

The OASIS Observatory Using Ground-Based Solar Absorption Fourier-Transform Infrared Spectroscopy in the Suburbs of Paris (Créteil-France)

P. Chelin, C. Viatte, M. Ray, M. Eremenko, J. Cuesta, F. Hase, J. Orphal, and J.-M. Flaud

Abstract Ground-based Fourier-transform infrared (FTIR) solar absorption spectroscopy has led to a number of significant advances in our understanding of the atmosphere by providing information on the vertical distribution of various trace gases. Previously used to analyse solar absorption spectra measured at high-resolution in unpolluted sites, the retrieval code PROFFIT has been adapted to deal with spectra recorded at medium spectral resolution with a Bruker Optics Vertex 80 FTIR spectrometer. As one of the major instruments of the experimental observatory named OASIS (Observations of the Atmosphere by Solar Infrared Spectroscopy), this instrument is dedicated to the study of air composition in the

P. Chelin (✉), M. Ray, M. Eremenko, J. Cuesta, and J.-M. Flaud
Laboratoire Inter-Universitaire des Systèmes Atmosphériques (LISA) CNRS UMR 7583,
Université Paris-Est Créteil, Université Paris Diderot, Institut Pierre-Simon Laplace, 61
Avenue du Général de Gaulle, 94010 Créteil Cedex, France
e-mail: pascale.chelin@lisa.u-pec.fr

C. Viatte
Laboratoire Inter-Universitaire des Systèmes Atmosphériques (LISA) CNRS UMR 7583,
Université Paris-Est Créteil, Université Paris Diderot, Institut Pierre-Simon Laplace, 61
Avenue du Général de Gaulle, 94010 Créteil Cedex, France

Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena,
CA, USA

F. Hase
Institute for Meteorology and Climate Research (IMK), Karlsruhe Institute of Technology
(KIT), Karlsruhe, Germany

J. Orphal
Laboratoire Inter-Universitaire des Systèmes Atmosphériques (LISA) CNRS UMR 7583,
Université Paris-Est Créteil, Université Paris Diderot, Institut Pierre-Simon Laplace, 61
Avenue du Général de Gaulle, 94010 Créteil Cedex, France

Institute for Meteorology and Climate Research (IMK), Karlsruhe Institute of Technology
(KIT), Karlsruhe, Germany

E. Jiménez et al. (eds.), *Environment, Energy and Climate Change I: Environmental Chemistry of Pollutants and Wastes*, Hdb Env Chem (2015) 32: 21–52,
DOI 10.1007/698_2014_270, © Springer-Verlag Berlin Heidelberg 2014,
Published online: 29 July 2014

suburbs of Paris. Accurate measurements of the most important atmospheric pollutants are indeed essential to improve the understanding and modelling of urban air pollution processes. Located in an urban region, OASIS enables to monitor key pollutants such as NO_x, O₃, CO and VOCs. In this chapter, 5 years intercomparison study with on-ground and satellite measurements for O₃ and CO is reported, demonstrating the performances of a medium-resolution ground-based instrument and especially confirming its capability for tropospheric ozone monitoring.

Keywords Air quality in megacity, Carbon monoxide, IR spectroscopy, Ozone, Remote sensing, Solar occultation

Contents

1	Introduction	23
2	OASIS Instrumentation	24
2.1	Sun Tracker	24
2.2	Fourier-Transform Infrared Spectrometer	26
2.3	Spectrometer Accuracy	27
3	Radiative Transfer Equation and Retrieval Code	28
3.1	Forward Calculation of a Synthetic Spectrum	28
3.2	Retrieval Code	29
3.3	Spectral Windows and Analysis	30
4	Results	33
4.1	Ozone Total Columns	34
4.2	Tropospheric Ozone Columns	41
4.3	CO Total Columns	46
5	Conclusions	48
	References	49

Abbreviations

DOAS	Differential optical absorption spectroscopy
DOF	Degrees of freedom
DTGS	Deuterated triglycine sulphate
DU	Dobson unit
EOS	Earth observing system
ESA	European Space Agency
FTIR	Fourier-transform infrared
GOME-2	Global Ozone Monitoring Experiment-2
HITRAN	High-resolution transmission molecular absorption database
IASI	Infrared Atmospheric Sounder Interferometer
ILS	Instrumental line shape
IR	Infrared
LAN	Local area network
MetOp	Meteorological operational polar satellite
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding

MOPITT	Measurements of Pollution in the Troposphere
MOZAIC	Measurements of ozone and water vapour by in-service airbus aircraft programme
MRD	Mean relative difference
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environment Prediction
NDACC	Network for the Detection of Atmospheric Composition Change
OASIS	Observations of the atmosphere by solar infrared spectroscopy
OMI	Ozone Monitoring Instrument
SAOZ	Système d'Analyse par Observation Zénithale
TCCON	Total Carbon Column Observing Network
TOMS	Total Ozone Mapping Spectrometer

1 Introduction

Ozone (O_3) plays an important role in the Earth's atmosphere. In the stratosphere, its presence is vital for life on Earth because it absorbs harmful ultraviolet radiation [1]; in the troposphere, it is involved in photochemical processes, a key parameter for both air quality and climate issues [2]. In the boundary-layer, O_3 is harmful to humans [3], animals and vegetation [4]. In the upper troposphere, O_3 impacts radiative forcing [5–7]. O_3 also controls the oxidizing capacity of the atmosphere [8]. In addition to O_3 , carbon monoxide (CO) is also involved in tropospheric photochemical processes: in fact O_3 production takes place when CO and hydrocarbons are photo-oxidized in the presence of nitrogen oxides (NO_x). Also CO is an excellent tropospheric air-mass tracer due to its rather long lifetime of 2 months on average.

In the international Network for the Detection of Atmospheric Composition Change (NDACC), around 20 high-quality, remote-sensing IR research stations employ ground-based Fourier-transform infrared (FTIR) solar absorption spectroscopy to observe and to analyse the physical and chemical states of the stratosphere and upper troposphere and to assess the impact of stratospheric changes on the underlying troposphere and on global climate. These high spectral resolution FTIR stations are preferentially operated at remote sites far away from sources of air pollution and often are located at high altitudes (e.g. Izaña, Jungfraujoch, Zugspitze, Table Mountain, etc.) so that measurements of tropospheric ozone are obviously limited at these stations. Hence, in order to perform air quality research in large megacities, we have assessed the capability of a medium-resolution FTIR solar absorption spectrometer for monitoring pollutants, especially O_3 and CO. We have demonstrated that such an observatory, named OASIS (Observations of the Atmosphere by Solar Infrared Spectroscopy) installed in Créteil near Paris (France) since 2008, is able to continuously monitor tropospheric ozone over Créteil with good accuracy as documented by a first analysis of information content in OASIS ozone retrievals [9].

The purpose of the present study is to confirm and expand this preliminary result by incorporating time series of total and tropospheric ozone during 5 years of measurements from February 2009 to July 2013 and by intercomparing satellite observations and in situ measurements. Another new aspect is to complement the O_3 observations with CO total columns (and its seasonal cycle) that are measured simultaneously with O_3 by taking advantage of the wide spectral range covered by the OASIS instrument.

This chapter firstly describes in detail the OASIS instrumentation (Sect. 2) and outlines the radiative transfer equation and the radiative transfer model and retrieval code applied (Sect. 3). In this latter section, a discussion on the separation of tropospheric and stratospheric columns of ozone based on the information content analysis is included. The overall results derived from the OASIS measurements are presented in Sect. 4 for the total columns of O_3 and CO and for the tropospheric ozone column. Also columns derived from OASIS measurements are compared with correlative satellite and ground-based observations. Finally, Sect. 5 is devoted to the conclusions.

2 OASIS Instrumentation

The OASIS observatory (48.79° N, 2.44° E, 56 m above sea level) was established in 2008 with the installation of a medium-resolution, Vertex model Fourier-transform infrared spectrometer manufactured by Bruker Optics (Ettlingen, Germany). This instrument collects infrared atmospheric absorption spectra using the sun as light source (Fig. 1) and monitors continuously the concentrations of important atmospheric constituents, such as H_2O , CO_2 , CH_4 , N_2O , O_2 , NH_3 , OCS , O_3 and CO. The observatory comprises an automatized cupola (Sirius 3.5 “School Model” observatory, 3.25 m high and 3.5 m in diameter) in which the upper part, the dome, equipped with a mobile aperture, rotates in order to be aligned with the solar tracker and the sun. The drive engine of the dome is fed by a battery recharged by two solar panels.

2.1 Sun Tracker

The alt-azimutal solar tracker in OASIS is the A547N model manufactured by Bruker Optics. To reach a tracking precision of ± 2 min of arc, the solar tracker uses a quadrant diode to register deviations from the precalculated pointing direction of the tracking system. The diode signal is then fed into the control loop of the tracker under cloudless blue sky conditions. In case of overcast sky, the diode signal drops down, and if it is under a minimal value, the sun tracker sustains tracking according to astronomic calculation.

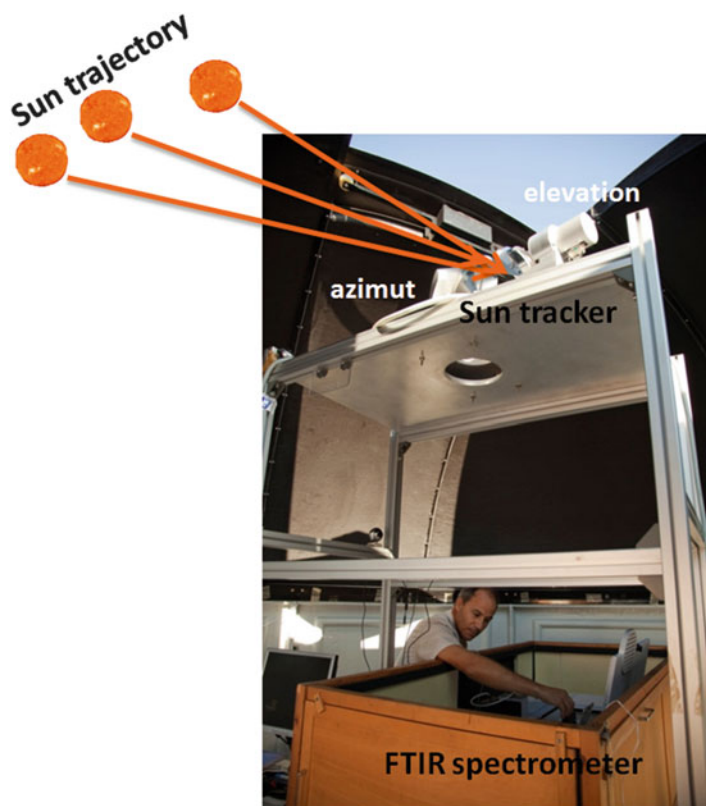


Fig. 1 Interior view of the OASIS observatory showing the FTIR spectrometer and the sun tracker

The solar light that is analysed by the quadrant diode is decoupled from the parallel beam a few cm in front of the entrance aperture by a small planar mirror, so that only a small subsection of the full beam diameter is used. Both tracker mirrors are coated with protected aluminium to cover the entire spectral range from 700 to $40,000\text{ cm}^{-1}$. However, we experienced corrosion problems with the Al mirrors. Visible damage appeared on the mirror's surface like white coatings after several months of use. Likely these problems are due to high humidity levels and large temperature excursions inside the cupola and maybe also to the presence of corrosive pollutants in the urban area. In the near future, the replacement of the current Al mirrors by bare gold-coated mirrors which cover the spectral range from 10 to $15,800\text{ cm}^{-1}$ will be tested. Moreover, two heaters have been installed to generate a less hostile environment during the cold season: one heater diminishes the overall humidity inside the cupola, the other one circulates dry air around the two mirrors. Indeed, relative global humidity dropped from 80 to 30%.

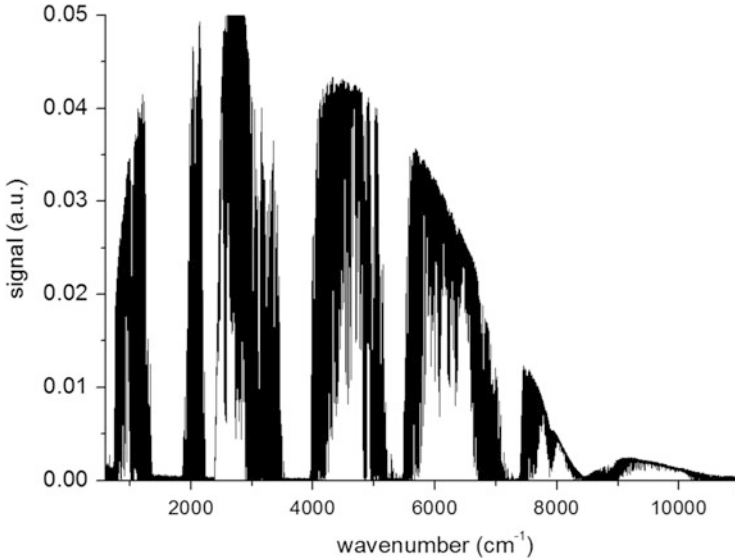


Fig. 2 Ground-based atmospheric solar spectrum recorded with an entrance aperture diameter of 1.5 mm and a maximum nominal spectral resolution of 0.075 cm^{-1}

A software provided by Bruker controls the sun tracker from the OASIS computer. The latter is also controlled by internet connection which permits the remote control of all the instruments from any computer in the university LAN.

2.2 *Fourier-Transform Infrared Spectrometer*

As one of the major instruments of the OASIS observatory, the Fourier-transform spectrometer is dedicated to the measurement of atmospheric spectra in solar occultation geometry using the infrared spectral region in order to investigate the air composition in the suburbs of Paris. The optical key element of the OASIS spectrometer is a linear Michelson interferometer that records single-sided interferograms with a maximum optical path difference of 12 cm. Infrared solar absorption spectra are nominally recorded on a DTGS (deuterated triglycine sulphate) detector using a potassium bromide (KBr) beam splitter to cover the spectral region from 700 to $11,000 \text{ cm}^{-1}$ ($0.9\text{--}14.3 \text{ }\mu\text{m}$). It is a dry air purged spectrometer to always maintain the humidity in the optical benchmark at values lower than 10%. During low temperature conditions, the spectrometer is placed inside a wood container with an additional heater.

To achieve a sufficiently high signal-to-noise ratio, each spectrum is produced by co-adding 30, 12-cm optical path difference scans, resulting in one interferogram recorded over a period of approximately 10 min (Fig. 2). Each interferogram is Fourier-transformed into a spectrum without further numerical apodization (i.e. unapodized/boxcar apodization).

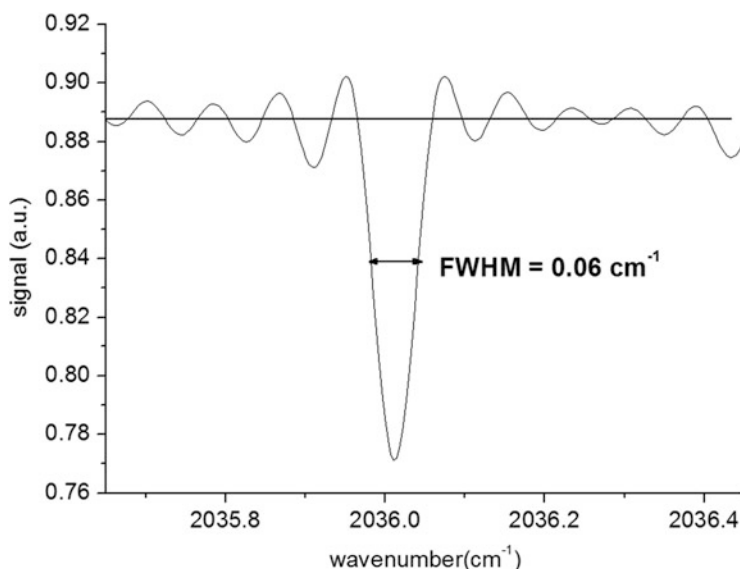


Fig. 3 Gas cell spectra recorded with OCS at low pressure for the determination of the ILS parameters

2.3 Spectrometer Accuracy

Any quantitative trace gas retrieval depends on a proper knowledge of the spectral characteristics of the instrument. For FTIR spectrometers, the Instrumental Line Shape (ILS) is advantageously separated into one part which refers to the inherent self-apodization due to the circular field stop. This contribution can be calculated easily using the spectrometer's field of view and the optical path difference of the interferometer. The second component of the ILS can be described by a complex modulation efficiency (represented by a modulation amplitude and a phase error, both functions of the optical path difference) which result from misalignments and optical aberrations [10]. In our case, the determination of the instrumental line shape (ILS) is made with a 25 cm long gas cell (using CaF_2 windows) filled with OCS (carbonyl sulphide) at very low pressure, which is put in the interferometer's sample compartment (Fig. 3). To analyse the results and to obtain the modulation efficiency and the phase error, the version 12 of the LINEFIT programme [11] is used.

The zero transmittance baseline has also been checked in an atmospheric spectrum on the ν_2 fundamental band of H_2O centred around $1,595 \text{ cm}^{-1}$ that is totally saturated as showed in Fig. 4. The accuracy on the zero transmittance is better than 0.15% checked between $1,600$ and $1,700 \text{ cm}^{-1}$. This is important since it demonstrates a very low nonlinearity of the detector.

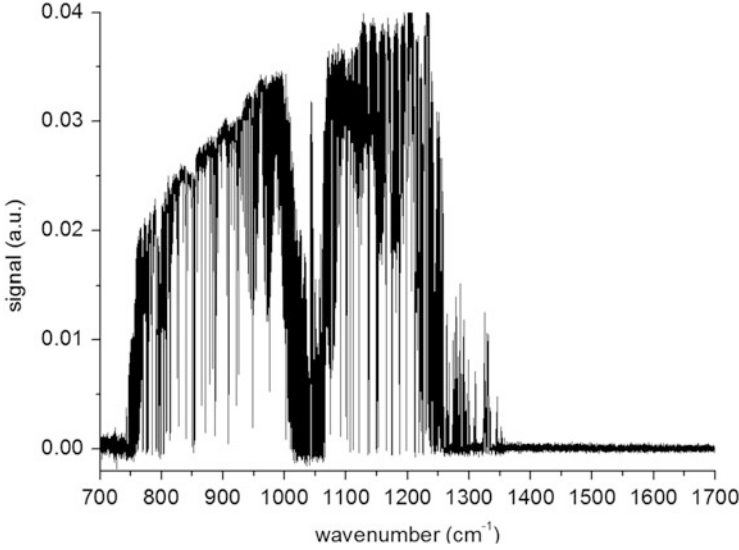


Fig. 4 Atmospheric spectrum with zero transmittance in the ν_2 band of H_2O

3 Radiative Transfer Equation and Retrieval Code

In order to retrieve the concentrations of the target species in the atmosphere, one needs first to calculate a synthetic atmospheric spectrum using a radiative transfer algorithm. This is done using the PROFile ForWard (PROFFWD) model of the PROFFIT 9.6 code [12] widely used by the NDACC community to retrieve trace gases from high-resolution FTIR measurements.

3.1 Forward Calculation of a Synthetic Spectrum

When the sun is used as the external source, the radiative transfer model is based on the integrated form of the Beer–Lambert law accounting only for absorption [13]:

$$I_{\tilde{\nu}}(l) = I_{\tilde{\nu}}(0) \times T_{\tilde{\nu}}(l, 0) \quad (1)$$

where $I_{\tilde{\nu}}(0)$ is the incident solar intensity at the top of the atmosphere (typically in $\text{W cm}^{-2} \text{sr}^{-1} (\text{cm}^{-1})^{-1}$ at the wavenumber $\tilde{\nu}$ (in cm^{-1}), $I_{\tilde{\nu}}(l)$ is the intensity at the position l (in cm) along the absorption path, and $T_{\tilde{\nu}}(l, 0)$ is the atmospheric transmittance between the positions l and 0. However, one can note that PROFFWD takes into account (in the long-wave part of the spectrum, below $1,000 \text{ cm}^{-1}$) also the atmospheric emission which becomes a non-negligible correction to the pure absorption spectrum.

The transmittance is given in case of line spectra by the following equation:

$$T_{\tilde{\nu}}(l, 0) = e^{-\tau_{\tilde{\nu}}(l, 0)} \quad (2)$$

where the optical depth $\tau_{\tilde{\nu}}(l, 0)$ between l and 0 is defined by

$$\tau_{\tilde{\nu}}(l, 0) = \sum_i \sum_j \int_0^l S_{\tilde{\nu}_j}^i(T(l')) \times \Phi(\tilde{\nu} - \tilde{\nu}_{j,p(l')}, T(l')) \times N_i(l') dl' \quad (3)$$

where i characterizes the various absorbing species; $N_i(l')$ is the local density of molecules of species (in mol cm^{-3}); $S_{\tilde{\nu}_j}^i$ is the intensity (in cm mol^{-1}) of the line j of the species i , with the line centre at $\tilde{\nu}_j$; and $\Phi(\tilde{\nu} - \tilde{\nu}_{j,p(l')}, T(l'))$ is the line profile (in cm) that depends on pressure (Lorentz profile) and temperature (Doppler and Lorentz profiles). For the species under consideration, the Voigt profile (the convolution of a Doppler and a Lorentz profile) is currently used and is commonly calculated in the atmospheric radiative transfer models (however, note that PROFFWD also supports non-Voigt line shapes and line mixing).

For the forward calculation of a theoretical spectrum, the spectroscopic reference data were taken from the HITRAN 2004 data base [14].

3.2 Retrieval Code

PROFFIT (PROFile FIT) [12] is the retrieval tool used to analyse the solar absorption spectra measured with high-resolution ground-based FTIR spectrometers. It is here adapted to the medium spectral resolution of the instrument. Note that to achieve sufficient information content in the retrievals, the micro-windows have to be widened as compared to high-resolution retrievals (as described in Sect. 3.3). The retrieval of trace gas profiles from such spectra is an ill-posed problem and needs a constrained nonlinear least squares fitting technique [15]. For this purpose, an analytical altitude-dependent regularization method with the regularization matrix containing first- and second-order Tikhonov constraints [16] is used, together with altitude-dependent coefficients that are optimized to maximize the information content of the retrievals.

For ozone, the a priori profile is taken from the mean annual McPeters climatology [17] adapted to the location of the observatory (i.e. between 40° and 50° N). It is worth noting that all retrievals are performed with the same a priori data set to ensure that all the variability seen in the retrieved profiles comes from the measurements. Furthermore, it was observed that the retrieved ozone profiles do not significantly depend on the choice of the a priori profile since a change of a priori profiles produced negligible differences on the results. For carbon monoxide and its interfering species, the a priori profiles were taken from the MIPAS project

[18]. They correspond to the mean annual profiles used for the inversion of MIPAS satellite data for latitudes between 30° and 50° N.

The temperature and pressure profiles, interpolated on the same grid as the species a priori profiles, are obtained from the Goddard Space Flight Center (NCEP, National Center for Environment Prediction). For the radiative transfer calculations, all profiles are discretized in 46 levels from the ground up to 85 km.

3.3 Spectral Windows and Analysis

Ozone and carbon monoxide concentrations shown in this chapter are derived from the spectra measured by the OASIS observatory, corresponding to 203 clear-sky days, from 25 February 2009 to 19 July 2013 at Créteil (France). Atmospheric ozone is retrieved using the spectral window from 991 to $1,073\text{ cm}^{-1}$ (where the interfering species are H_2O , SO_2 and NH_3), while CO is retrieved in the spectral region between $2,134$ and $2,174\text{ cm}^{-1}$ (where the interfering species are H_2O , CO_2 , O_3 , N_2O and OCS).

3.3.1 Ozone

Figure 5 shows a measured spectrum, the corresponding simulated spectrum and the difference between observation and simulation for the spectral window used for the ozone retrievals. As the radiance values are small below $1,000\text{ cm}^{-1}$, a quality filter is introduced selecting only spectra with a signal-to-noise ratio higher than 30 measured between 960 and 990 cm^{-1} where there is a CO_2 band.

Retrievals are characterized by the averaging kernel matrix which represents their sensitivity to the true atmospheric state and also by the degrees of freedom (DOF) which are the trace of this matrix [15]. The DOF of a given atmospheric layer reaches unity when the retrieval contains sufficient information to consider that the partial column in this layer is quasi-independent from the others. Figure 6 shows typical averaging kernels of OASIS retrievals. From the ground up to 8 km (empty square symbols) and from 8 to 17 km (solid square symbols), the DOF reaches 1.03 and 1.08, respectively, showing that these two partial columns can be separated. Typical degrees of freedom obtained through OASIS retrievals reach at least 3, which is a surprisingly good result for a spectrometer of medium resolution, given that an NDACC system (using very high-resolution spectrometers) reaches DOF around 4 [19, 20].

To validate the separation of tropospheric and stratospheric ozone columns, stratospheric and tropospheric ozone column time series are compared and the correlation between these two partial columns is evaluated (Fig. 7). The total uncertainties of tropospheric ozone, including statistical, systematical and smoothing errors, are estimated to about 13–15% (depending on the solar elevation angle and the meteorological conditions), while the uncertainty of the stratospheric ozone column is estimated to about 3%. In Fig. 7, one can see that stratospheric (solid circle symbols) and tropospheric (empty square symbols) ozone time series do not

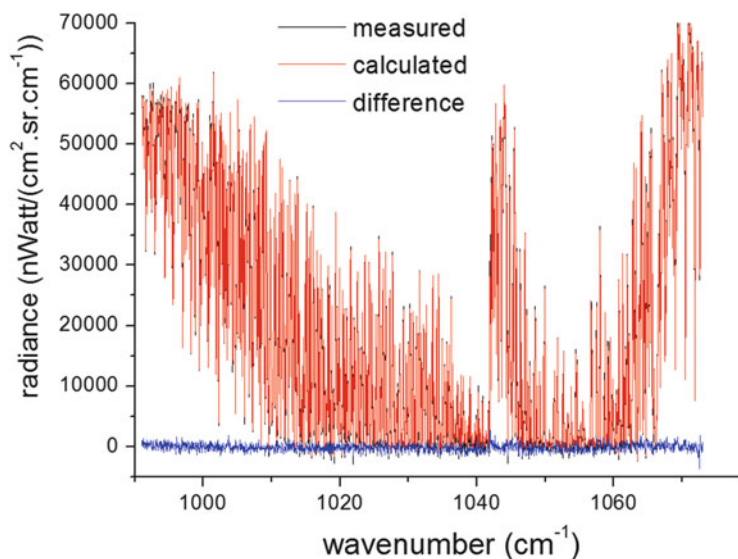


Fig. 5 Spectral window for the ozone retrievals recorded with OASIS on 31 March 2009 at 12:58 p.m. (UT). *Black*: the measured spectrum. *Red*: the calculated spectrum. *Blue*: the difference between the measured and calculated spectra

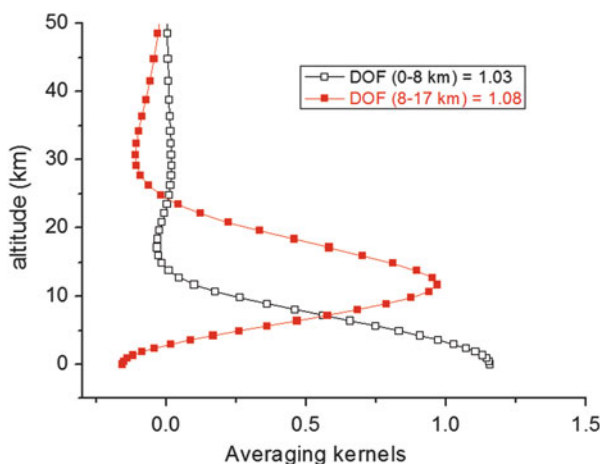


Fig. 6 OASIS typical averaging kernels in partial column from ground to 8 km and 8–17 km in *empty* and *solid square* symbols, respectively, corresponding to the spectra in Fig. 5

present the same structures and that a correlation coefficient of 0.39 is observed for the 203 measurements. The averaging kernels, which reflect the vertical sensitivity of the retrievals, show that the retrieved tropospheric amounts (integrated from the ground to 8 km) have a small stratospheric contribution through vertical transport, and vice versa (Fig. 7). Viatte et al. [9] demonstrated by a first analysis of the

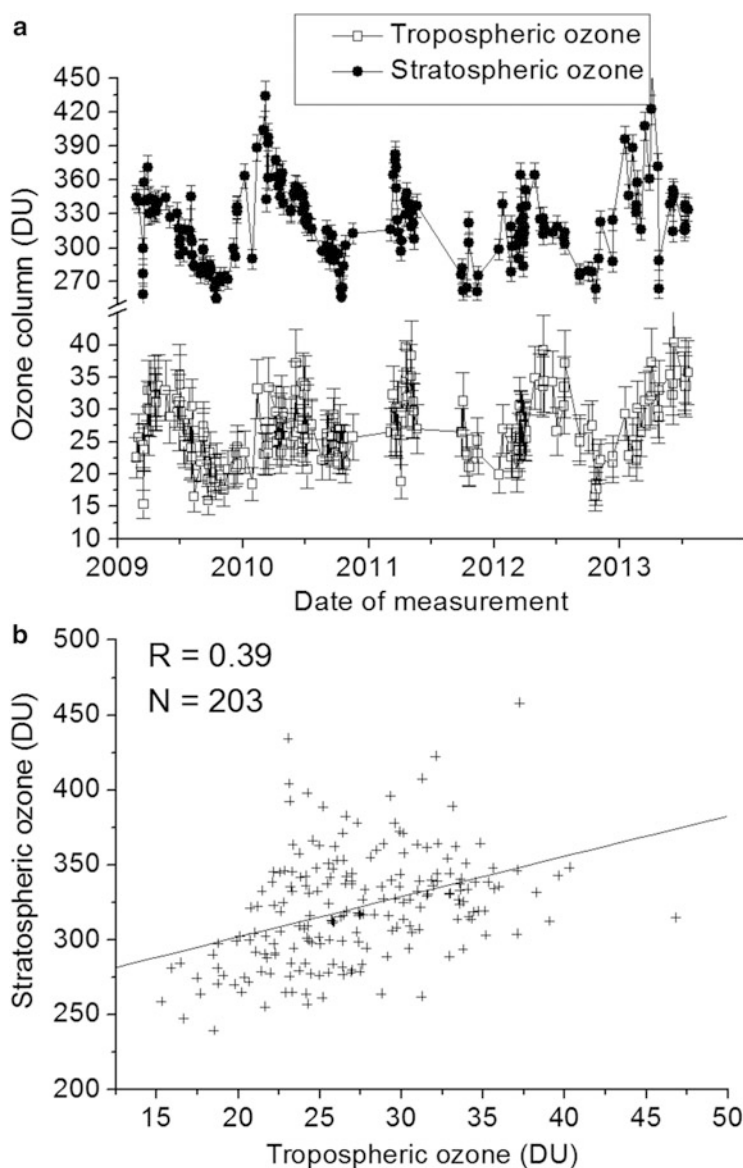


Fig. 7 *Upper plot*: times series of tropospheric (empty square symbols) and stratospheric (solid circle symbols) ozone columns derived from OASIS measurements from 25 February 2009 to 19 July 2013 at Créteil (France). *Lower plot*: stratospheric ozone related to tropospheric ozone derived from OASIS spectra

information content in OASIS ozone retrievals that using a medium-resolution instrument, tropospheric ozone can be monitored separately from stratospheric ozone since degrees of freedom reach unity in those two partial atmospheric layers.

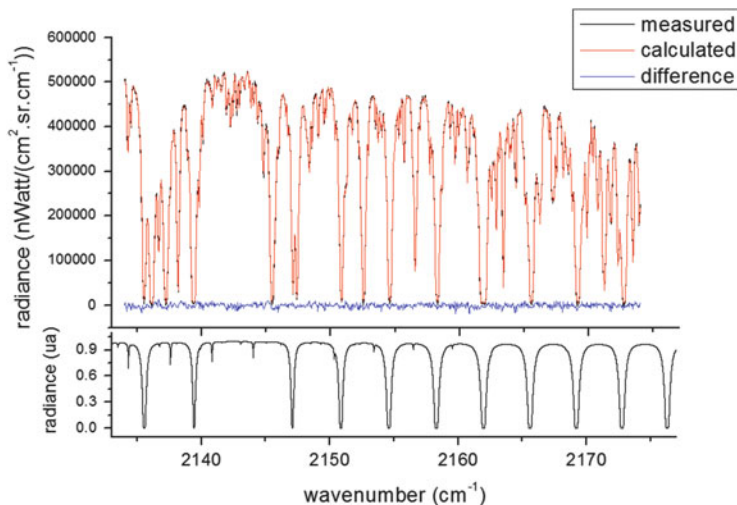


Fig. 8 *Upper plot:* spectral window for the carbon monoxide retrievals recorded with OASIS on 16 December 2009 at 13:28 p.m. (UT). *Black:* the measured atmospheric spectrum. *Red:* the calculated spectrum. *Blue:* the difference between the measured and calculated spectra. *Lower plot:* pure CO absorption spectrum

In this work, the performance for tropospheric ozone monitoring by OASIS is confirmed by 5 years time series.

3.3.2 Carbon Monoxide

Carbon monoxide is simultaneously measured with ozone due to the wide spectral range covered by the DTGS detector from 700 to 11,000 cm^{-1} .

The absorption of carbon monoxide is too weak to justify a retrieval of a vertical profile. Instead, only the CO total column is determined using the spectral window from 2,134 to 2,174 cm^{-1} (Fig. 8). A single parameter, the scaling factor, is retrieved which scales the whole a priori profile for all altitudes. Since in this spectral range, radiance values are roughly twice higher than in the 10 μm window, a quality filter selects spectra only for signal-to-noise ratio larger than 50. The total uncertainty of CO total columns, including statistical, systematical and smoothing errors, is estimated to 4.5%.

4 Results

In this section, the performances of a mid-resolution ground-based instrument are demonstrated to retrieve separately stratospheric and tropospheric ozone and carbon monoxide total columns through 203 measurement days from 25 February

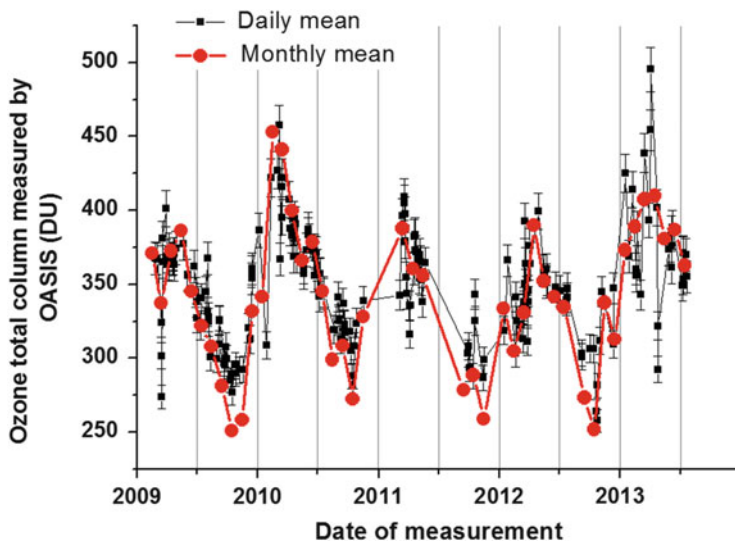


Fig. 9 Daily and monthly means (respectively in *solid square* and *solid circle* symbols) of ozone total columns from OASIS derived from 203 days measurements between 25 February 2009 and 19 July 2013. Error bars of 3% are added for daily means

2009 to 19 July 2013. For each trace species, seasonal variability at mid-latitude was derived. Also comparisons of data from different sources were performed using coincidence criteria based on space and time. More precisely all measurements were referred to a precise location around Creteil: satellite data were selected using a 2° latitude and 2° longitude belt, i.e. between 47.8° and 49.6° N and 1.6° and 3.4° E for GOME-2 and OMI, and between 47.7° and 49.7° N and 1.0° and 4.0° E for IASI for ozone comparisons, and between 47.5° and 49.5° N and 1.5° and 3.5° E for MOPITT for CO comparisons. For the temporal criterion, daily mean total and partial columns were derived from ground-based measurements. A significantly stricter temporal criterion of 1 h would be indeed insufficient for capturing small-scale ozone variations: ozone variability is rather fast and local in urban regions [21], but the number of coincidences with satellite data would decrease too much using this restrictive selection. For this reason, the above-mentioned criteria (spatial and temporal) are typically used for O_3 retrievals at the cost of increased scatter, in agreement with criteria found in the literature [22–25].

4.1 Ozone Total Columns

4.1.1 Seasonal Variability of OASIS Ozone Total Columns

Daily and monthly ozone total columns are given on Fig. 9 derived from the 203 days measurements between 25 February 2009 and 19 July 2013. Note that

the total uncertainty of ozone total columns derived from OASIS measurements, including statistical, systematical and smoothing errors, is estimated to 3%. The existence of a seasonal variability of the total column ozone content is shown with respective maximum values observed in February–March and minimum values observed in October due to the Brewer–Dobson circulation at mid-latitude. This ozone variability is well known [26] and defined as the stratospheric mean meridional circulation due to dynamics in stratosphere coupled with stratosphere–troposphere exchange. The results are also in very good agreement with the climatology from McPeters [17].

4.1.2 Comparison of OASIS Total Ozone Columns with IASI Products

IASI (Infrared Atmospheric Sounding Interferometer, Clerbaux et al. [27, 28]) is a nadir-viewing Fourier-transform spectrometer designed for operation on the meteorological MetOp satellites (ESA/EUMETSAT). The first instrument was launched in orbit aboard the satellite MetOp-A on 19 October 2006 and started operational measurements in June 2007. It measures the thermal infrared radiation emitted by the Earth's surface and the atmosphere. IASI is a Michelson-type Fourier-transform spectrometer, with a spectral resolution of 0.5 cm^{-1} after a Gaussian apodization. The MetOp-A satellite flies in a polar sun-synchronous orbit and covers each geographic region at least twice per day (at 09:30 and 21:30 LT – local time). At the nadir point, the size of one view is $50 \times 50 \text{ km}$. It consists of four individual ground pixels with 12 km diameter each (at the nadir point). The ozone total columns derived from the OASIS instrument are compared with the data obtained from the IASI retrievals which are performed between 980 and $1,073 \text{ cm}^{-1}$, using a physical method regularization (analytical) algorithm [29]. Figure 10 shows the time series of O_3 total columns retrieved by IASI (solid circle symbols) and OASIS (solid square symbols).

Relative differences were calculated as follows:

$$\frac{(\text{X data} - \text{OASIS data})}{\text{OASIS data}} \times 100 \quad (4)$$

The mean relative difference (MRD), for the 173 coincidences, between ozone total columns derived from OASIS and IASI, is $-5.9 (\pm 4.3)\%$ showing a very good agreement between those two sets of data. The correlation coefficient for the regression plot of IASI columns against OASIS measurements (Fig. 11) is 0.92.

4.1.3 Comparison of OASIS Total Ozone Columns with OMI and GOME-2 Observations

In this section, comparisons are performed between OASIS measurements and two satellite observations both derived from the UV spectral region (OMI and

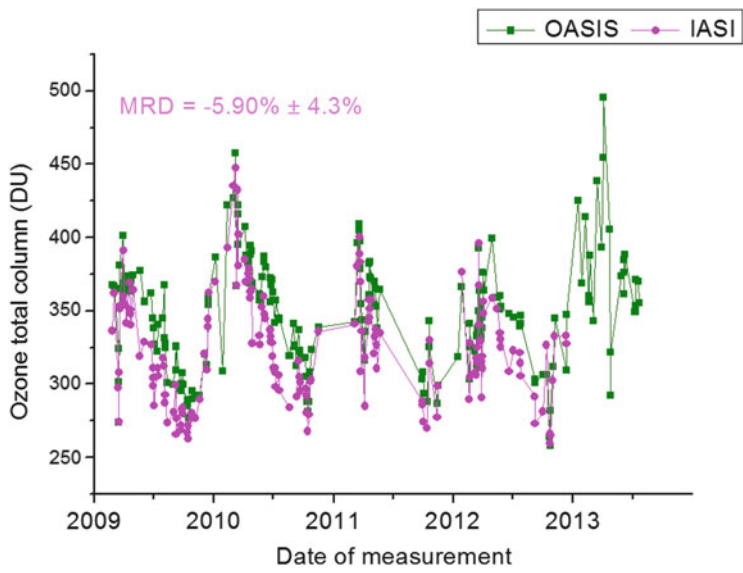


Fig. 10 Time series of O₃ total columns retrieved by IASI (*solid circle symbols*) and OASIS (*solid square symbols*) on 173 days from 25 February 2009 to 12 December 2012

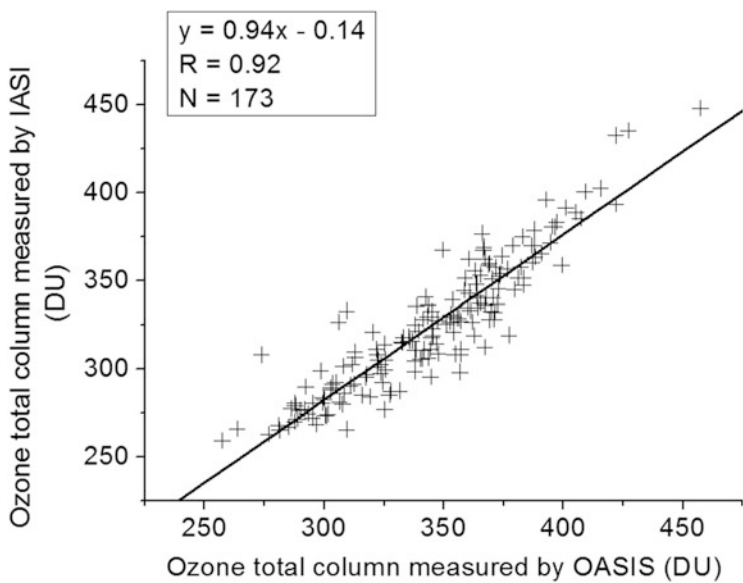


Fig. 11 O₃ total columns derived from IASI measurements as a function of OASIS data

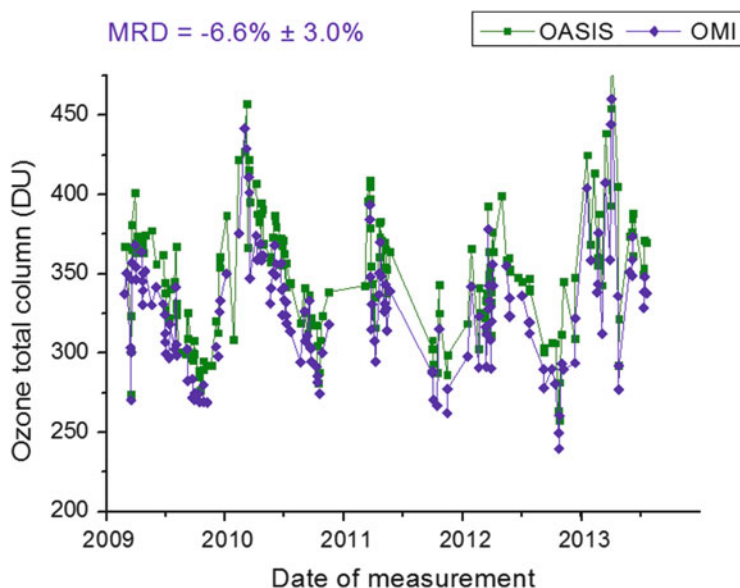


Fig. 12 Time series of O_3 total columns retrieved by OMI (*solid diamond symbols*) and OASIS (*solid square symbols*) on 162 days from 25 February 2009 to 19 July 2013

GOME-2). The Ozone Monitoring Instrument, OMI [30], is one of the four sensors aboard the EOS-Aura satellite (launched in July 2004). It is a nadir-viewing imaging spectrograph that measures the solar radiation backscattered by the Earth's atmosphere and surface between 290 and 340 nm with a spectral resolution of about 0.5 nm. O_3 total column data, measured from ground to approximately 80 km, are retrieved using both the TOMS (Total Ozone Mapping Spectrometer) technique (developed by NASA) [31] and a DOAS (Differential Optical Absorption Spectroscopy) technique developed at KNMI. The OMI O_3 products used in the present study are from the level 3 Aura/OMI data based on the level 2 OMDOA product that uses a DOAS multiwavelength algorithm [32]. The O_3 total column uncertainty from OMI is estimated to 3% [31]. Furthermore, recent validations of OMI O_3 products have been performed [17, 33–35]. In Figure 12, the mean relative difference (MRD), for 162 coincidences, between ozone total columns derived from OASIS (solid square symbols) and OMI (solid diamond symbols), is $-6.6 (\pm 3.0)\%$ showing very good agreement between those two sets of data with correlation coefficient of 0.96 (Fig. 13).

The Global Ozone Monitoring Experiment-2 (GOME-2) aboard MetOp-A is a scanning spectrometer that captures light reflected from the Earth's surface and backscattered by aerosols and the atmosphere. The measured spectra are mainly used to derive ozone total columns and vertical profiles in the same UV region (290–340 nm) than OMI, as well as concentrations of nitrogen dioxide, bromine monoxide, water vapour, sulphur dioxide, and other trace gases and also cloud properties and aerosols. The O_3 columns used here are from the level 3 data of

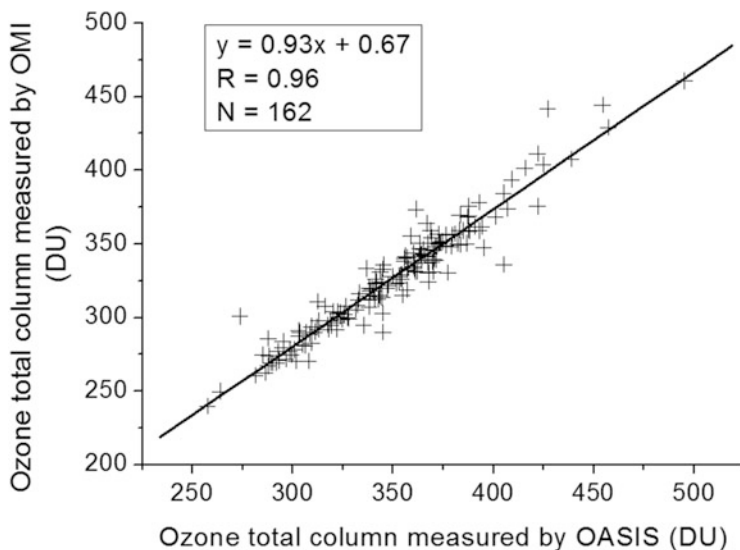


Fig. 13 O₃ total columns derived from OMI observations as a function of OASIS data

GOME-2, i.e. geophysical parameters that have been spatially and/or temporally resampled from level 2 data. The O₃ algorithm retrieval, GOME Data Processor (GPD), version 4.2 has been applied and is based on two methods: the DOAS (Differential Optical Absorption Spectroscopy) method [36] and the iterative AMF/VCD (Air-Mass Factor/Vertical Column Density) computation [37]. Total ozone columns derived from this algorithm have been validated using ground-based networks [38]. Error analysis indicates an accuracy and precision of O₃ total columns of 3.6–4.3% and 2.4–3.3%, respectively [39]. A very good agreement between ozone total columns derived from OASIS (solid square symbols) and GOME-2 (solid triangle symbols) (Fig. 14) was found with a mean relative difference (MRD), for 186 coincidences, of $-7.3 (\pm 3.0)\%$ and correlation coefficient of 0.96 (Fig. 15).

The FTIR measures systematically higher O₃ total columns than the UV instruments (OMI and GOME-2), which may be due to inconsistencies in the spectroscopic parameters also observed in laboratory UV/IR intercomparison experiments [40–42]. But also when compared with IASI observations, OASIS measures higher ozone columns, however, with a lower MRD. One can then suspect that the OASIS O₃ total columns may be slightly high biased.

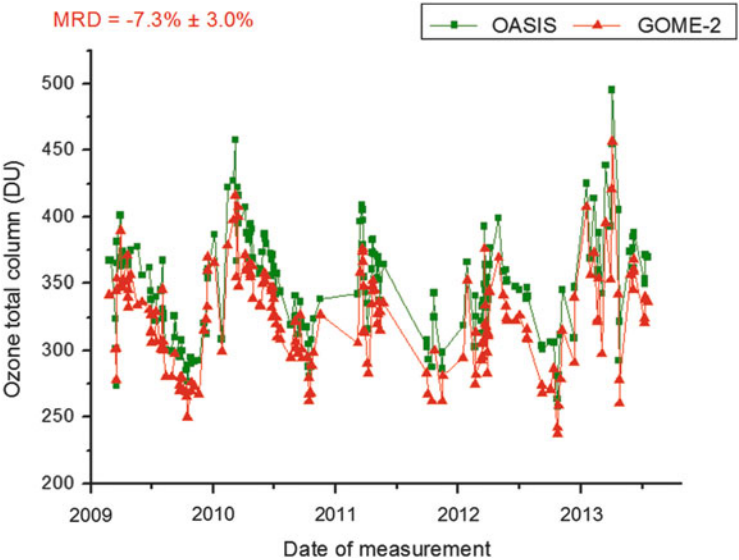


Fig. 14 Time series of O₃ total columns retrieved by GOME-2 (*solid triangle symbols*) and OASIS (*solid square symbols*) on 186 days from 25 February 2009 to 19 July 2013

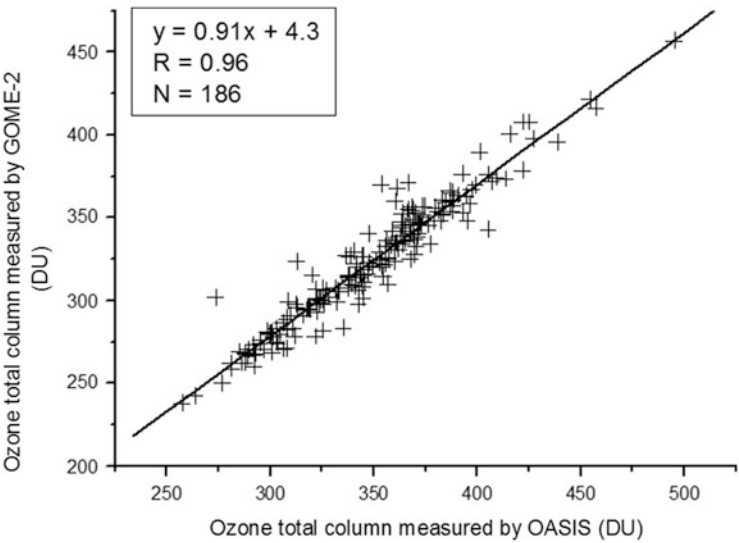


Fig. 15 O₃ total columns derived from GOME-2 observations as a function of OASIS data

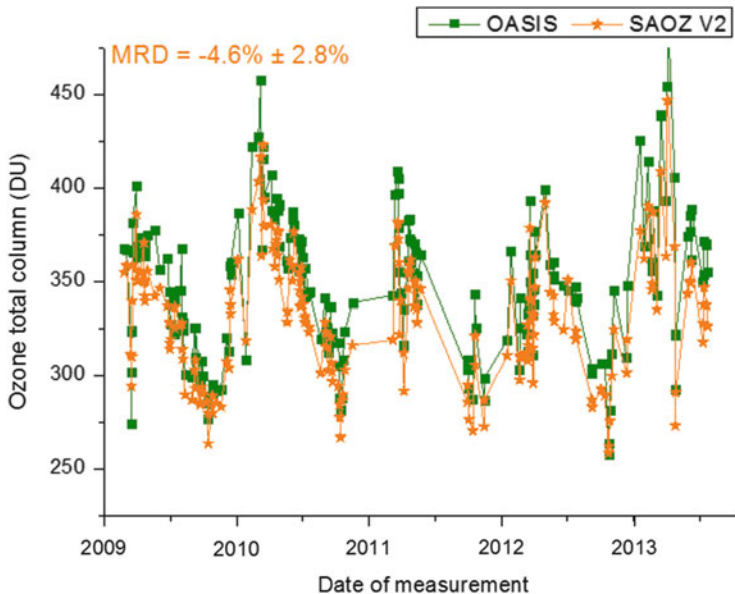


Fig. 16 Time series of O_3 total columns retrieved by SAOZ (solid star symbols) and OASIS (solid square symbols) on 177 days from 25 February 2009 to 22 July 2013

4.1.4 Comparison Between Two Ground-Based Measurements: OASIS and SAOZ

The SAOZ (Système d'Analyse par Observation Zénithale, Pommereau and Goutail [43]) instrument is part of the NDACC international network. It has been developed at Service d'Astronomie in the late 1980s following the discovery of the ozone hole in Antarctica. The SAOZ, which measures the absorption by the atmosphere of scattered sunlight at the zenith in the visible region (450–600 nm in the Chappuis band for ozone) at 1 nm resolution during twilight using the DOAS technique, allows the continuous monitoring of the daily integrated ozone columns. Data were collected from the SAOZ Paris instrument, located at the University of Pierre and Marie Curie in Paris (48.84° N, 2.35° E), using an improved retrieval, called SAOZ version V2 [44] as recommended by the NDACC. The total accuracy in ozone retrievals from SAOZ V2 is estimated to around 5.9%. The mean relative difference (MRD), for 177 coincidences, between ozone total columns derived from OASIS and SAOZ, is $-4.6 (\pm 2.8)\%$ showing a very good agreement between those two sets of ground-based measurements (Fig. 16). The correlation coefficient for the regression plot of SAOZ columns against OASIS ones (Fig. 17) is 0.96.

In order to resume all these results concerning intercomparisons of ozone total columns, Table 1 collects the number of coincidences N , the correlation coefficients of the linear regression R , and the bias between measurements derived from the OASIS observatory and from satellite or local instruments. In addition to very good

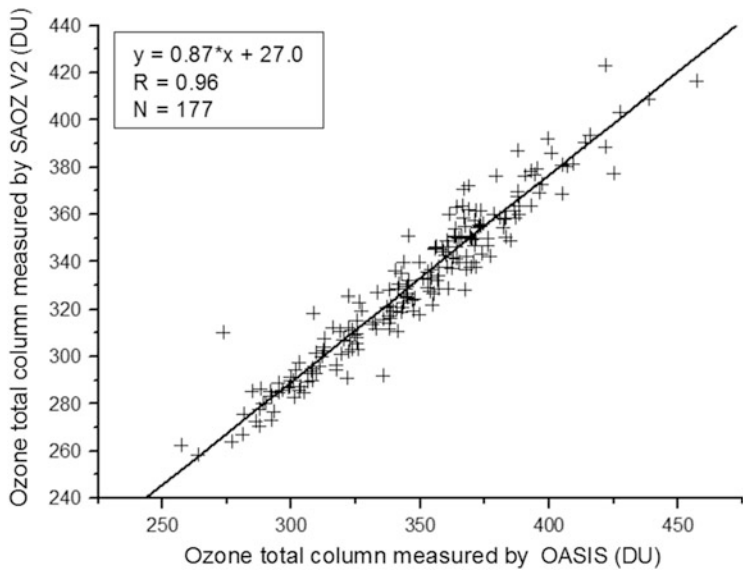


Fig. 17 O₃ total columns derived from SAOZ V2 measurements as a function of OASIS data

Table 1 Summary of the comparison between O₃ total columns derived from OASIS and from various satellites or local data. “N” is the number of daily averaged total ozone columns for the coincidences, “MRD” is the mean relative difference (in %) with the relative rms at 1σ, “R” is the correlation coefficient of the linear regression and the relative slope of the linear regression is given in the last line

	IASI	OMI	GOME-2	SAOZ
N	173	162	186	177
R	0.92	0.96	0.96	0.96
MRD in % (rms 1σ)	−5.9 (±4.3)	−6.6 (±3.0)	−7.3 (±3.0)	−4.6 (±2.8)
Slope	0.94	0.93	0.91	0.87

correlation coefficients between 0.92 and 0.96, these comparisons show the good quality of the OASIS measurements with mean relative difference always consistent with the data precision of all the independent data.

4.2 Tropospheric Ozone Columns

In Sect. 3.3.1, the performance for tropospheric ozone monitoring using the OASIS instrument was discussed. Indeed the DOF reaches 1.03 for the partial column integrated from ground to 8 km. In this paper, using 5 years of OASIS measurements, we are then capable of studying the seasonal variability of tropospheric ozone.

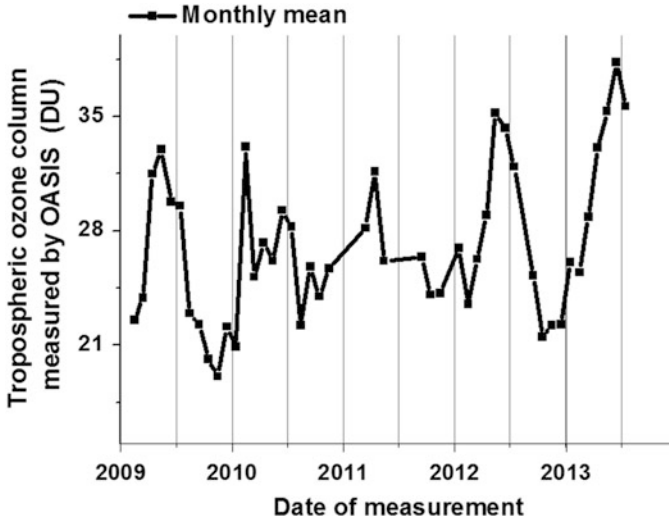


Fig. 18 Monthly means (*solid square symbols*) of the OASIS tropospheric ozone column (integrated from ground to 8 km) derived from 203 days between 25 February 2009 and 19 July 2013

4.2.1 Seasonal Variability of Tropospheric Ozone Columns

Figure 18 shows monthly means of tropospheric ozone measured by the OASIS instrument derived from 203 days between 25 February 2009 and 19 July 2013. In this figure, one can observe a seasonal cycle with a small summer maximum in May/June and a winter minimum in October/November. The summer maximum is well correlated to the maximum of photochemical production of ozone in the lower troposphere. Other part can come from vertical transport from stratosphere as highlighted by the OASIS averaging kernels showing that tropospheric ozone has a small stratospheric contribution. The OASIS variability is in very good agreement with recent results on climatology of pure tropospheric profiles and column contents of ozone and carbon monoxide using the MOZAIC (Measurements of OZone and water vapour by in-service AIrbus airCRAFT programme, Marengo et al. [45]) results in the mid-northern latitudes from 1994 to 2009 [46]. Indeed the monthly averaged pure tropospheric columns of ozone, based on the ascent and descent phase of MOZAIC flights, strictly from the surface to the altitude of the dynamical tropopause exhibit for Paris and Germany a summer maximum with 35.6 DU and a winter minimum with 24.3 DU.

4.2.2 Comparison of OASIS Tropospheric Ozone Columns with IASI Product

The capabilities of IASI to monitor total and tropospheric ozone have been demonstrated previously [9, 25, 29, 47]. Note that IASI has indeed a good sensitivity to lower atmospheric layers under conditions of higher surface temperatures and

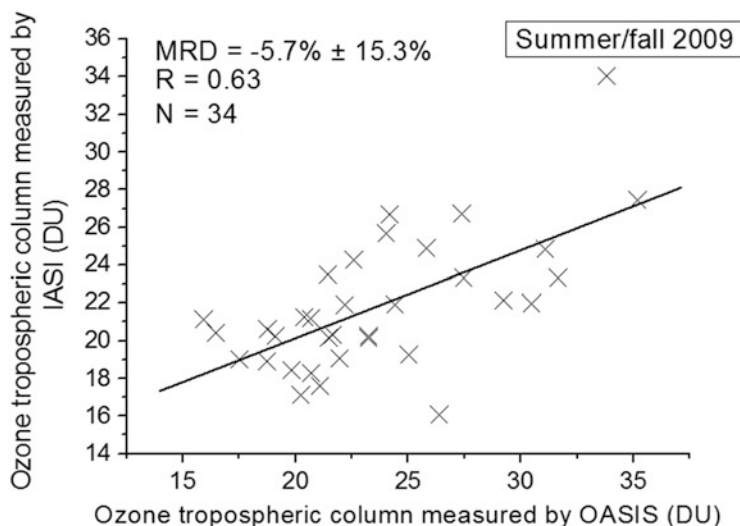


Fig. 19 Tropospheric ozone columns derived from IASI observations as a function of OASIS data for summer/fall 2009

larger thermal contrast conditions [29]. This is why the comparisons in this paper focus on measurements acquired during the summer/fall months in 2009 and 2010. Figures 19 and 20 show rather good correlations between the two sets of data with coefficient of 0.63 for 2009 and 2010 and with mean relative differences of -5.7 (± 15.3)% in 2009 for 34 coincidences, and of 1.3 (± 11.0)% in 2010 for 25 coincidences. Concerning the other years, results are not shown because comparisons with IASI are not statistically representative. It must be acknowledged that IASI and OASIS have different averaging kernels which reflect differing vertical sensitivities, due to different observation geometries, spectral scenes and analysis methods. OASIS retrievals are slightly more sensitive to tropospheric ozone compared to IASI given values of DOF in the troposphere (1.03 compared to 0.92).

4.2.3 Comparison of OASIS Tropospheric Ozone Columns with Surface Ozone Measurements from Airparif

In order to verify the quality of tropospheric ozone columns derived from OASIS, the OASIS time series are compared with surface ozone data delivered by the Airparif in situ network. Indeed, Fig. 6 shows that OASIS ozone retrievals are strongly sensitive to the variability of the lower atmospheric layers. The AirParif network was created in 1979 and approved by the Ministry of Environment to monitor air quality over Paris by analysing major pollutants (such as ozone, SO_2 , CO, NO_x , particles, etc.) in various sites of Ile-de-France. Concerning the comparison with OASIS ozone data, the nearest station in Champigny-sur-Marne, 10 km

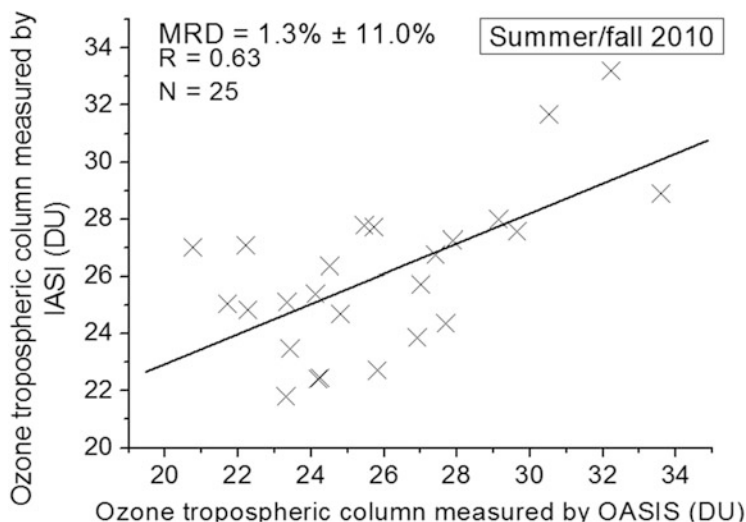


Fig. 20 Tropospheric ozone columns derived from IASI observations as a function of OASIS data for summer/fall 2010

away from the OASIS observatory was selected among the 24 stations monitoring ozone. Time series of daily tropospheric ozone columns derived from OASIS (solid square symbols) and in situ measurements of O_3 provided by Airparif (solid star symbols) for the 198 coincidence days (25 February 2009 to 22 July 2013) are given in Fig. 21.

Although measurements from both sites are not quantitatively comparable, the correlation coefficient calculated for the regression plot of Airparif surface ozone in $\mu g\ m^{-3}$ against OASIS measurements in DU is 0.68 (Fig. 22). This result confirms that a large part of the tropospheric ozone columns derived from OASIS is dominated by photochemical production in the lower troposphere. In addition, twelve sharp maxima are observed by OASIS and Airparif showing that OASIS is also able to monitor high-pollution episodes (arrows, Fig. 21).

Future work plans to compare tropospheric ozone measured by OASIS every 10 min to the tropospheric chemistry–transport model CHIMERE [48] to study diurnal variability. Indeed ground-based FTIR measurements made by OASIS are a cost-effective approach for pollutant diurnal variations monitoring compared to satellite observations with their low time dependence, low vertical resolution, cloud screening, etc.

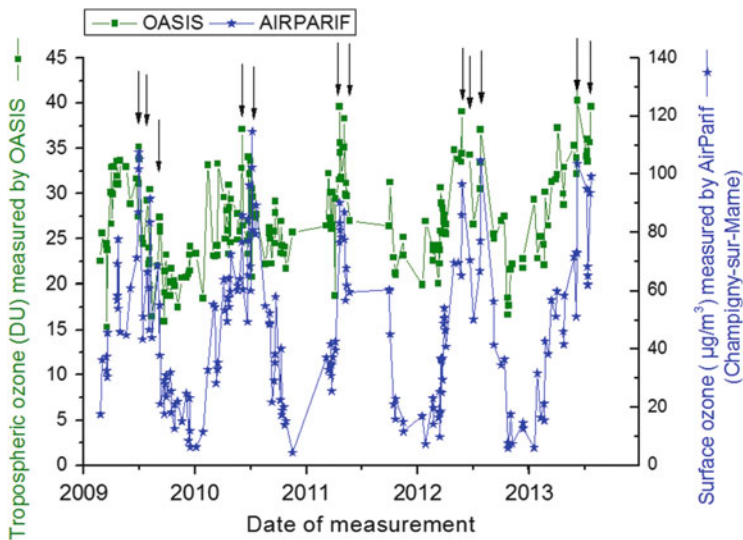


Fig. 21 Time series of tropospheric ozone from OASIS (*solid square symbols*) and ozone surface concentrations from in situ measurements of the Airparif network (*solid star symbols*) on 198 days from 25 February 2009 to 22 July 2013. The Aiparif station location is Champigny-sur-Marne (10 km away from OASIS observatory). *Arrows* represent high pollution episodes measured by OASIS and also observed by Airparif

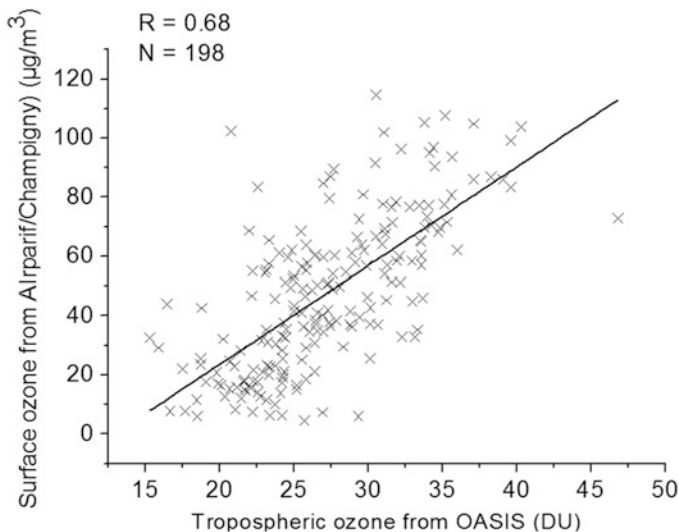


Fig. 22 Surface ozone (µg/m³) derived from Airparif station as a function of OASIS tropospheric ozone column (DU)

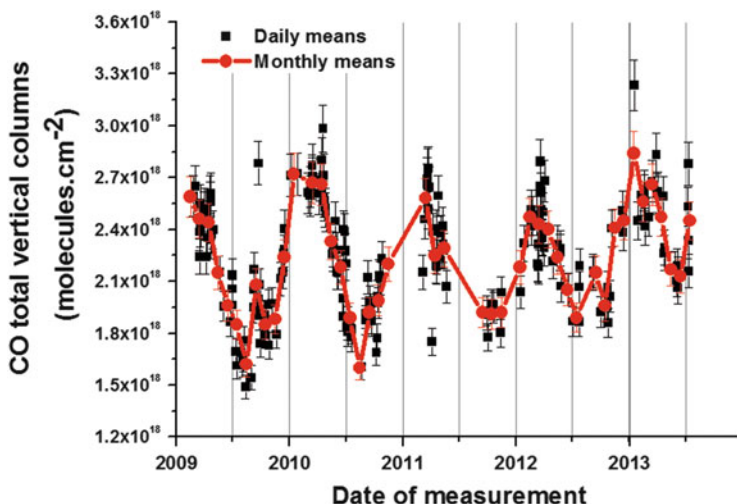


Fig. 23 Daily and monthly means (respectively in *solid square* and *solid circle* symbols) of CO total columns from OASIS derived from 202 days between 25 February 2009 and 12 July 2013. Error bars of 4.5% are added for daily means

4.3 CO Total Columns

In addition to ozone, carbon monoxide (CO) was also retrieved from OASIS measurements. As already mentioned in Sect. 3.3.2, only carbon monoxide total columns were measured by retrieving a scaling factor to scale the whole a priori profile for all altitudes.

4.3.1 Seasonal Variability of CO Total Columns

Figure 23 shows daily and monthly means of CO total columns measured by the OASIS instrument derived from 202 days measurements between 25 February 2009 and 12 July 2013. In this figure, one can observe a seasonal cycle with a winter maximum in February/March and a summer minimum in August/September. This variability and the sharp depletion in May/June also observed by Zbinden et al. [46] for European pure tropospheric CO cycles are evidence of powerful OH cleansing efficiency regulated by NO_x [49]. The very good agreement between OASIS and the Zbinden CO climatology is also seen for the quantitative results with a $1.9\text{--}2.7 \times 10^{18} \text{ mol cm}^{-2}$ cycle. This result confirms for the first time the good quality of CO total columns measured by the OASIS medium-resolution instrument.

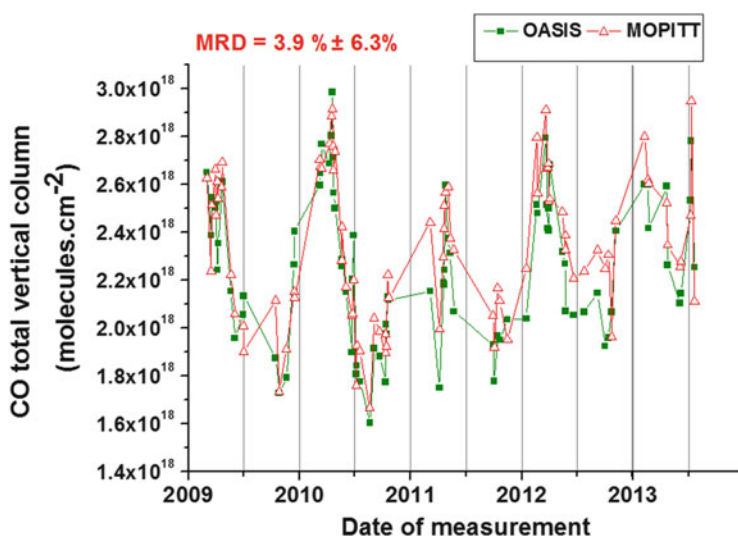


Fig. 24 Time series of CO total columns retrieved by MOPITT (*empty triangle symbols*) and OASIS (*solid square symbols*) on 87 days from 03 March 2009 to 22 July 2013

4.3.2 Comparison of OASIS CO Total Columns with MOPITT Observations

MOPITT (Measurements of Pollution in the Troposphere) is an instrument flying on the NASA's Earth Observing System Terra spacecraft, measuring tropospheric carbon monoxide (CO) on the global scale since 2000. MOPITT measurements enable scientists to analyse the distribution, transport, sources and sinks of CO. MOPITT is a nadir-sounding instrument with a 22 km nadir resolution, 3 km vertical resolution and 640 km swath width which measures upwelling infrared radiation at 4.7 μm and 2.2–2.4 μm . It uses correlation spectroscopy to derive total columns and profiles of carbon monoxide in the lower atmosphere. For the comparison with OASIS, MOPITT data are derived from the inversion code version 3 which has not been yet validated but compared to the Jungfraujoch (Switzerland) station data of the NDACC: error on MOPITT CO total column has been evaluated to about 7.9% [50].

Figure 24 shows time series of daily CO total ozone columns derived from OASIS (solid square symbols) and MOPITT observations (empty triangle symbols) for the 87 coincidence days (03 March 2009 to 22 July 2013). The mean relative difference (MRD), for these 87 coincidences is 3.9 (± 6.3)% showing a very good agreement between the two sets of measurements. The correlation coefficient for the regression plot of MOPITT columns against OASIS measurements is 0.90 (Fig. 25).

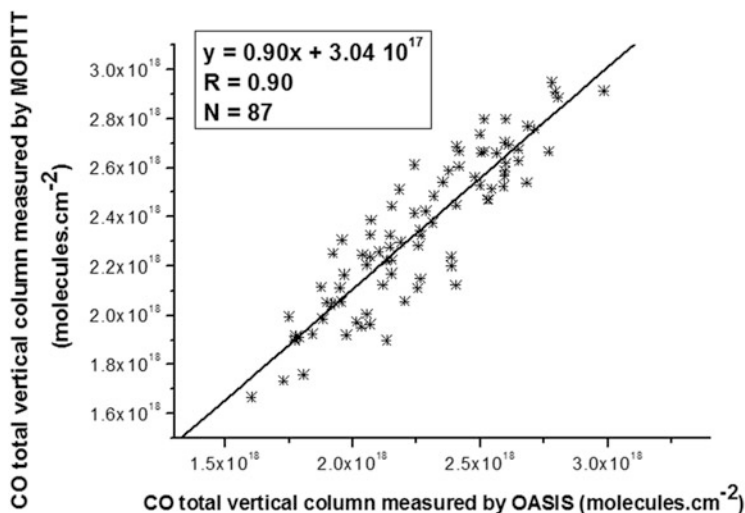


Fig. 25 CO total columns derived from MOPITT observations as a function of OASIS data

5 Conclusions

In this chapter, a new ground-based medium spectral resolution Fourier-transform spectrometer (OASIS) installed in an urban region was presented showing its capabilities of retrieving atmospheric trace gases (particularly ozone and carbon monoxide). A detailed description of the OASIS observatory and its different subsystems has been given. Total columns of ozone and carbon monoxide and also tropospheric ozone columns have been derived from about 200 days of clear-sky OASIS measurements from February 2009 to July 2013 using the PROFFIT retrieval code adapted to the medium spectral resolution of the instrument.

First, ozone total columns over OASIS were compared to satellite and ground-based measurements showing the good quality of the OASIS measurements with mean relative difference always consistent with the data precision and very good correlation coefficients (between 0.92 and 0.96). Furthermore, the performance of OASIS for tropospheric ozone monitoring is demonstrated showing that the retrieved tropospheric amounts (integrated from the ground to 8 km) have a small stratospheric contribution through vertical transport, and vice versa. This latter result is confirmed by the observed seasonal cycle of OASIS tropospheric ozone with a small summer maximum in May/June and a winter minimum in October/November, very well correlated to recent results on climatology of tropospheric ozone profiles using MOZAIC [46]. Moreover, when comparing the OASIS tropospheric ozone with in situ surface data of the Airparif network, a good correlation coefficient of 0.68 indicates that a large part of the tropospheric ozone columns derived from OASIS is dominated by photochemical production in the lower troposphere.

Finally, in addition to ozone, carbon monoxide (CO) total columns were also retrieved from OASIS measurements. The very good agreement between OASIS measurements and a reference CO climatology [46] in the mid-northern latitudes was shown.

Future work has already begun to analyse the diurnal variations of tropospheric ozone and CO and to perform comparisons with atmospheric chemistry–transport models. Also, using the large spectral domain ($700\text{--}11,000\text{ cm}^{-1}$) recorded by the OASIS spectrometer, tests will be performed to assess the capability of OASIS to monitor also greenhouse gases such as CH_4 and CO_2 . In this case, we will use the wide spectral coverage of the OASIS instrument to record the $1.27\text{ }\mu\text{m}$ O_2 band which is necessary to get accurate results (see TCCON (Total Carbon Column Observing Network) [51]). Finally, given the moderate costs and the compactness of a system such as OASIS, deployment of analogous systems nearby large megacities might be envisaged in support of satellite and air quality studies in many regions of the world.

Acknowledgements The authors wish to thank F. Goutail for SAOZV2 data, AirParif for in situ data, the NASA Goddard Space Flight Center for providing the temperature and pressure profiles of the National Centers for Environmental Prediction (NCEP). The ETHER French atmospheric database (<http://ether.ipsl.jussieu.fr>) is acknowledged for providing the IASI data. We are also grateful to the European Centre for Medium-Range Weather Forecasts (ECMWF), the Global Monitoring for Environment and Security (GMES) and the Monitoring of the Atmospheric Composition and Climate (MACC) project for supplying data. Acknowledgements are addressed to the University of Paris-Est Créteil for their technical support during all phases of the OASIS observatory installation.

References

1. Brasseur GP, Solomon S (2005) *Aeronomy of the middle atmosphere*. Springer, Dordrecht
2. Finlayson-Pitts BJ, Pitts JN (1999) *Chemistry of the upper and lower atmosphere: theory, experiments, and applications*. Academic, San Diego
3. West JJ, Szopa S, Hauglustaine DA (2007) Human mortality effects of future concentrations of tropospheric ozone. *C R Geosci* 339:775–783
4. Felzer BS, Cronin T, Reilly JM et al (2007) Impacts of ozone on trees and drops. *C R Geosci* 339:784–798
5. de Forster PM, Shine KP (1997) Radiative forcing and temperature trends from stratospheric ozone changes. *J Geophys Res* 102:10841–10855
6. Aghedo AM, Bowman KW, Worden HM et al (2011) The vertical distribution of ozone instantaneous radiative forcing from satellite and chemistry climate models. *J Geophys Res*. doi:[10.1029/2010JD014243](https://doi.org/10.1029/2010JD014243)
7. Riese M, Ploeger F, Rap A et al (2012) Impact of uncertainties in atmospheric mixing on simulated UTLS composition and related radiative effects. *J Geophys Res*. doi:[10.1029/2012JD017751](https://doi.org/10.1029/2012JD017751)
8. Seinfeld JH, Pandis SN (2006) *Atmospheric chemistry and physics: from air pollution to climate change*, 2nd edn. Wiley, New York

9. Viatte C, Gaubert B, Eremenko M et al (2011) Tropospheric and total ozone columns over Paris (France) measured using medium-resolution ground-based solar-absorption Fourier-transform infrared spectroscopy. *Atmos Measure Tech* 4:2323–2331
10. Hase F (2012) Improved instrumental line shape monitoring for the ground-based, high-resolution FTIR spectrometers of the network for the detection of atmospheric composition change. *Atmos Measure Tech* 5:603–610
11. Hase F, Blumenstock T, Paton-Walsh C (1999) Analysis of the instrumental line shape of high-resolution fourier transform IR spectrometers with gas cell measurements and new retrieval software. *Appl Optics* 38:3417–3422
12. Hase F, Hannigan JW, Coffey MT et al (2004) Intercomparison of retrieval codes used for the analysis of high-resolution, ground-based FTIR measurements. *J Quant Spectrosc Rad Trans* 87:25–52
13. Flaud JM, Orphal J (2011) Spectroscopy of the earth's atmosphere. In: Quack M (ed) *Handbook of high-resolution spectroscopy*. Wiley, London, p 1971
14. Rothman LS, Jacquemart D, Barbe A et al (2005) The HITRAN 2004 molecular spectroscopic database. *J Quant Spectrosc Rad Trans* 96:139–204
15. Rodgers CD (2000) *Inverse methods for atmospheric sounding: theory and practice*. World Sci, Hackensack, NJ
16. Tikhonov AN (1963) Solution of incorrectly formulated problems and the regularization method. *Soviet Math Dokl* 4:1035–1038 English translation of. *Dokl Akad Nauk SSSR* 151:501–504
17. McPeters RD, Kroon M, Labow G et al (2008) Validation of the aura ozone monitoring instrument total column ozone product. *J Geophys Res*. doi:[10.1029/2007JD008802](https://doi.org/10.1029/2007JD008802)
18. Remedios JJ, Leigh RJ, Waterfall AM et al (2007) MIPAS reference atmospheres and comparisons to V4.61/V4.62 MIPAS level 2 geophysical data sets. *Atmos Chem Phys Discuss* 7:9973–10017
19. Schneider M, Hase F, Blumenstock T et al (2008) Quality assessment of O₃ profiles measured by a state-of-the-art ground-based FTIR observing system. *Atmos Chem Phys* 8:5579–5588
20. Vigouroux C, De Mazière M, Demoulin P et al (2008) Evaluation of tropospheric and stratospheric ozone trends over Western Europe from ground-based FTIR network observations. *Atmos Chem Phys* 8:6865–6886
21. Antón M, López M, Serrano A et al (2010) Diurnal variability of total ozone column over Madrid (Spain). *Atmos Environ* 44:2793–2798
22. Cortesi U, Lambert JC, De Clercq C et al (2007) Geophysical validation of MIPAS-ENVISAT ozone data. *Atmos Chem Phys* 7:1–61
23. Dupuy E, Walker KA, Kar J et al (2009) Validation of ozone measurements from the atmospheric chemistry experiment (ACE). *Atmos Chem Phys* 9:287–343
24. Nassar R, Logan JA, Worden HM et al (2008) Validation of tropospheric emission spectrometer (TES) nadir ozone profiles using ozone sonde measurements. *J Geophys Res*. doi:[10.1029/2007JD008819](https://doi.org/10.1029/2007JD008819)
25. Keim C, Eremenko M, Orphal J et al (2009) Tropospheric ozone from IASI: comparison of different inversion algorithms and validation with ozone sondes in the northern middle latitudes. *Atmos Chem Phys* 9:11441–11479
26. Dobson GMB, Harrison DN, Lawrence J (1929) Measurements of the amount of ozone in the earth's atmosphere and its relation to other geophysical conditions. Part III *Proc R Soc Lond A* 122:456–486
27. Clerbaux C, Hadji-Lazaro J, Turquety S et al (2007) The IASI/MetOp mission: first observations and highlights of its potential contribution to GMES. *Space Res Today (COSPAR Inf Bul)* 168:19–24
28. Clerbaux C, Boynard A, Clarisse L et al (2009) Monitoring of atmospheric composition using the thermal infrared IASI/MetOp sounder. *Atmos Chem Phys* 9:6041–6054

29. Eremenko M, Dufour G, Foret G et al (2008) Tropospheric ozone distributions over Europe during the heat wave in July 2007 observed from infrared nadir spectra recorded by IASI. *Geophys Res Lett*. doi:[10.1029/2008GL034803](https://doi.org/10.1029/2008GL034803)
30. Levelt PF (2002) OMI algorithm theoretical basis document, vol. I, OMI instrument, Level0–1b processor, calibration and operations. <http://eospsso.gsfc.nasa.gov/eoshompage/forscientists/atbd/docs/OMI/ATBD-OMI-01.pdf>. Accessed 11 Mar 2011
31. Bhartia PK, Wellemeyer CW (2002) OMI TOMS-V8 total O₃ algorithm, algorithm theoretical baseline document: OMI ozone products, vol. II, ATBD-OMI-02, version 2.0. <http://eospsso.gsfc.nasa.gov/eoshompage/forscientists/atbd/docs/OMI/ATBD-OMI-02.pdf>. Accessed 11 Mar 2011
32. Veefkind JP, de Haan JF, Brinksma EJ et al (2006) Total ozone from the ozone monitoring instrument (OMI) using the DOAS technique. *IEEE T Geosci Remote* 44:1239–1244
33. Balis D, Kroon M, Koukouli ME et al (2007) Validation of ozone monitoring instrument total ozone column measurements using brewer and Dobson spectrophotometer ground-based observations. *J Geophys Res*. doi:[10.1029/2007JD008796](https://doi.org/10.1029/2007JD008796)
34. Liu X, Bhartia PK, Chance K et al (2010) Validation of ozone monitoring instrument (OMI) ozone profiles and stratospheric ozone columns with microwave limb sounder (MLS) measurements. *Atmos Chem Phys* 10:2539–2549
35. Kroon M, Petropavlovskikh I, Shetter R et al (2008) OMI total ozone column validation with Aura-AVE CAFS observations. *J Geophys Res*. doi:[10.1029/2007JD008795](https://doi.org/10.1029/2007JD008795)
36. Platt U (1994) Differential optical absorption spectroscopy (DOAS) in: air monitoring by spectroscopic techniques. Wiley, New York, p 8427
37. Van Roozendael M, Loyola D, Spurr RJD et al (2006) Reprocessing the 10-year GOME/ERS-2 total ozone record for trend analysis: the new GOME data processor version 4.0, algorithm description. *J Geophys Res*. doi:[10.1029/2005JD006375](https://doi.org/10.1029/2005JD006375)
38. Balis D, Lambert JC, Van Roozendael M et al (2007) Ten years of GOME/ERS2 total ozone data the new GOME data processor (GDP) version 4.2: ground-based validation and comparisons with TOMS V7/V8. *J Geophys Res*. doi:[10.1029/2005JD006376](https://doi.org/10.1029/2005JD006376)
39. Van Roozendael M, Lambert JC, Spurr RJD et al (2004) GOME direct fitting (GODFIT) GDOAS delta validation report. ERS Exploitation AO/1-4235/02/I-LG, Oberpfaffenhofen, Germany
40. Viatte C, Schneider M, Redondas A et al (2011) Comparison of ground-based FTIR and Brewer O₃ total column with data from two different IASI algorithms and from OMI and GOME-2 satellite instruments. *Atmos Measure Tech* 4:535–546
41. Gratien A, Picquet-Varrault B, Orphal J (2010) New laboratory intercomparison of the ozone absorption coefficients in the mid-infrared (10 μ m) and ultraviolet (300–350 nm) spectral regions. *J Phys Chem A* 14:10045–10048
42. Picquet-Varrault B, Orphal J, Doussin JF et al (2005) Laboratory intercomparison of the ozone absorption coefficients in the mid-infrared (10 μ m) and ultraviolet (300–350 nm) spectral regions. *J Phys Chem A* 109:1008–1014
43. Pommereau JP, Goutail F (1988) O₃ and NO₂ ground-based measurements by visible spectrometry during arctic winter and spring 1988. *Geophys Res Lett* 15:891–894
44. Hendrick F, Pommereau JP, Goutail F et al (2011) NDACC/SAOZ UV-visible total ozone measurements: improved retrieval and comparison with correlative ground-based and satellite observations. *Atmos Chem Phys* 11:5975–5995
45. Marenco A, Thouret V, Nédélec P et al (1988) Measurement of ozone and water vapor by Airbus in-service aircraft: the MOZAIC airborne program, an overview. *J Geophys Res* 103:631–642
46. Zbinden RM, Thouret V, Ricaud P et al (2013) Climatology of pure tropospheric profiles and column contents of ozone and carbon monoxide using MOZAIC in the mid-northern latitudes (24° N to 50° N) from 1994 to 2009. *Atmos Chem Phys Discuss* 13:14695–14747

47. Dufour G, Eremenko M, Orphal J et al (2010) IASI observations of seasonal and day-to-day variations of tropospheric ozone over three highly populated areas of China: Beijing, Shanghai, and Hong Kong. *Atmos Chem Phys* 10:3787–3801
48. Schmidt H, Derognat C, Vautard R et al (2001) A comparison of simulated and observed ozone mixing ratios for the summer of 1998 in western Europe. *Atmos Environ* 35:6277–6297
49. Lamsal LN, Martin RV, Padmanabhan A et al (2011) Application of satellite observations for timely updates to global anthropogenic NO_x emission inventories. *Geophys Res Lett*. doi:[10.1029/2010GL046476](https://doi.org/10.1029/2010GL046476)
50. Barret B, De Mazière M, Mahieu E (2003) Ground-based FTIR measurements of CO from the Jungfraujoch: characterisation and comparison with in situ surface and MOPITT data. *Atmos Chem Phys* 3:2217–2223
51. Wunch D, Toon GC, Blavier JFL et al (2011) The total carbon column observing network. *Phil Trans Roy Soc A* 369:2087–2112

Environment, Energy and Climate Change I

Environmental Chemistry of Pollutants and Wastes

Jiménez, E.; Cabañas, B.; Lefebvre, G. (Eds.)

2015, XIV, 432 p. 50 illus., 44 illus. in color., Hardcover

ISBN: 978-3-319-12906-8