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Ground-based validation of EOS-Aura OMI NO₂ vertical column data in the midlatitude mountain ranges of Tien Shan (Kyrgyzstan) and Alps (France)

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[1] Ground-based UV-visible instruments for NO₂ vertical column measurements have been operating at Issyk-Kul station, in Kyrgyzstan, and Observatoire de Haute-Provence (OHP), in France, since 1983 and 1992, respectively. These measurements have already been used for validation of ERS-2 Global Ozone Monitoring Experiment (GOME) and Envisat Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) NO₂ column data. Building upon the successful missions of GOME and SCIAMACHY, the Ozone Monitoring Experiment (OMI) was launched by NASA onboard the EOS Aura satellite in July 2004. Here we present the results of recent comparisons between OMI NO₂ operational data (standard product) and correlative ground-based twilight measurements in midlatitudes, at Issyk-Kul and OHP, in 2004–2006. The stratospheric NO₂ columns, observed by OMI and our ground-based instruments, have been corrected for NO₂ diurnal change and normalized to local noon values using a photochemical box model. According to our comparison, OMI stratospheric NO₂ columns underestimate ground-based measurements by $(0.3 \pm 0.3) \times 10^{15}$ molecules/cm² and $(0.7 \pm 0.6) \times 10^{15}$ molecules/cm² at Issyk-Kul and OHP, respectively. The effect of tropospheric pollution on the NO₂ measurements in both regions of observations has been identified and discussed.

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1. Introduction

[2] Nitrogen dioxide (NO₂) plays an important role in atmospheric chemistry, both in the stratosphere and in the troposphere. It is one of the key species in the chemistry of ozone, and its tropospheric content is an indicator of poor air quality. Therefore, along with ozone, the global monitoring of NO₂ is a key objective of NASA's Ozone Monitoring Experiment (OMI). In this regard, OMI succeeds two other space experiments: ESA's GOME and SCIAMACHY. GOME (Global Ozone Monitoring Experiment) was launched in April 1995 onboard the ERS-2, into a sun-synchronous polar orbit [Burrows *et al.*, 1999a]. It is a nadir-viewing UV-visible spectrometer that measures the solar irradiance and the solar radiation backscattered from both the atmosphere and the Earth's surface. Besides providing global maps of atmospheric ozone, GOME was

also the first spaceborne instrument capable of measuring the total column amount of NO₂. The trace gas column densities given in the GOME data products (ozone and NO₂), are derived by the Differential Optical Absorption Spectroscopy (DOAS) technique [Platt, 1994]. GOME was followed by the Scanning Imaging Spectrometer for Atmospheric Cartography (SCIAMACHY) onboard Envisat in 2002, which could also measure NO₂ vertical columns [Bovensmann *et al.*, 1999].

[3] Like the GOME and SCIAMACHY satellite instruments, OMI is a nadir viewing, wide swath UV-visible imaging spectrometer. It was launched on 15 July 2004, onboard NASA's EOS Aura platform, into sun-synchronous near polar orbit [Levelt *et al.*, 2006]. According to numerous validation studies, the overall accuracy of operational GOME and SCIAMACHY NO₂ vertical column data is estimated to fall within $\sim 0.3 \times 10^{15}$ molecules/cm² in the areas of low tropospheric NO₂ [Lambert and Balis, 2004; Piters *et al.*, 2006]. The scientific requirements for the OMI data products call for an accuracy of $\sim 0.2 \times 10^{15}$ molecules/cm², for the same conditions [Brinkma *et al.*, 2003]. The present study contributes to the geophysical validation of operational NO₂ vertical column measurements from Aura OMI (standard product) using collocated ground-based observations at two stations: Issyk-Kul in the central

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Asia and OHP in Europe. Section 2 describes the ground-based UV-visible instruments. Section 3 gives a brief description of the OMI satellite instrument and its operational algorithm to retrieve NO₂ vertical columns. Section 4 presents correlative ground-based and satellite data sets and explains the comparison methodology, going back to the recent validation of GOME NO₂ vertical column data over Issyk-Kul and OHP. Section 5 shows the results and analysis of the comparison with OMI. Finally, the conclusions of our study are given in section 6 and possible future work is discussed.

2. Ground-Based UV-Visible Measurements of NO₂ Vertical Columns

2.1. Issyk-Kul Station

[4] Measurements of NO₂ vertical columns were begun at Issyk-Kul station in 1983 [Aref'ev et al., 1995]. The station is located on the northern coast of Issyk-Kul lake in the Tien Shan mountains, Kyrgyzstan (42.6°N/77.0°E, 1650 m above sea level). The instrument design and retrieval technique is similar to the zenith sky-viewing setup operating at Zvenigorod station in the region of Moscow (Russia), and described in detail in [Elokhov and Gruzdev, 1993]. The system uses a Russian manufactured scanning monochromator MDR-23 (LOMO) with 1200 groove/mm grating, providing a spectral sampling of ~0.01 nm. Thus, the measurements are carried out by means of a grating spectrometer operating in ~435–453 nm range with a spectral resolution of ~1.0 nm. The Issyk-Kul instrument was certified by the Network for the Detection of Atmospheric Composition Change (NDACC) (formerly the Network for the Detection of Stratospheric Change, NDSC) as a complementary station, following the results of intercomparison carried out at Zvenigorod, Russia, in 1997 (more information available at <http://www.ndsc.ncep.noaa.gov/data/madir>).

2.2. Haute-Provence Observatory

[5] Measurements of NO₂ vertical columns were begun at OHP in 1992, when the French Système d'Analyse par Observation Zénithale (SAOZ) UV-visible zenith sky spectrometer was installed. The station is situated in the southeast of France, on a plateau in the Alps (43.9° N/5.7° E, 650 m above sea level). The SAOZ spectrometer was developed in 1988 at Service d'Aéronomie/CNRS [Pommereau and Goutail, 1988] and allows measurements of total column ozone and NO₂ from the ground by UV-visible spectrometry of the zenith sky at twilight. Twenty SAOZ instruments have been installed around the globe, creating the SAOZ network, with 10 of them being run by CNRS. This network has been established within international collaborations following the recommendations for long-term monitoring and data quality requirements of NDACC. SAOZ records zenith sky spectra using a wide spectral range (300–620 nm) in the UV-visible, with a spectral resolution of about ~1.0 nm. The instrument is composed of a flat field spectrometer with a concave holographic grating and a 1024 pixel photodiode array. The SAOZ instrument has been qualified for ozone and NO₂ measurements in the NDACC framework during several international intercomparison campaigns [Vaughan et al., 1997; Roscoe et al., 1999; Vandaele et al., 2005].

2.3. NO₂ Vertical Column Retrieval

[6] The NO₂ column amounts at Issyk-Kul and OHP are retrieved using the DOAS technique applied to zenith sky measurements in the 435–453 nm (Issyk-Kul) or 410–530 nm (OHP) spectral range. The measurements are averaged over the solar zenith angle (SZA) range of 85–92° (Issyk-Kul) or 86–91° (OHP), to provide an accurate estimate of NO₂ vertical column at sunrise and sunset. The spectral analysis takes the ratio of the observed spectrum to a reference spectrum, measured at noon under clear sky conditions, and assumed to be less perturbed by molecular absorption. The logarithm of the ratio of twilight to noon spectra is analyzed using a least squares fit to laboratory absorption spectra of ozone and NO₂, along with molecular scattering, aerosol extinction and the Ring effect (inelastic scattering). The resulting NO₂ line-of-sight amounts (or slant columns), corrected for residual absorption in the reference spectra, are then converted to corresponding vertical columns with an air mass factor (AMF) calculated using a radiative transfer model (RTM) for each constituent at each SZA. Both ground-based instruments, Issyk-Kul and OHP, use similar NO₂ absorption cross sections in the DOAS analysis [Vandaele et al., 1998]. A single solar reference spectrum is used for the spectral retrieval of the entire data set at each location. The residual amount of NO₂ present in the reference spectrum was determined by the Langley method, and found to be 4.65×10^{15} molecules/cm² and 5.25×10^{15} molecules/cm² at Issyk-Kul and OHP, respectively. The AMFs used to convert from the NO₂ slant column to vertical, are different for the retrieval of measurements at Issyk-Kul and OHP. At Issyk-Kul, the seasonal midlatitude AMFs are used on the basis of Air Force Geophysics Laboratory standard atmosphere and calculated using a ray-tracing model for 440 nm, considering multiple scattering in spherical atmosphere. The resulting AMF values at 90° SZA are 18.76, 17.96, 18.17, and 18.19 in March, July, September, and December, respectively (M. Van Roozendaal, personal communication, 2003). The SAOZ at OHP uses a midlatitude AMF, calculated by the RTM for 470 nm from the average summer composite evening profiles, measured by the POAM satellite and SAOZ balloon sondes [Sarkissian et al., 1995a]. The resulting AMF value at 90° SZA is 15.65. Generally, the zenith sky UV-visible observations allow measurements even in cloudy conditions, because the stratospheric light path at twilight is large compared to the tropospheric one (roughly 20 times), and multiple scattering in the clouds affects measurements only slightly [Sarkissian et al., 1995b]. However, the studies of NO₂ AMF sensitivity to the tropospheric clouds demonstrate an increase of ~5% at 90° SZA, relative to clear sky RTM calculations [Pfeilsticker et al., 1998; Bassford et al., 2001].

[7] According to conclusions from NDACC intercomparison campaigns [Vaughan et al., 1997; Roscoe et al., 1999; Vandaele et al., 2005], the agreement between NDACC-certified instrument measurements of NO₂ slant column amounts falls within the 5% to 10% range, when common spectral ranges and analysis parameters are imposed. However, the accuracy of NO₂ vertical column retrievals is limited by several uncertainties [Van Roozendaal et al., 1994], which contribute to the full error as follows: measurement random error (~4%), the error associated with

NO₂ absorption cross section and its temperature dependence (~15%), the error, associated with the determination of residual amount of NO₂ in the reference spectrum (~10%), and the uncertainty on the AMF calculation (~10%). The total error budget of the ground-based visible NO₂ measurements is a precision of ~11% and an accuracy of ~21%. Assuming the average NO₂ vertical column at midlatitudes is $\sim 3 \times 10^{15}$ molecules/cm², this estimate corresponds to $\sim 0.6 \times 10^{15}$ molecules/cm² absolute accuracy.

3. Satellite Aura OMI Data on Total NO₂

[8] OMI combines the advantages of its predecessors (GOME and SCIAMACHY), by measuring the complete spectrum in the UV-visible wavelength range (270–500 nm) with a very high spatial resolution (13×24 km²). It achieves daily global coverage with a 2600 km wide swath. OMI uses 2-D detectors for simultaneous spatial and spectral registration (0.4–0.6 nm spectral resolution). The DOAS technique is applied in the visible to derive the NO₂ vertical column density (VCD).

[9] The operational OMI algorithm improves the accuracy of the NO₂ VCD retrieval (compared to GOME and SCIAMACHY) by discriminating between two components of the column density: an unpolluted component, which includes stratospheric and free tropospheric NO₂, and a polluted component, containing boundary layer NO₂ [Boersma *et al.*, 2002; Bucselá *et al.*, 2006]. The unpolluted component is identified through spatial filtering of the geographic NO₂ field. Small-scale geographical variation of NO₂ is taken to indicate tropospheric NO₂ pollution. In that case, a more appropriate AMF is used to compute more accurate column NO₂ and tropospheric NO₂ concentrations. The AMF is calculated using specific assumed NO₂ profiles for unpolluted (stratospheric and small amount of upper tropospheric) and polluted (lower tropospheric) columns. The amount of tropospheric NO₂ is calculated from these column amounts and the assumed profile shapes.

[10] The DOAS fitting algorithm is applied in the spectral range 405–465 nm to the logarithmic ratio of the measured earthshine radiance spectrum to a solar irradiance spectrum. A much wider fit window (compared to 425–450 nm window, used by GOME and SCIAMACHY) compensates for OMI's lower signal-to-noise ratio in this wavelength region [Boersma *et al.*, 2002]. The functions fitted to the spectral ratio are trace gas cross sections of NO₂ [Vandaele *et al.*, 1998] and O₃ [Burrows *et al.*, 1999b], a reference Ring spectrum [Chance and Spurr, 1997] and the coefficients of a polynomial function to model the spectrally slowly varying components of scattering by clouds and aerosols and reflection by the Earth's surface. The nominal fitting temperature of NO₂ absorption cross section is 220 K [Boersma *et al.*, 2002]. Resulting NO₂ slant column densities (SCD) are then converted to VCDs by means of the AMF, which depends upon a number of parameters including viewing geometry, surface albedo and the shape of the NO₂ vertical profile. For each location, the algorithm uses a single mean unpolluted profile derived from a stratospheric model and a geographically gridded set of annual mean polluted profiles obtained from a tropospheric model. An initial estimate of the NO₂ VCD is obtained by dividing the SCD by an unpolluted AMF, which is then geographically

gridded using the data acquired within ± 12 h from the target orbit. Areas shown by the model to contain climatologically high tropospheric NO₂ amounts are then masked, and the remaining regions are smoothed in latitude bands to construct a global stratospheric field. The smoothing algorithm employs a boxcar smoothing over a 10° latitude band, followed by a zonal planetary wave smoothing. Where the initial VCD exceeds the estimated stratospheric NO₂, the presence of tropospheric NO₂ is inferred, and the VCD is recalculated using an AMF computed from an assumed tropospheric NO₂ profile [Bucselá *et al.*, 2006].

[11] The accuracy of the OMI algorithm for NO₂ vertical columns splits into errors of the slant column retrieval and of the AMF calculation [Boersma *et al.*, 2002]. The slant column errors come from the uncertainty of the NO₂ absorption cross sections and their temperature dependence, spectral calibration and stability, and measurement noise. AMF errors arise from incorrect day-to-day assumptions regarding the NO₂ profile shape, surface albedo, cloud parameters, and aerosol effects. The estimated accuracy of the OMI NO₂ vertical column under clear sky conditions is ~5% ($\sim 0.2 \times 10^{15}$ molecules/cm²) and ~20% ($\sim 0.8 \times 10^{15}$ molecules/cm²) in unpolluted and polluted cases, respectively. In the presence of pollution and clouds, the NO₂ vertical column error can be as large as 50%. The relative errors in the tropospheric NO₂ column estimate are ~30% and ~60% under clear and cloudy conditions, respectively [Boersma *et al.*, 2002].

4. Ground-Based Validation of Satellite NO₂ Data: Comparison Methodology

[12] Satellite total NO₂ vertical columns have been previously compared to ground-based UV-visible measurements at Zvenigorod (Moscow region) and St. Petersburg in Russia. The latter measurements are similar to those carried out at Issyk-Kul station. Correlative data of GOME and SCIAMACHY operational NO₂ products were analyzed. However, these observations were found to be affected by high tropospheric pollution in the region of Moscow [Timofeev *et al.*, 2000] and St. Petersburg [Poberovsky *et al.*, 2007]. The Issyk-Kul station is located in a remote plateau of the Tien Shan mountains in northeast Kyrgyzstan, which is presumed to be a pollution-free area. Operational GOME measurements of NO₂ VCDs (GOME Data Processor 3 (GDP 3)) have been compared with collocated ground-based observations at Issyk-Kul for the period of 1996–2002 [Ionov *et al.*, 2006a]. According to that study, the GOME data are reasonably close to the corresponding ground-based sunrise observations, within $\pm 0.7 \times 10^{15}$ molecules/cm², while the agreement with ground-based sunset measurements is not as close, about $\pm 2.2 \times 10^{15}$ molecules/cm² (RMS). Some seasonal variation in the absolute difference between GOME and ground-based measurements is present. A number of effects have been proposed to explain and remove that discrepancy, including the use of similar molecular absorption cross sections and seasonal NO₂ AMFs in the processing of Issyk-Kul ground-based data. Also, simulated NO_x photochemistry has been used to adjust sunrise ground-based measurements to the time of GOME overpass, near noon. The GOME data were still found to overestimate twilight

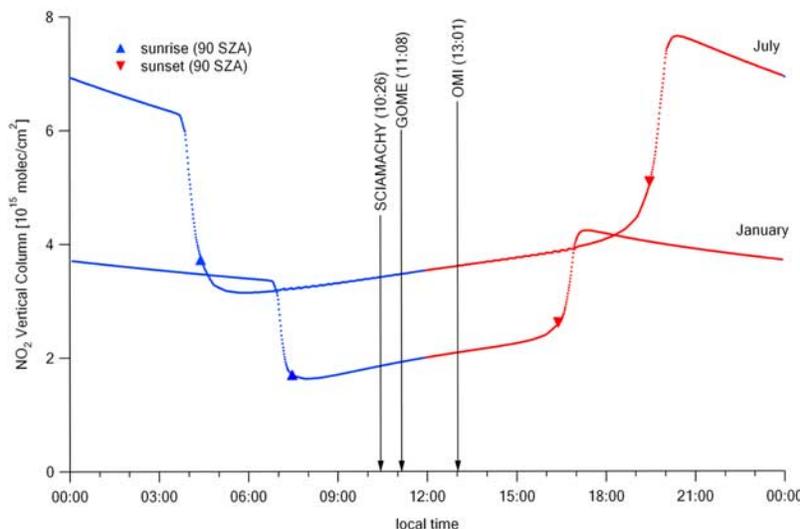


Figure 1. Diurnal cycle of NO₂ vertical column at Issyk-Kul, simulated for January and July. The time of 90° SZA (sunrise and sunset) is shown by markers. The average time of satellite overpass for ERS-2 GOME, Envisat SCIAMACHY, and Aura OMI over Issyk-Kul is indicated by arrows.

ground-based measurements at Issyk-Kul, adjusted to noon, by $(0.6 \pm 0.5) \times 10^{15}$ molecules/cm². This may be an indication of some additional source of disagreement, e.g., incorrect treatment of tropospheric NO₂ content in the region of ground-based measurements. Nonetheless, these results are consistent with other GOME validation efforts by NDACC and SAOZ ground-based networks [Lambert, 2002; Lambert and Balis, 2004].

[13] One difficulty that hampers direct comparison of satellite NO₂ columns measured at nadir and correlative data of ground-based twilight measurements is the diurnal cycle of NO₂, which is season dependent. Atmospheric NO₂ is known to exhibit a strong photochemical cycle throughout the day because of its daytime photolysis into NO and nighttime conversion into N₂O₅, which photolyzes back into NO₂ and NO₃ after sunrise. The typical daily cycle of NO₂ at low and middle latitudes starts with a rapid drop a little after sunrise, followed by a quasi-linear slow increase during the day, then a fast increase at sunset, and finally a slow decrease during night. The diurnal cycle has been simulated with a photochemical box model derived from the SLIMCAT 3-D chemical-transport model [Denis *et al.*, 2005]. It includes 98 chemical and 39 photochemical reactions, including heterogeneous chemistry on liquid and solid particles. Calculations are made at 17 altitude levels with a time step of 1 min. The NO₂ total column is obtained by integrating the profile assuming a constant density in each layer. An example of such a calculation, carried out for the location of Issyk-Kul in January and July, is presented in Figure 1 (the calculation for OHP is quite similar, as it is almost the same latitude). As is also observed in the measurements, the noontime column is relatively close to its sunrise value. However, the ratio between these two changes with season. The noontime column is larger than that of sunrise in the winter and smaller in the summer. In addition, a difference also appears between the satellite measurement times of ~10:30 (SCIAMACHY), ~11:10 (GOME) and ~13:00 (OMI), so the exact satellite overpass

time needs to be taken into account. The daily variation of the ratio NO₂(sunset)/NO₂ has been calculated for each of the 12 months at the location of Issyk-Kul. As we take an average of ground-based measurements between 85 and 92 SZA during twilight, the NO₂ column at 88.5° SZA is considered to be the sunrise reference. All satellite measurements can be normalized to sunrise values using these ratios. (This is different from what was used before by Ionov *et al.* [2006a] for the validation of GOME NO₂ column data at Issyk-Kul, when the ground-based sunrise measurements were adjusted to satellite overpass.) This approach proved to be useful for the comparison of satellite NO₂ data with ground-based SAOZ instruments [Ionov *et al.*, 2006b; Ionov *et al.*, 2007]. We have also tested it for the comparison of GOME NO₂ data with our ground-based measurements at Issyk-Kul in 2001–2003. Unfortunately, there are no GOME data to compare since June 2003 because of the failure of the on-board recorder. Time series of NO₂ VCD ground-based measurements (sunrise, sunset) are compared in Figure 2 (top) with GOME (GDP 4) data in 2001–2003. The average difference between ground-based (GB) and satellite (normalized to sunrise) data (“GOME-GB”) is $(0.31 \pm 0.47) \times 10^{15}$ molecules/cm², ($R = 0.86$). A similar comparison, but for the measurements of SAOZ instrument at OHP with GOME data in 2004–2006, provides an estimate of average difference GOME-GB as $(0.01 \pm 0.73) \times 10^{15}$ molecules/cm² ($R = 0.61$). The time series of NO₂ VCD measurements by SAOZ and collocated GOME (GDP 4) data in 2004–2006 are presented in Figure 2 (bottom). To use both sunrise and sunset ground-based observations for the OMI validation, we apply our simulated NO₂ ratios to adjust both the satellite and ground-based twilight measurements to local noon. The average of the adjusted ground-based sunrise and sunset measurements is then compared with the OMI measured values.

[14] For OMI validation we used the ground-based twilight NO₂ observations at Issyk-Kul and OHP, collected for the period from January 2004 to December 2006. The total

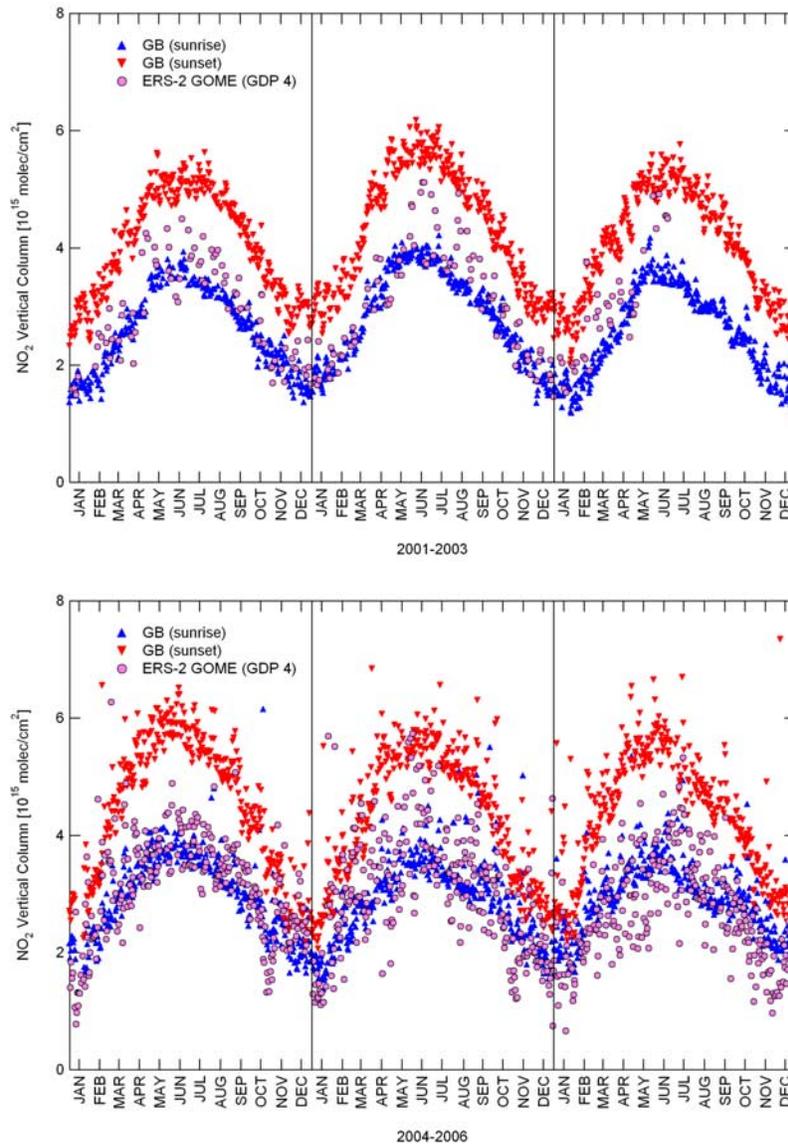


Figure 2. Comparison of GB measurements at (top) Issyk-Kul in 2001–2003 and (bottom) OHP in 2004–2006 with collocated NO₂ vertical column data by ERS-2 GOME (GDP 4.0), normalized to sunrise (SZA $\sim 88.5^\circ$).

number of data available for comparison amounts to ~ 1000 sunrise/sunset values at each of the ground sites. For these days the corresponding NO₂ vertical columns have been extracted from the OMI NO₂ station overpass files provided by the Aura Validation Data Center (available at <http://avdc.gsfc.nasa.gov>). Whenever several OMI overpasses occur during the day, the one that is closer to the ground-based station was selected. Overall, about 1500 pairs of collocated satellite and ground-based measurements were compared (~ 700 at Issyk-Kul, and ~ 800 at OHP). The distance of OMI ground pixel centers from the ground-based instrument location was less than 40 km (average ~ 10 km). The average cloud fraction of selected OMI pixels was 0.25, indicating clear sky conditions for most observations ($\sim 70\%$ of measurements with cloud fraction < 0.25). The solar zenith angle varied between 20° in

summer and 70° in winter (50° on average). The average NO₂ column, measured by the ground-based instrument at Issyk-Kul, was 2.55×10^{15} molecules/cm² at sunrise and 3.96×10^{15} molecules/cm² at sunset; the average OMI value was 3.21×10^{15} molecules/cm². The ground-based SAOZ measurements at OHP provide somewhat higher NO₂ columns: the average is 2.94×10^{15} molecules/cm² at sunrise and 4.39×10^{15} molecules/cm² at sunset; the average OMI value was 4.91×10^{15} molecules/cm². Although at the same latitude, the ground-based data sets at Issyk-Kul and OHP show prominent differences: the time series of NO₂ vertical columns at OHP are noisier, and the sunrise/sunset ratios larger in summer and lower in winter, compared to Issyk-Kul data. This may be attributed to the use of seasonal AMFs at Issyk-Kul, compared to fixed AMFs for OHP, and to the effects of tropospheric pollution,

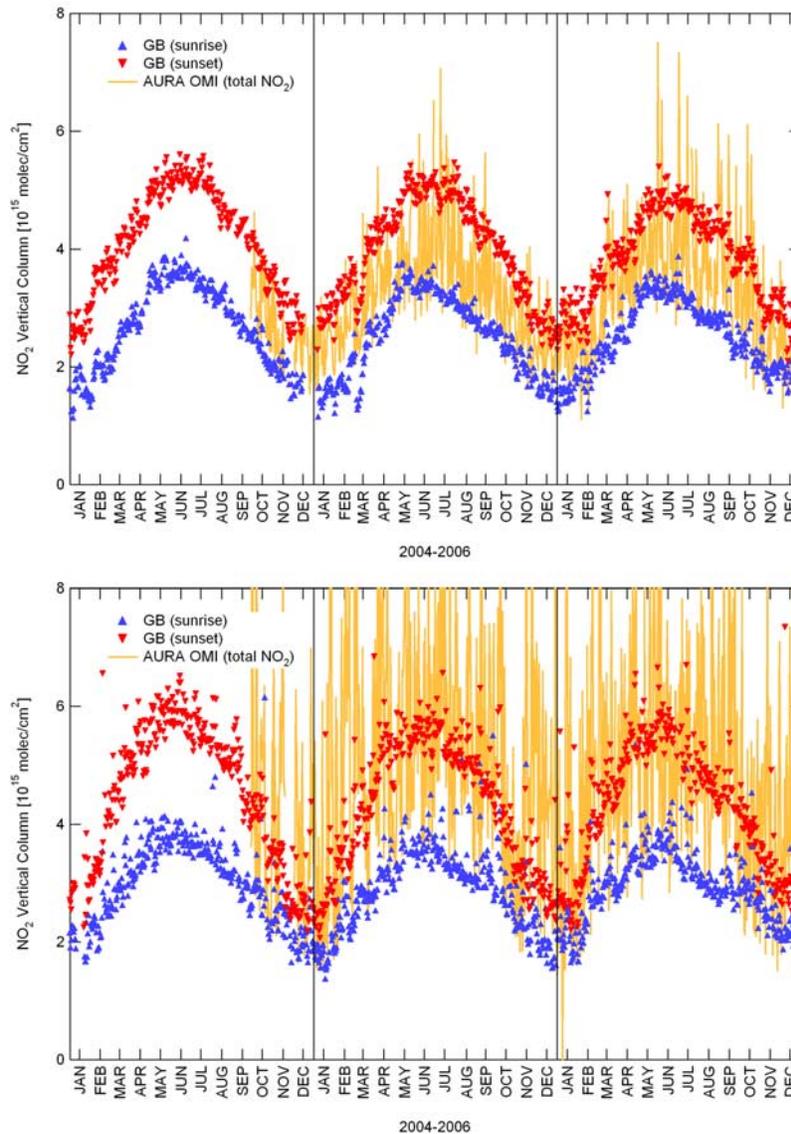


Figure 3. Comparison of Aura OMI NO₂ vertical column data with collocated GB measurements at (top) Issyk-Kul and (bottom) OHP in 2004–2006.

which we assume more likely to occur at OHP than at the remote Issyk-Kul site. This is discussed in section 5.

5. Comparison of OMI NO₂ With Ground-Based Measurements: Results and Analysis

[15] The time series of collocated OMI NO₂ VCDs and ground-based NO₂ measurements at Issyk-Kul and OHP for 2004–2006 are presented in Figure 3. Although both data sets (satellite and ground-based) reproduce the known seasonal variation of NO₂, with maximum values in summer and minimum in winter, OMI VCD data look rather noisy compared to the ground-based measurements, and displays very high day-to-day NO₂ variation (especially at OHP). This may come from tropospheric NO₂ detected by OMI, but not observed in the ground-based measurements, the zenith sky observation mode at twilight being little sensitive to tropospheric NO₂. Therefore it is more appropriate to compare our ground-based measurements with the

stratospheric part of OMI NO₂ VCD data. There is no such data field of the OMI NO₂ data product, OMNO₂, in the overpass files, but one can obtain it by taking the difference between total (NO₂) and tropospheric (“NO_{2Trop}”) NO₂ columns [Celarier *et al.*, 2006]. The resulting estimate of the stratospheric NO₂ column, compared with correlative Issyk-Kul and OHP measurements in 2004–2006, is presented in Figure 4. The stratospheric part of OMNO₂ data over Issyk-Kul is rather smooth, compared to total VCD data, and reasonably close to ground-based measurements at sunrise, as expected from NO₂ diurnal cycle simulations (see Figure 4 (top)). However, it looks more noisy at OHP and systematically lower than SAOZ sunrise measurements (see Figure 4 (bottom)). The absolute difference between ground-based NO₂ data and OMI stratospheric columns, adjusted to local noon, is plotted in Figure 5, as a function of month. As is seen in the plot, the satellite and ground-based data over Issyk-Kul agree within $(\sim 0.26 \pm 0.28) \times 10^{15}$ molecules/cm² (“OMI-GB”), with a correlation coef-

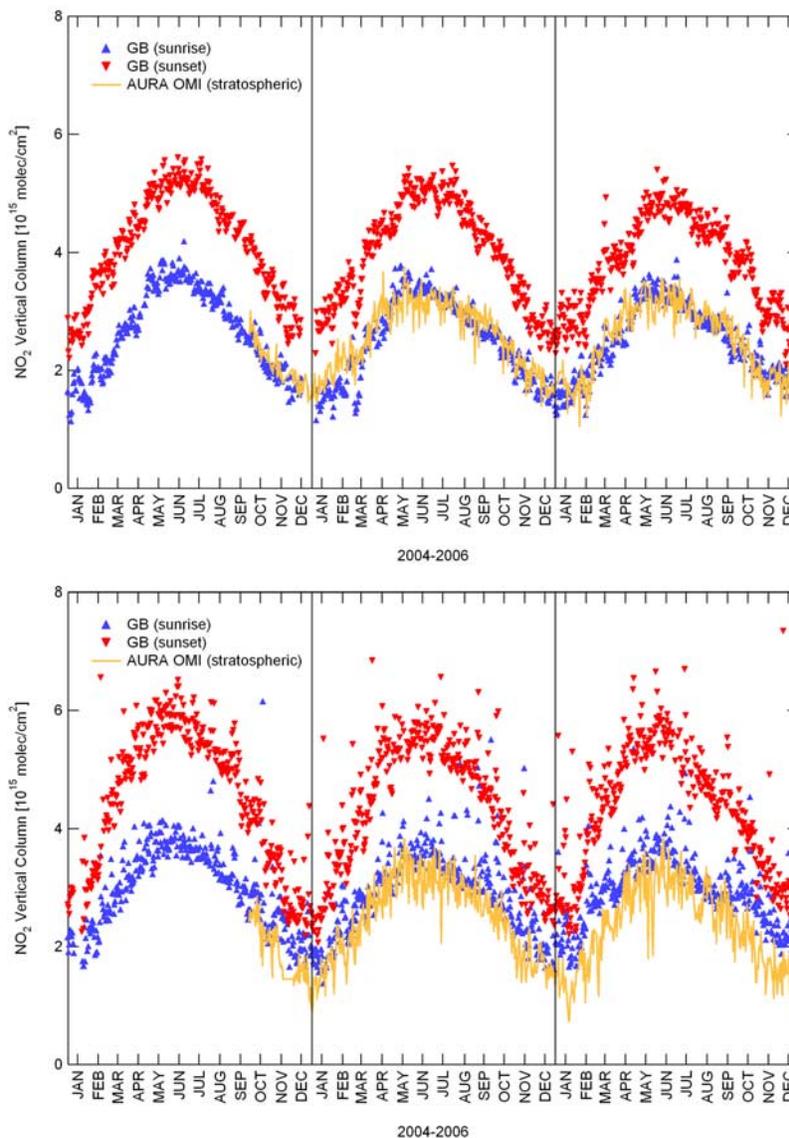


Figure 4. Comparison of GB measurements at (top) Issyk-Kul and (bottom) OHP with collocated NO₂ data by Aura OMI (stratospheric vertical column) in 2004–2006.

cient of 0.87. This kind of agreement is somewhat better than that achieved in similar comparisons between Issyk-Kul measurements and GOME data in 1996–2002 (GDP 3) and 2001–2003 (GDP 4): $(+0.61 \pm 0.53) \times 10^{15}$ and $(+0.31 \pm 0.47) \times 10^{15}$ molecules/cm² (GOME-GB), respectively. The correlation coefficient is 0.73 in comparison with GDP3, and 0.86 with GDP4. The SAOZ observations at OHP agree with stratospheric OMNO2 data within $(\sim 0.71 \pm 0.58) \times 10^{15}$ molecules/cm² (OMI-GB), with a correlation coefficient of 0.62. In addition, there is a clear seasonal dependence of OMI-GB absolute difference at OHP, larger in winter, smaller in summer.

[16] Remaining systematic differences between OMI and ground-based stratospheric NO₂ columns may be attributed to the estimation of the tropospheric NO₂ column, which has different impact on the ground-based measurements and observations from the space. The time series of the relevant data field (NO_{2Trop}) from the OMNO2 overpass file over

Issyk-Kul and OHP are presented in Figure 6. At first glance, the episodes of anthropogenic pollution are surprisingly intense and frequent in the remote and mountainous area of Issyk-Kul lake. However, satellite global mapping of NO₂ tropospheric columns reveals a number of NO_x sources near Issyk-Kul station. Thus, we have computed a map of the annual tropospheric NO₂ in the region of Kyrgyzstan on the basis of the global data of SCIAMACHY monthly mean tropospheric NO₂ in 2003–2006, available at the Tropospheric Emission Monitoring Internet Service (TEMIS, <http://www.temis.nl>) [Boersma *et al.*, 2004], and presented in Figure 7 (top). Locations of the main anthropogenic pollution sources, as revealed from the map, are presented in Table 1, with an estimation of the annual tropospheric NO₂ column. According to the OMI overpass OMNO2 data set, the average value of the tropospheric NO₂ column is 0.72×10^{15} molecules/cm². That is even less than the estimation from SCIAMACHY tropospheric NO₂ mapping

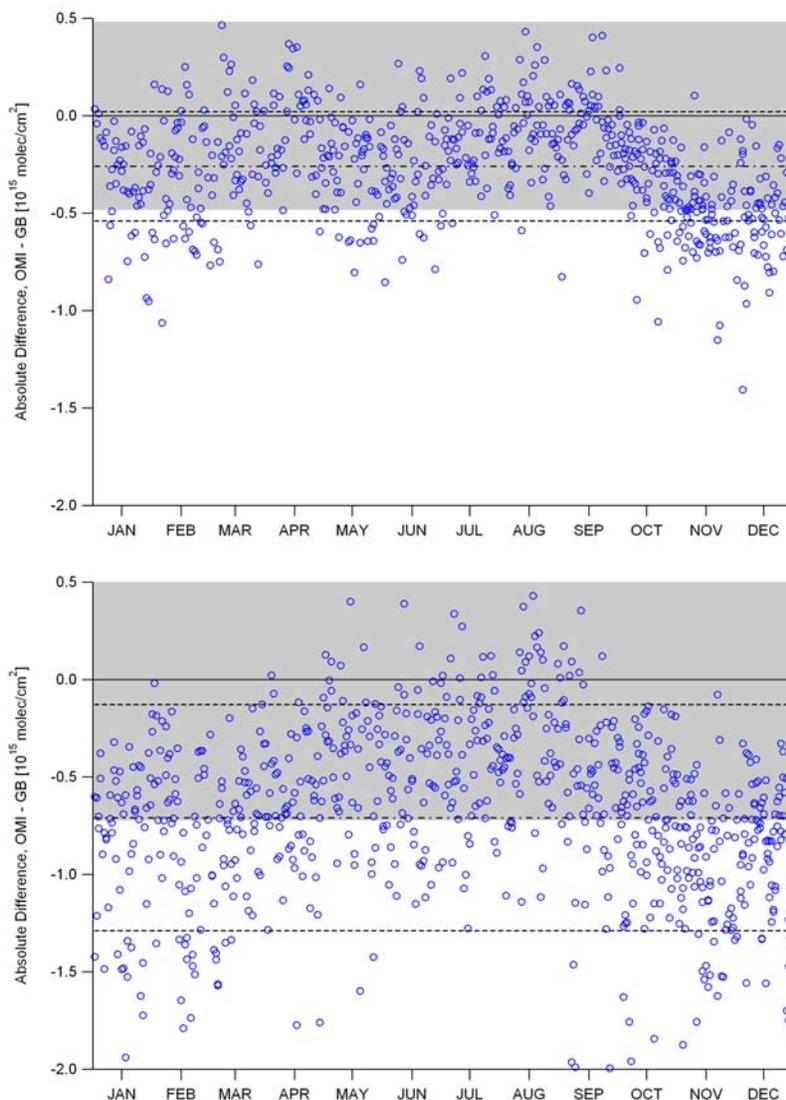


Figure 5. Absolute difference in NO₂ vertical column between Aura OMI (stratospheric) and GB measurements at (top) Issyk-Kul and (bottom) OHP, plotted as a function of month. The average difference and standard deviation are indicated with dotted-dashed and dashed lines, respectively. The grey area indicates expected RMS difference OMI-GB.

at Issyk-Kul, $\sim 1.19 \times 10^{15}$ molecules/cm² (Figure 7 (top), Table 1). The most intense NO_x source near the Issyk-Kul station is the city of Alma-Ata, Kazakhstan, ~ 60 km to the north (NO₂ tropospheric column $\sim 3.96 \times 10^{15}$ molecules/cm²). There are two more distant sources, which may also affect Issyk-Kul observations in case of extended air transport: the city of Tashkent, Uzbekistan (~ 700 km to the southwest, $\sim 5.29 \times 10^{15}$ molecules/cm²), and Urumqi, China (~ 900 km to the east, $\sim 10.47 \times 10^{15}$ molecules/cm²). By considering only the OMI stratospheric NO₂ column, we may lose a portion of tropospheric NO₂ that may still be detectable with the ground-based instrument. Tropospheric pollution is much higher over OHP than over Issyk-Kul, according to the OMI overpass OMNO2 data set, with an average tropospheric NO₂ column of 2.56×10^{15} molecules/cm². The SCIAMACHY data provides an estimate of the mean annual tropospheric NO₂ column at OHP as 3.14×10^{15} molecules/cm² (Figure 7 (bottom), Table 1). As is seen from

the map, there are numerous NO_x pollution sources near OHP station, including the cities of Marseille and Toulon (France), ~ 60 km to the south (NO₂ tropospheric column up to 8.80×10^{15} molecules/cm²) and the Po river valley in northern Italy, ~ 600 km to the northeast (NO₂ tropospheric column up to 20.26×10^{15} molecules/cm²).

[17] In addition to proper treatment of the tropospheric contribution to satellite and ground-based NO₂ VCD measurements, there are a number of uncertainties (as mentioned in section 3), that may also introduce disagreements: NO₂ absorption cross sections and their temperature dependence, AMF changes associated with seasonal variations of NO₂ profile shape and different effects linked to the presence of clouds in the ground-based and/or satellite field of view. However, both ground-based and OMI retrievals use the same NO₂ absorption cross sections, [Vandaele *et al.*, 1998] and fitting temperature, 220 K. The SAOZ measurements at OHP are processed with a fixed AMF, as are the OMI stratospheric

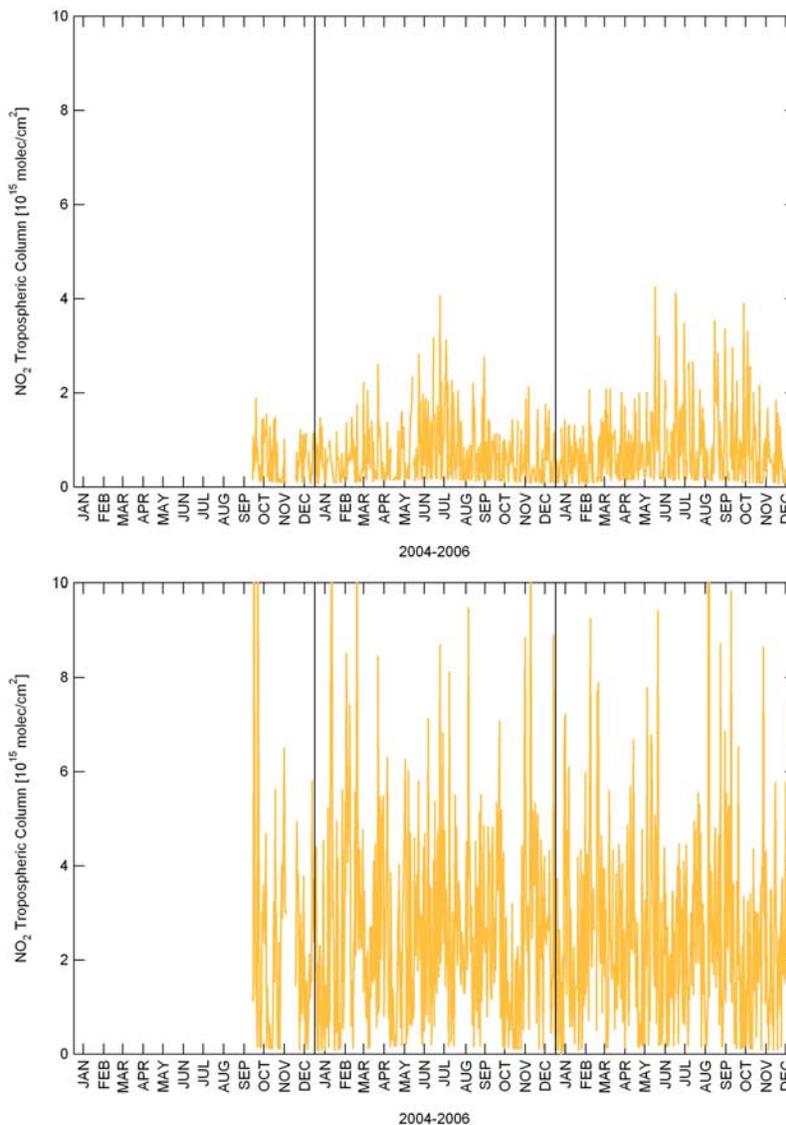


Figure 6. Time series of tropospheric NO₂ vertical column over (top) Issyk-Kul and (bottom) OHP, as measured by Aura OMI in 2004–2006.

NO₂ columns. This may introduce a systematic bias between OMI and SAOZ at OHP, but not the seasonal difference we observe. Clouds have a small effect on the ground-based AMF, and a larger effect on the satellite AMF. Clouds obscure NO₂ below them and increase the sensitivity to NO₂ above clouds because of the relatively high cloud albedo [Boersma *et al.*, 2002]. However, $\sim 70\%$ of OMI NO₂ data selected for comparison have a cloud fraction less than 0.25, which is almost cloud free. The level of agreement depends also on the accuracy of the photochemical model correction for the NO₂ diurnal cycle, which we apply to the OMI data. The error arising from the uncertainties in model initialization data (ozone, temperature, aerosol distribution and the main reaction and photolysis rates) may be as large as 8–14% [Bracher *et al.*, 2005].

[18] To estimate the potential difference between the twilight ground-based and daytime satellite NO₂ vertical column measurements, the results of sunrise and sunset

ground-based observations, both adjusted to local noon, were compared to each other. Resulting RMS difference is 0.29×10^{15} molecules/cm² ($\sim 12\%$) and 0.72×10^{15} molecules/cm² ($\sim 22\%$) for the measurements at Issyk-Kul and OHP, respectively. According to the ground-based measurement error budget (see section 2.3), this difference includes the measurement random error, the uncertainty of the AMF calculation, and the error due to mismatch of air masses, in addition to the uncertainty of the photochemical model calculation. The difference is higher at OHP than at Issyk-Kul, as the tropospheric pollution is more frequent and intense near OHP. Obviously, the systematic errors related to NO₂ absorption cross section and residual NO₂ amount in the reference spectrum, does not contribute to these differences. Considering the same NO₂ absorption cross section used by OMI, and same photochemical model used to adjust its measurements to local noon, potential OMI-GB RMS difference may be characterized by these

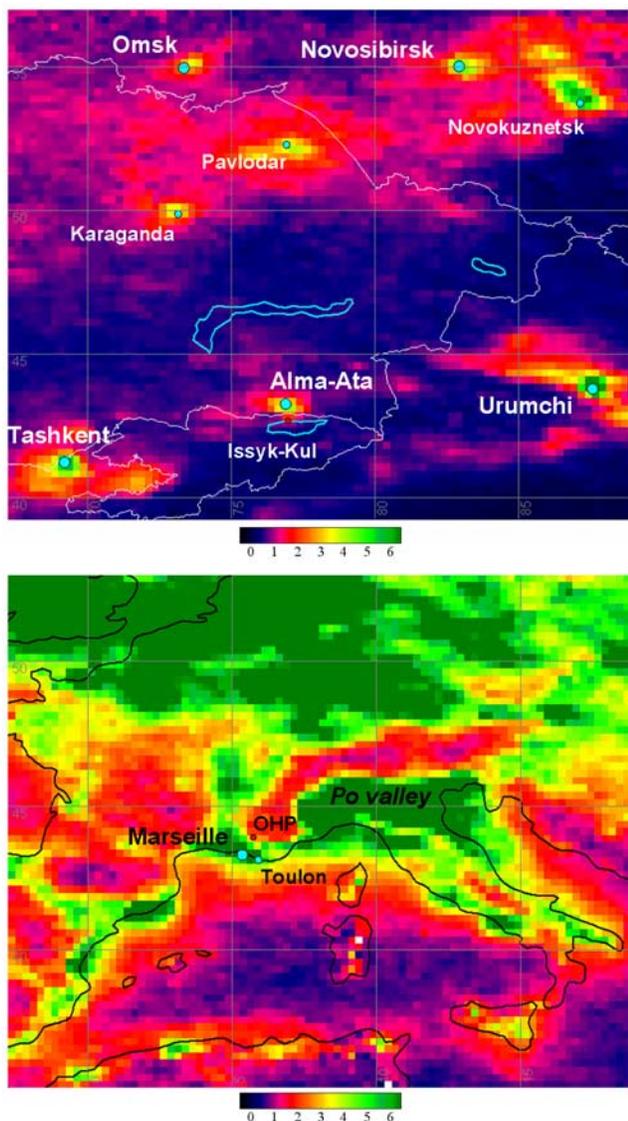


Figure 7. Annual maps of tropospheric NO₂ vertical column over (top) central Asia and (bottom) central Europe, produced from the global data of Envisat SCIAMACHY monthly mean tropospheric NO₂ in 2003–2006, given in 10¹⁵ molecules/cm² (available at <http://www.temis.nl>).

estimates (increased by the error of residual NO₂ in the ground-based reference spectrum, ~10%): ~16% at Issyk-Kul and ~24% at OHP. The resulting comparison error bars are presented in Figure 5 (grey area).

[19] Basically, the total error of remote sensing is a sum of three components [Rodgers, 2000]: the smoothing error, the measurement error and the forward model error. The last two components have been discussed above. The smoothing error may also be important, especially in the intercomparison of different remote sensing instruments [Rodgers and Connor, 2003]. To account for smoothing error, the averaging kernel concept, providing the relation between the retrieved quantities and the true trace gas spatial distribution, is by now well established in remote sensing (also for DOAS total column retrievals [Eskes and Boersma, 2003]). The difference between the averaging kernels of ground-based UV-visible and satellite OMI NO₂ vertical column measurements may introduce certain disagreements in their comparison, especially in the presence of tropospheric pollution. The problem is not only the difference in vertical sensitivity, but also the horizontal smoothing; thus, for the ground-based zenith sky twilight measurements the horizontal projection of the probed air mass is estimated to extend from nearby the station to the distance of few hundred kilometers toward the sun [Lambert and Balis, 2004]. Although detailed investigation of satellite and ground-based retrieval averaging kernels is outside the scope of the present study, additional tests were run to analyze the influence of some intercomparison parameters on the agreement between the two data sets. Statistical characteristics of OMI-GB differences for the subsets of OMI data, selected by the pixel distance, cloud fraction, and cross track position, are presented in Table 2. A threshold of 10 km was used for the distance of OMI pixel from the ground-based instrument. We selected OMI pixels with cloud fraction <0.25. The OMI cross track position was selected either in the middle of the scan (cross track pixel numbers 15–35), or at the edges, to account for the OMI spatial resolution change (from ~13 × 24 km² in the nadir to ~78 × 128 km² at the edges) and known OMI cross-track anomaly [Celarier et al., 2006]. According to the estimates provided in Table 2, the difference between OMI stratospheric NO₂ column and correlative ground-based measurements at Issyk-Kul does not depend much on any of these selection criteria. However, this is not the case for the measurements at OHP station. For example, selecting OMI pixels more than 10 km distance from OHP increases the scatter (standard deviation) from ± 0.43

Table 1. Anthropogenic NO_x Pollution Sources Near Issyk-Kul and OHP Stations^a

Ground-Based Station	Anthropogenic Pollution Source			
	Location Name	Distance From the Station, km	Direction From the Station	Tropospheric NO ₂ , 10 ¹⁵ molecules/cm ²
Issyk-Kul	-	-	-	1.19
Issyk-Kul	Alma-Ata	60	north	3.96
Issyk-Kul	Tashkent	700	southwest	5.29
Issyk-Kul	Urumchi	900	east	10.47
OHP	-	-	-	3.14
OHP	Marseille, Toulon	60	south	8.80
OHP	Po Valley	600	northeast	20.26

^aRevealed from the annual tropospheric NO₂ mapping of SCIAMACHY monthly mean tropospheric NO₂ data in 2003–2006 (available at <http://www.temis.nl>).

Table 2. Statistical Difference Between Ground-Based UV-Visible and Satellite OMI Stratospheric NO₂ Column Measurements at Issyk-Kul and OHP in 2004–2006^a

Station	OMI Pixel Distance		OMI Pixel Cloud Fraction		OMI Pixel Cross-Track Number	
	<10 km	>10 km	<0.25	>0.25	15–35	<15, >35
Issyk-Kul	–0.27 ± 0.28 0.88	–0.25 ± 0.29 0.86	–0.26 ± 0.29 0.87	–0.28 ± 0.28 0.88	–0.30 ± 0.27 0.89	–0.26 ± 0.28 0.87
OHP	–0.71 ± 0.43 0.78	–0.70 ± 0.76 0.43	–0.63 ± 0.46 0.75	–0.88 ± 0.76 0.44	–0.70 ± 0.49 0.71	–0.71 ± 0.60 0.61

^aWith respect to OMI pixel distance, cloud fraction, and cross-track pixel number (the average OMI-GB difference ± standard deviation, given in 10¹⁵ molecules/cm², and correlation coefficient).

to $\pm 0.76 \times 10^{15}$ molecules/cm², and decreases the correlation with ground-based measurements from 0.78 to 0.43. A similar effect is observed when going from the middle of the OMI cross scan to the edges – the standard deviation of OMI-GB difference is increased from ± 0.49 to $\pm 0.60 \times 10^{15}$ molecules/cm², and the correlation decreased from 0.71 to 0.61. The major change in the level of agreement between OMI and OHP measurements is obtained when the cloud fraction selection criteria are applied. Both the average OMI-GB difference and its standard deviation increase for OMI pixels with cloud fraction larger than 0.25, from -0.63 ± 0.46 to $-0.88 \pm 0.76 \times 10^{15}$ molecules/cm²; the correlation is reduced from 0.75 to 0.44.

[20] Considering the fact that both Issyk-Kul and OHP instruments are at the same latitude, applying a similar measurement technique and comparison methodology, such a sensitivity of the OMI-GB difference to pixel distance, spatial resolution, and cloud fraction is likely to indicate the influence of tropospheric pollution on the agreement between OMI data and ground-based measurements at OHP (in contrast to the similar comparison at Issyk-Kul). In the presence of tropospheric NO₂ pollution, comparison of OHP measurements with the data of more distant and larger OMI pixels is affected by a possible mismatch of air masses actually probed by correlative ground-based and satellite observations. Normally, the air mass may travel for hundred kilometers during the hours between daytime satellite and twilight ground-based observation. However, the most marked episodes of NO_x pollution, detectable from the ground and space, are likely to coincide with the thermal inversion and stable air mass. Further, the presence of clouds in OMI's field of view will hide a part of the NO₂ tropospheric column below the cloud cover, while the ground-based measurements will overestimate the NO₂ column because of the increase of light path by multiple scattering inside the cloud. The effects of tropospheric pollution on the processing of OMI NO₂ measurements are likely to be responsible for most of the difference we observe between the satellite and ground-based NO₂ data. An operational stratosphere-troposphere separation of satellite NO₂ measurements was first implemented with the OMI processing algorithm. Similar comparisons of ground-based NO₂ measurements with correlative satellite data from GOME and SCIAMACHY do not reveal such systematic differences as those observed here between the OMI data and SAOZ measurements at OHP [Ionov *et al.*, 2006b]. On the other hand, the measurements at seven more SAOZ stations in the tropics and polar regions were found to agree with OMI NO₂ data within -0.3×10^{15} molecules/cm² (OMI-GB), except

Bauru, Brazil (22.4°S/49.0°W), which is also exposed to tropospheric pollution [Ionov *et al.*, 2006b].

[21] The zonal distribution of NO₂ vertical columns (total, stratospheric, and tropospheric) over a 0.25°-wide latitude belt centered at 43.25°N (the mean of the Issyk-Kul and OHP latitudes) is presented in Figure 8. The OMI total and stratospheric NO₂ columns were taken from OMNO2 Level2G daily gridded data, available at Goddard Earth Sciences Distributed Active Archive Center (GES DAAC, <http://disc.sci.gsfc.nasa.gov>). Average NO₂ total and tropospheric columns were computed from the OMI measurements within each 0.25° × 0.25° grid cell, and the stratospheric column was, as before, estimated as the difference between total and tropospheric columns. SCIAMACHY tropospheric NO₂ columns were calculated from the monthly mean tropospheric NO₂ mapping in 2003–2006, provided by TEMIS (<http://www.temis.nl>). Although not usable for the direct comparison with OMI daily NO₂ data, the annual tropospheric NO₂ columns from SCIAMACHY are a good global reference for the regions of permanent pollution. Thus, highly increased NO₂ total columns in the OMI daily data mostly correlate with high tropospheric NO₂ values of the annual SCIAMACHY data (e.g., over the known polluted regions of USA, Europe and Asia, see Figure 8). According to the plot, the OMI stratospheric NO₂ column is rather smooth over some parts of the globe, suggesting that it represents the zonal wave fit used in the OMI algorithm, rather than true values (see section 3). Thus, the daily stratospheric NO₂ column determined by OMI is unlikely slowly varying with longitude in the range of 10°W–70°E in March and September (Figure 8). Most of that midlatitude region belongs to the densely populated Europe (10°W–30°E), providing a considerable tropospheric pollution, indicated also by the annual tropospheric NO₂ from SCIAMACHY (Figure 8, gray values). Hence, a large polluted area around OHP station at 44°E is presumed to be masked out of the stratospheric field smoothing within the standard OMI processing [Bucsela *et al.*, 2006; Celarier *et al.*, 2006]. Since the true OMI measurements do not contribute to the resulting stratospheric NO₂ column in that region, such estimation is likely to be inaccurate over OHP. This is not the case for Issyk-Kul, because of the large area of relatively clean troposphere found to the east and west of the station.

6. Conclusions and Further Work

[22] Operational Aura OMI measurements of the NO₂ vertical column have been compared with collocated UV-Visible ground-based observations in midlatitudes, at

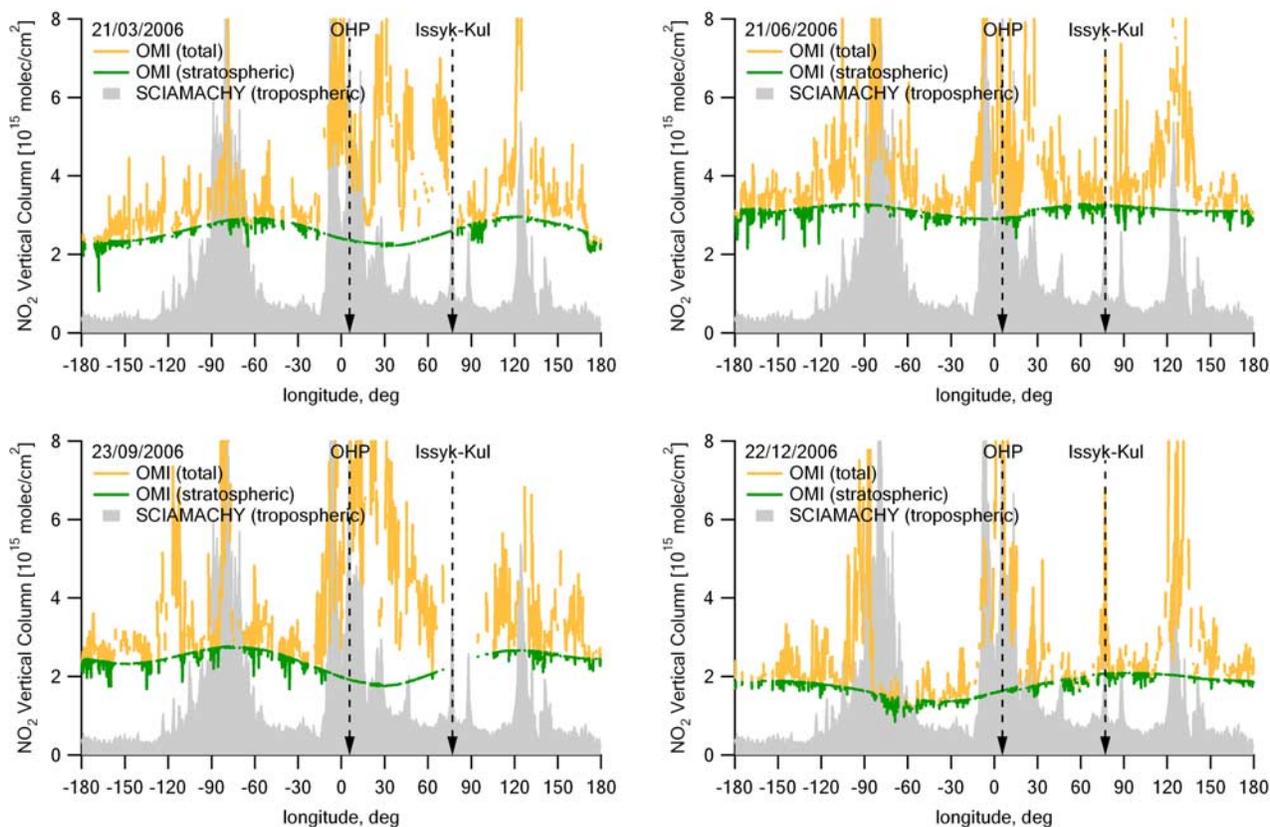


Figure 8. Longitudinal distribution of Aura OMI total and stratospheric NO₂ vertical column (Level2G) over a 0.25°-wide latitude belt at 43.25°N for the different seasons (spring, summer, autumn, and winter) of 2006. Grey values represent annual tropospheric NO₂ vertical column for the same latitude, calculated from the global data of Envisat SCIAMACHY monthly mean tropospheric NO₂ in 2003–2006 (available at <http://www.temis.nl>).

Issyk-Kul station in Kyrgyzstan and Observatoire de Haute-Provence in France for the period 2004–2006. Although located in remote mountainous sites, both stations were found to be exposed to local pollution sources. Considerable tropospheric pollution in the region of Issyk-Kul and OHP was detected by OMI, and also observed by SCIAMACHY. The annual tropospheric NO₂ column over Issyk-Kul is estimated to be 0.72×10^{15} molecules/cm² and 1.19×10^{15} molecules/cm², as measured by OMI and SCIAMACHY, respectively. At OHP, the annual tropospheric NO₂ column is estimated to be even much higher: 2.56×10^{15} molecules/cm² and 3.14×10^{15} molecules/cm², as measured by OMI and SCIAMACHY. Therefore, direct comparison between OMI and ground-based measurements of the NO₂ total column is impossible, as the ground-based twilight measurements are much less sensitive to tropospheric NO₂, than satellite nadir measurements. Consequently, the stratospheric NO₂ column was calculated as a difference between OMI total and tropospheric column [Celarier *et al.*, 2006], and compared with ground-based measurements at Issyk-Kul and OHP. All OMI data and ground-based measurements have been compensated for NO₂ diurnal photochemical change and normalized to local noon values using a photochemical box model. According to the comparison results, midlatitude OMI stratospheric NO₂ column data underestimates ground-based measurements by

$(0.26 \pm 0.28) \times 10^{15}$ molecules/cm² and $(0.71 \pm 0.58) \times 10^{15}$ molecules/cm² at Issyk-Kul and OHP, respectively. These differences are at the limit of the comparison error derived from estimates of measurement absolute accuracy and photochemical model uncertainty: $\sim 0.5 \times 10^{15}$ molecules/cm² and $\sim 0.7 \times 10^{15}$ molecules/cm², for the measurements at Issyk-Kul and OHP, respectively. The present study shows better agreement, compared to similar validation of GOME data over Issyk-Kul in 1996–2003, but worse agreement, compared to validation of GOME data over OHP in 2004–2006 and SCIAMACHY in 2004–2005. The latter may be partly attributed to the difficulties of stratosphere-troposphere separation within the OMI processing algorithm in the presence of heavy NO_x pollution at OHP.

[23] For the accurate validation of satellite OMI NO₂ data, the effects of tropospheric pollution should be further studied in detail. The smoothing errors, arising from the difference in spatial sensitivity (both vertical and horizontal) of both ground-based and space-based remote sensing measurements, can be evaluated by means of the careful investigation of corresponding averaging kernels [Rodgers and Connor, 2003; Eskes and Boersma, 2003; Lambert and Balis, 2004]. Comparison of UV-visible ground-based measurements with the initial OMI NO₂ data (assuming a stratospheric AMF, and without stratospheric/tropospheric

separation) may be useful as well, as it will be more consistent with similar validation studies of GOME and SCIAMACHY satellite instruments.

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