself, the mean difference between the *a priori* and NDSC profiles has been compared at all stations to the mean difference between the retrieved and NDSC profiles. Retrieved and *a priori* profiles are found to yield statistically different deviations from NDSC data between 15 km and 35-40 km, and sometimes below 10 km. Between 40 km and 50 km, the retrieved profile follows its *a priori*, and beyond 55 km they remain very close. Near the tropopause, the low vertical resolution of GOME combines with the high ozone variability to enhance the scatter of comparison results. Below 10 km, the mean agreement is fairly good and the retrieved and *a priori* profiles seem to be relatively independent. Nevertheless, individual comparisons show that the retrieved information in the lower troposphere is strongly influenced by higher altitudes. In conclusion, the

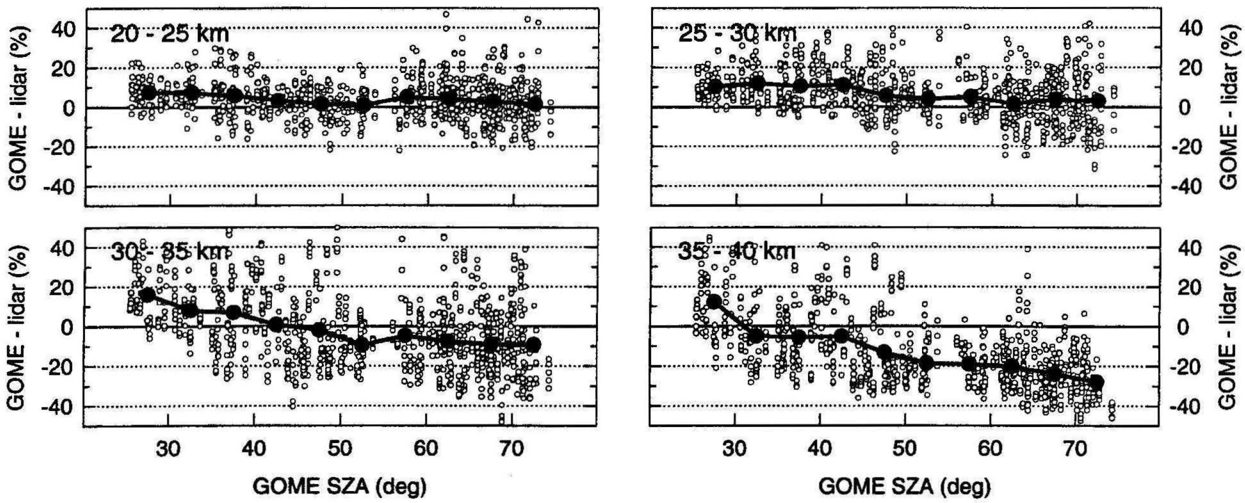

Figure 2. Relative difference (and average over 5° SZA) between the GOME/FURM and lidar ozone number density at the Observatoire de Haute Provence, at four altitudes, as a function of the solar zenith angle of the GOME measurement.

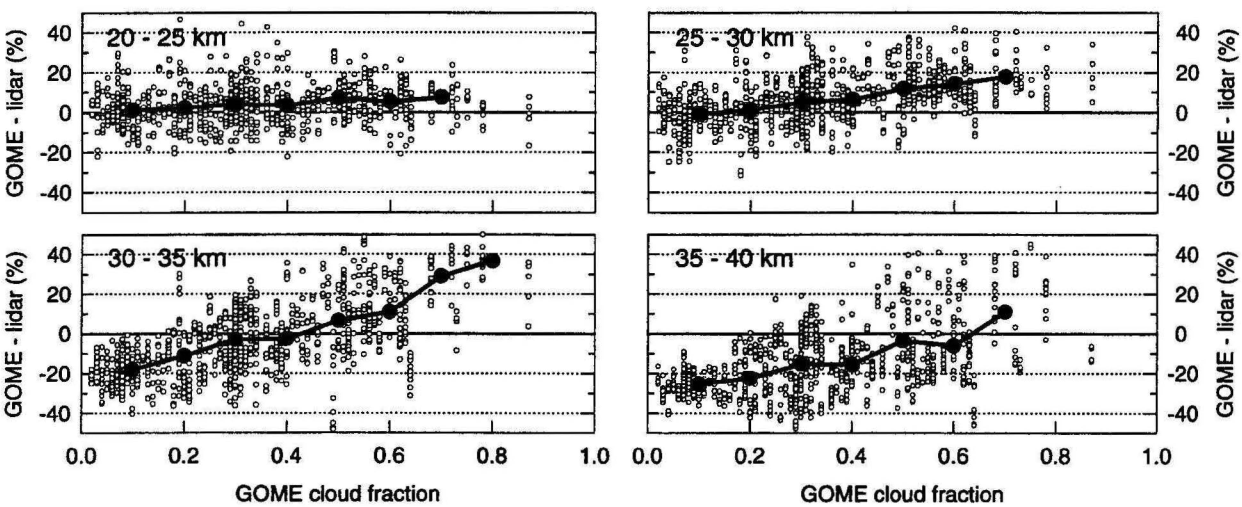

Figure 3. Relative difference (and average in bins of 0.1) between the GOME/FURM and lidar ozone number density at the Observatoire de Haute Provence, at four altitudes, as a function of the cloud fraction inside the GOME field-of-view.

retrieved information can be considered as fairly independent in the altitude range from 15 km to 40 km. The conclusion is consistent with results of theoretical studies of FURM which predicted a reasonable gain of information between 11 km and 42 km (Hoogen *et al.*, 1999).

The influence of other parameters controlling the radiative transfer, namely the solar zenith angle and the cloud fraction, has been investigated in detail at the NDSC Alpine station. Figures 2 and 3 depict results obtained with lidar data at the Observatoire de Haute Provence. Compared to lidar, microwave and ozonesonde data, GOME/FURM ozone density values decrease with the SZA and increase with the cloud fraction. The effect is clearly detected between 25 km and 40 km, that is, within the estimated altitude range of information gain from the GOME measurement. The decrease towards high SZA ranges from 5% to 30%, depending on the altitude. The increase due to clouds ranges from 10% to more than 40%, depending on the altitude as well.

5. GENERAL CONCLUSIONS

Ground-based observations associated with the NDSC have proven to provide a powerful experimental support to pole-to-pole validation studies of GOME ozone data products. NDSC-based correlative studies of nearly four years of GOME total ozone conclude to: (a) a reasonable general agreement in the Northern Hemisphere under normal geophysical conditions; (b) a systematic seasonal SZA dependence with GOME beyond 70°; and (c) a difference of sensitivity to ozone between the GOME and ground-based sensors at high latitudes and in the southern Tropics, resulting in a pronounced overestimation of low ozone values by GOME. Possible solutions have been proposed, namely, an iterative treatment of the profile shape effect, the use of a column-resolved climatology based on real profile measurements, and refinements of the current spectral analysis approach. From the ground up to 55 km, ozone profiles inferred from GOME data with the FURM algorithm are found to offer a reasonable agreement, within 5% to 15%, with correlative measurements acquired with three independent techniques. Between 15 km and 40 km, GOME/FURM ozone profiles contain information derived mainly from the measurement itself. At other altitudes, the contribution of the measurement is limited compared to the contribution of the *a priori* information used in the retrieval. Comparisons highlight a clear height-resolved dependence on the cloud fraction and on the solar zenith angle in the stratosphere, requiring further investigation.

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