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**Validation of  
SCIAMACHY and OMI  
NO<sub>2</sub> in Israeli cities**

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# Validation of urban NO<sub>2</sub> concentrations and their diurnal and seasonal variations observed from space (SCIAMACHY and OMI sensors) using in situ measurements in Israeli cities

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## Abstract

We compare a full-year (2006) record of surface air NO<sub>2</sub> concentrations measured in Israeli cities to coinciding retrievals of tropospheric NO<sub>2</sub> columns from satellite sensors (SCIAMACHY aboard ENVISAT and OMI aboard Aura). This provides a large statistical data set for validation of NO<sub>2</sub> satellite measurements in urban air, where validation is difficult yet crucial for using these measurements to infer NO<sub>x</sub> emissions by inverse modeling. Assuming that NO<sub>2</sub> is well-mixed throughout the boundary layer (BL), and using observed average seasonal boundary layer heights, near-surface NO<sub>2</sub> concentrations are converted into BL NO<sub>2</sub> columns. The agreement between OMI and (13:45) BL NO<sub>2</sub> columns (slope=0.93,  $n=542$ ), and the comparable results at 10:00 h for SCIAMACHY, allow a validation of the seasonal, weekly, and diurnal cycles in satellite-derived NO<sub>2</sub>. OMI and BL NO<sub>2</sub> columns show consistent seasonal cycles (winter NO<sub>2</sub> 1.6–2.7× higher than summer). BL and coinciding OMI columns both show a strong weekly cycle with 45–50% smaller NO<sub>2</sub> columns on Saturday relative to the weekday mean, reflecting the reduced weekend activity, and validating the weekly cycle observed from space. The diurnal difference between SCIAMACHY (10:00) and OMI (13:45) NO<sub>2</sub> is maximum in summer when SCIAMACHY is up to 40% higher than OMI, and minimum in winter when OMI slightly exceeds SCIAMACHY. A similar seasonal variation in the diurnal difference is found in the source region of Cairo. The surface measurements in Israel cities confirm this seasonal variation in the diurnal cycle. Using simulations from a global 3-D chemical transport model (GEOS-Chem), we show that this seasonal cycle can be explained by a much stronger photochemical loss of NO<sub>2</sub> in summer than in winter.

## 1 Introduction

Nitrogen oxides (NO<sub>x</sub>≡NO+NO<sub>2</sub>) are of central importance for atmospheric chemistry. They are precursors of tropospheric ozone, aerosol nitrate, and the hydroxyl radical

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(OH) which is the main atmospheric oxidant. About 2/3 of the global source of NO<sub>x</sub> is from fossil fuel combustion (IPCC, 2007) and is concentrated in urban areas. Satellite observations of tropospheric NO<sub>2</sub> columns by solar backscatter from the GOME, SCIAMACHY, and OMI sensors have provided increasing information over the past decade to quantify NO<sub>x</sub> emissions and their trends at various scales (e.g. Martin et al., 2003, 2006; Richter et al., 2004; Konovalov et al., 2006; Wang et al., 2007; van der A et al., 2008). Validating these satellite observations is difficult, however. We show here that long-term surface NO<sub>2</sub> measurements from urban air quality monitoring networks provide valuable validation data and can test the seasonal, weekly, and diurnal variations seen from space by the SCIAMACHY and OMI sensors.

The atmospheric lifetime of NO<sub>x</sub> against oxidation is of the order of hours (Liang et al., 1998), resulting in large spatial and temporal variability around source areas. High concentrations are mainly restricted to the boundary layer up to 1–2 km, with rapid drop-off at higher altitudes. Drop-off is particularly sharp for NO<sub>2</sub> because of the decrease of the NO<sub>2</sub>/NO ratio with decreasing temperature (Martin et al., 2004). Validation of NO<sub>2</sub> column measurements from space has relied on aircraft vertical profiles coincident with satellite overpasses to capture the full extent of the column (Heland et al., 2002; Martin et al., 2004, 2006; Bucselá et al., 2008). This is expensive and as a result validation data are few. Horizontal variability over the satellite footprint, aircraft traffic restrictions, and the need to extrapolate from the aircraft floor to the surface can further lead to significant errors in comparing aircraft-derived columns to the satellite column measurements. This is particularly problematic in urban areas which are of prime interest for validation (Boersma et al., 2008b).

Surface observations of NO<sub>2</sub> concentrations in urban areas offer an alternate vehicle for satellite validation. Most developed countries have dense urban monitoring networks for NO<sub>2</sub> because it is a regulated pollutant (Ellis, 1975; Hjelbrekke and Fjæraa, 2008). The standard monitoring instrumentation is subject to interferences from NO<sub>x</sub> oxidation products (Gerboles et al., 2003; Steinbacher et al., 2007; Dunlea et al., 2007; Lamsal et al., 2008), and the lack of vertical information above the surface induces

error. On the other hand, the high spatial and temporal density of the data greatly improve the validation statistics (Schaub et al., 2006; Ordóñez et al., 2006; Blond et al., 2007) over what is possible from aircraft profiles. The lack of vertical information in the surface data may in fact be less of a problem than the need to extrapolate aircraft observations down to the surface.

## 2 NO<sub>2</sub> observations

### 2.1 SCIAMACHY tropospheric NO<sub>2</sub> columns

We use tropospheric NO<sub>2</sub> columns retrieved from SCIAMACHY on board ESA's ENVISAT. This satellite (launched March 2002) orbits the Earth in a polar, sun-synchronous way in a descending node crossing the equator at approximately 10:00 local time. SCIAMACHY observes the atmosphere alternately in nadir and limb viewing modes. Tropospheric information is available from the nadir spectra only. In combination with the SCIAMACHY nadir field-of-view, corresponding to a swath width of 960 km on the Earth's surface, this leads to global coverage approximately once every six days. The nadir surface spatial resolution is 30×60 km<sup>2</sup>.

We use the SCIAMACHY NO<sub>2</sub> retrievals (v1.1) available from the Tropospheric Emission Monitoring Internet Service (<http://www.temis.nl>) for the year 2006. The retrieval algorithm has been described in detail in Boersma et al. (2004), and Blond et al. (2007). In brief, slant column densities are determined with Differential Optical Absorption Spectroscopy (DOAS) in the 426.3–451.3 nm spectral window. The stratospheric (background) slant column is estimated from data assimilation of slant columns in the global chemistry-transport model TM4 (Dentener et al., 2003). After subtraction of the stratospheric slant column, the residual tropospheric slant column is translated into a tropospheric vertical column by a tropospheric air mass factor that accounts for viewing geometry, the NO<sub>2</sub> and temperature profile shape, as well as the pressure and reflectivity of clouds and surface. The SCIAMACHY NO<sub>2</sub> retrieval (v1.1) is improved

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relative to earlier versions (v1.04) because it includes cloud parameters retrieved from FRESKO+. The FRESKO+ algorithm uses a more realistic physical model of the atmosphere by accounting for single Rayleigh scattering, and this leads to higher cloud fractions and cloud pressures. These in turn result in NO<sub>2</sub> columns that are lower for polluted situations with low clouds, leading to better agreement with independent NO<sub>2</sub> validation data (Wang et al., 2008).

Errors in the slant column fitting, the stratospheric correction, and in the air mass factor lead to an overall error in the SCIAMACHY tropospheric NO<sub>2</sub> columns with an absolute component of approximately  $0.65 \times 10^{15}$  molecules cm<sup>-2</sup> (from the tropospheric slant column) and a relative component of approximately 30% (from the tropospheric air mass factor).

## 2.2 OMI tropospheric NO<sub>2</sub> columns

OMI onboard NASA's EOS-Aura satellite (launched July 2004) provides tropospheric NO<sub>2</sub> columns at approximately 13:45 local time. Together with the 10:00 measurements by SCIAMACHY, this provides valuable information on the diurnal cycle in NO<sub>2</sub>. OMI also improves on SCIAMACHY because it observes the Earth's atmosphere continuously in nadir mode with a 114° field-of-view (2600 km on the Earth's surface), thereby achieving daily global coverage. Furthermore, the nadir spatial resolution of 13×24 km<sup>2</sup> allows for the observation of finer details, and increases the likelihood of encountering cloud-free scenes (Krijger et al., 2007). We use the DOMINO (Dutch OMI NO<sub>2</sub>) product (v1.02) available from <http://www.temis.nl> for the year 2006. The retrieval algorithm has been described in detail in Boersma et al. (2007), and recent updates can be found in the DOMINO Product Specification Document ([http://www.temis.nl/docs/OMI\\_NO2\\_HE5\\_1.0.2.pdf](http://www.temis.nl/docs/OMI_NO2_HE5_1.0.2.pdf)). Slant columns are determined with DOAS in the 405–465 nm spectral window. As for SCIAMACHY, a stratospheric slant column (from assimilation in TM4) is subtracted from the slant column, and the residual is converted into a vertical tropospheric column by the tropospheric AMF. The approach to calculate the AMF is identical to SCIAMACHY, except that dif-

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ferent cloud retrievals are used (FRESCO+ for SCIAMACHY and O<sub>2</sub>-O<sub>2</sub>; Acarreta et al., 2004 for OMI). The a priori profile shapes are sampled from the same TM4 model, at 10:00 and 13:30 h for SCIAMACHY and OMI respectively (Boersma et al., 2008a).

OMI retrieval errors have an absolute component of approximately  $1.0 \times 10^{15}$  molecules cm<sup>-2</sup> and a relative (AMF) component of 30% (Boersma et al., 2007). The spectral fitting error is smaller for SCIAMACHY than for OMI because of better SCIAMACHY signal-to-noise ratios, but OMI errors are generally much reduced by averaging over multiple days or over multiple pixels.

### 2.3 Surface NO<sub>2</sub> concentrations

We use here near-surface concentrations of NO<sub>2</sub> measured every 30 min at 8 sites in Israel for the whole year 2006. Figure 1 and Table 1 show the station locations. Measurements are with standard chemiluminescence instruments using molybdenum oxide converters. NO<sub>2</sub> is catalytically converted to NO on a heated (310°C) molybdenum surface and then measured as NO by chemiluminescence after reaction with ozone. The molybdenum converter also partly converts other oxidized nitrogen compounds such as nitric acid (HNO<sub>3</sub>), alkyl nitrates, and peroxyacetyl nitrate (PAN) to NO (see e.g. Steinbacher et al., 2007; Dunlea et al., 2007 and references therein). This will cause NO<sub>2</sub> concentrations to be overestimated, especially in photochemically aged airmasses. Steinbacher et al. (2007) have shown biases up to +50% at rural locations downwind of pollution sources in Switzerland. For urban air in Mexico City, Dunlea et al. (2007) find no significant bias in the morning but increasing bias in the afternoon, presumably reflecting the diurnal formation of NO<sub>x</sub> oxidation products.

Recognizing that most NO<sub>y</sub> (with NO<sub>y</sub> defined as the sum of all reactive nitrogen oxides; NO+NO<sub>2</sub>+HNO<sub>3</sub>+organic nitrates) is NO<sub>x</sub> within urban areas at mid-morning with little prior photochemical activity, and given the lack of evidence for morning-interference in the study by Dunlea et al. (2007), we do not correct the surface concentrations measured at 10:00 (SCIAMACHY overpass). For measurements at 13:45 (OMI overpass) we show results from two approaches:

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1. no correction, i.e. interpreting the NO<sub>2</sub> measurements as an upper limit for the true NO<sub>2</sub> concentrations;
2. correction based on the concurrently observed increase of O<sub>3</sub> from 10:00 to 13:45 as an indicator for the interference  $\Delta[\text{NO}_z]$  (with NO<sub>z</sub> defined as NO<sub>y</sub>-NO<sub>x</sub>), assuming  $\Delta[\text{NO}_z]=0.1\cdot\Delta[\text{O}_3]$  on a molar basis based on Mexico City data (Dunlea et al., 2007), and with no correction if  $\Delta[\text{O}_3]$  smaller or equal to 0.

### 3 Ensemble validation

Table 1 shows direct comparisons of OMI tropospheric NO<sub>2</sub> columns to surface NO<sub>2</sub> concentrations measured at 8 different stations in Israel at 13:30–14:00 h throughout 2006. From a reduced-major axis (RMA) regression analysis (Clarke, 1980), we find the lowest slopes ( $0.30, 0.59 \times 10^{15}$  molecules cm<sup>-2</sup>/ppb) for the stations of Haifa and Ashdod that are situated immediately downwind of a large port (Haifa), and within 2 km of a large power plant and refinery complex (Ashdod). The other six stations are not influenced by such nearby NO<sub>x</sub> point sources. For Afula, no summertime data were available, which reduces the range of observed values, but other than that we did not see a good reason to exclude data from Afula from our analysis. Excluding data from Haifa and Ashdod (but maintaining Afula), OMI and surface NO<sub>2</sub> are well-correlated ( $r=0.63, n=542$ ). Correcting the 13:45 h surface NO<sub>2</sub> observations for NO<sub>z</sub> interference as described above, leads to surface NO<sub>2</sub> concentrations that are on average smaller by 8%. We conclude that the effect of applying an interference correction for urban NO<sub>2</sub> in the early afternoon is modest, reducing surface-based NO<sub>2</sub> concentrations by approximately 0.7 ppb.

Table 2 shows comparisons of NO<sub>2</sub> concentrations measured at 10:00 to SCIAMACHY tropospheric NO<sub>2</sub>. For the locations of Haifa and Ashdod, correlations and slopes are low, consistent with their situation downwind of strong point sources and with the results found for OMI (Table 1). The agreement between SCIAMACHY and

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surface NO<sub>2</sub> amounts to  $r=0.48$  ( $n=173$ ). Sharpening the spatial coincidence criterion to  $\pm 0.1^\circ$ , as for OMI, improves the correlation ( $r=0.55$ ) between surface and SCIAMACHY NO<sub>2</sub>, at the expense of the number of coincidences ( $n=29$ ).

We derive BL NO<sub>2</sub> columns from the near-surface NO<sub>2</sub> mixing ratios by assuming vertical uniformity in the BL and negligible concentrations above. We take the noon-time mixing depths for Israel from a climatology of mixing depth observations (Table 2 in Dayan et al., 1988) with noontime mixing depths of [1.12, 0.87, 0.65, 0.95] km for winter, spring, summer, and fall respectively. Mixing depths in Israel are minimum in summer due to strong subsidence, and have an uncertainty of  $\approx 25\%$  (Dayan et al., 2002). Neglecting NO<sub>2</sub> above the BL is a reliable assumption (Martin et al., 2002; Boersma et al., 2008b). Figure 2 (left panel) compares tropospheric NO<sub>2</sub> columns retrieved from OMI and SCIAMACHY with interference-corrected BL NO<sub>2</sub> columns derived from near-surface measurements. BL NO<sub>2</sub> columns show a similar correlation with OMI ( $r=0.64$ ,  $n=542$ ) as the surface concentrations ( $r=0.63$ ). The slope of the RMA regression is  $0.93 \pm 0.06$  and the intercept is  $-0.37 \times 10^{15}$  molecules cm<sup>-2</sup>, indicating that on average OMI does not deviate significantly from the BL NO<sub>2</sub> columns. Not correcting for interference gives similar agreement ( $r=0.67$ , slope  $0.90 \pm 0.05$ ) and a slightly larger negative smaller intercept ( $-0.72 \times 10^{15}$  molecules cm<sup>-2</sup>). The right panel of Fig. 2 shows the agreement between SCIAMACHY and BL NO<sub>2</sub> ( $r=0.46$ ,  $n=173$ ). Selecting pixels within  $\pm 0.1^\circ$ , as for OMI, improves the correlation ( $r=0.53$ , slope=0.94) between BL and SCIAMACHY NO<sub>2</sub> columns.

## 4 Temporal variability

### 4.1 Annual cycle

Figure 3 shows the seasonal variation of NO<sub>2</sub> over Israel in 2006 for the five stations with comparable NO<sub>2</sub> concentrations and seasonal variations and year-round coverage (for Afula, no summer data were available). The grey dashed line is for all surface

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measurements including cloudy conditions. The black dashed line is for measurements coinciding with satellite data, i.e. measured under mostly-clear conditions only. Exclusion of cloudy scenes in the validation data subset decreases concentrations by 15% on average but does not affect the seasonal variation.

Both OMI (red squares) and boundary-layer  $\text{NO}_2$  columns (black symbols) are highest in the winter months, presumably reflecting the seasonal variation of  $\text{NO}_2$  lifetime. We see that monthly mean  $\text{NO}_2$  columns from the in situ observations and from OMI are similar within their error margins for all months. For the boundary-layer columns, error bars mainly reflect the uncertainty in the boundary-layer depths (25%, based on estimates from Dayan et al., 1988). If there is a bias in the BL-depths, it directly propagates into our BL column estimates, and this could explain the large differences between BL columns and OMI in winter. For OMI, error bars indicate the standard deviation of the mean. The seasonal cycle, expressed as the ratio of winter-to-summer mean  $\text{NO}_2$ , is  $2.7 \pm 0.6$  in the boundary-layer  $\text{NO}_2$  columns, and  $1.6 \pm 0.5$  in surface and OMI  $\text{NO}_2$ .

## 4.2 Weekly cycle

The weekly cycle of coinciding ground-based and OMI  $\text{NO}_2$  is shown in Fig. 4 for five stations in the period between March and November 2006 (Afula was rejected because no summertime data were available). Wintertime observations have been excluded because in this season no coincidences were available for Saturdays. The weekly cycle is due to reduced  $\text{NO}_x$  emissions on Fridays and Saturdays corresponding to the week-end pattern and days of rest. We observe reductions in  $\text{NO}_2$  on Friday and Saturday in surface  $\text{NO}_2$  concentrations (dashed line), corrected BL  $\text{NO}_2$  columns (black diamonds), as well as in OMI  $\text{NO}_2$  columns (red squares). The reduction on Saturday is significant, 50% relative to the weekday mean. Beirle et al. (2003) observed a similar Saturday  $\text{NO}_2$  reduction over Israel on the regional scale from GOME. Their reduction (30%) is smaller because the relatively large GOME pixel ( $320 \times 40 \text{ km}^2$ ) covers not just the strong source region of Israel, but also adjacent parts of the Mediterranean Sea

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and Jordan where sources are weaker and less likely to show a distinct weekend effect. In contrast, the small-pixel OMI observations used here are representative for the urban scale and more likely to show the local weekend emission reductions.

### 4.3 Diurnal cycle

5 Figure 5 shows average  $\text{NO}_2$  columns measured at the locations of the Israeli stations on the same days at 10:00 and 13:45 in cloud-free conditions in the period March–November 2006. BL and satellite-retrieved  $\text{NO}_2$  columns are consistent at 10:00 and at 13:45. The geometric mean of the ratio of SCIAMACHY and OMI  $\text{NO}_2$  columns over Israeli cities is 1.22, and this tendency is quantitatively consistent with the geometric  
10 mean of 1.18 of 10:00 and 13:45 surface-based  $\text{NO}_2$  columns. It is unlikely that these results are due to retrieval differences, as SCIAMACHY and OMI  $\text{NO}_2$  columns have been retrieved with a consistent algorithm (Boersma et al., 2008a), and both datasets agree well with the independent data shown in Fig. 5. The results appear consistent with findings of Boersma et al. (2008a) over fossil fuel source regions at northern mid-latitudes, where SCIAMACHY observed 5–40% higher  $\text{NO}_2$  than OMI in summer, explained by daytime photochemical loss of  $\text{NO}_2$ , dampened by the diurnal cycle of anthropogenic  $\text{NO}_x$  emissions that has a broad daytime maximum. Comparing 10:00 and 13:45  $\text{NO}_2$  observed on the same days during winter months in Israel did not show a clear diurnal cycle, and we will now investigate this further.

20 Figures 6a–d show seasonally averaged differences between SCIAMACHY and OMI tropospheric  $\text{NO}_2$  measured on the same day in mostly clear conditions over Israel and the surrounding regions in 2006 on a  $0.5^\circ \times 0.5^\circ$  grid. The inset shows the corresponding scatter plot with the Israeli grid cells marked in light blue. For comparison to a nearby industrialized region, we also plotted the Cairo grid cells, in red. In winter (DJF 2006), when  $\text{NO}_2$  lifetimes are longest and  $\text{NO}_2$  columns largest, we see in Fig. 6a that SCIAMACHY tends to observe similar or lower  $\text{NO}_2$  amounts at 10:00 than OMI at 13:45 h over the  $\text{NO}_x$  source regions of Israel and Cairo. The geometrical mean ratios are  $<1.0$  for both Israel and Cairo as indicated by the solid light blue and red  
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lines in the inset. In summer, with shorter chemical lifetimes and smaller  $\text{NO}_2$  columns than in winter, we see the reverse effect in Fig. 6c with 10:00–13:45 ratios of 1.29 over Israel and 1.16 over Cairo. Spring and autumn show diurnal variations in between the winter and summer extremes. Table 3 summarizes the mean 10:00–13:45 ratios for all seasons.

To evaluate this apparent seasonal cycle in the diurnal cycle, we compare ratios of  $\text{NO}_2$  at 10:00 and 13:45 observed from satellites and from surface stations. We do not require spatial or temporal coincidence between satellite and surface measurements (as we did before), but only that both techniques measured under mostly-clear situations. The left panel of Fig. 7 shows significant 10:00–13:45 decreases in both satellite and surface-based observations over Israel in summer, and no decrease, or even a slight increase, in winter months. This is consistent with simulations from the 3-D chemistry-transport model GEOS-Chem (Bey et al., 2001) for the same location and time, as shown in the right panel of Fig. 7. In summer, GEOS-Chem simulates up to 21% higher  $\text{NO}_2$  columns at 10:00, compared to smaller differences in winter. That the GEOS-Chem summertime ratios are smaller than observed by the two measurement techniques, is explained by the spatial extent of the GEOS-Chem grid cell ( $2^\circ \times 2.5^\circ$ ). The GEOS-Chem grid cell covers not only the region of Israel where  $\text{NO}_x$  sources are strong, but also a large part of the Mediterranean Sea where these sources are weak. To bridge the gap between the simulation and the higher-resolution observations, we sampled the satellite measurements according to the boundaries of the GEOS-Chem grid cell. The seasonal cycle in the diurnal cycle observed at  $2^\circ \times 2.5^\circ$  (solid red curve) agrees much better with the GEOS-Chem simulations than the high-resolution curve ( $2^\circ \times 1^\circ$ , dashed line).

The diurnal variation of tropospheric  $\text{NO}_2$  columns depends on the diurnal cycle of  $\text{NO}_x$  emissions and chemical loss (see Eq. 3 in Boersma et al., 2008a). Over urban areas,  $\text{NO}_x$  emissions show a daytime maximum that mainly reflects intense vehicle use between early morning and late afternoon. This pattern is very similar for all seasons. In absence of strong seasonal changes in background  $\text{NO}_x$ , the seasonal variation in

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the diurnal cycle of tropospheric NO<sub>2</sub> columns can therefore be understood mainly in terms of seasonally varying photochemistry.

Figure 8 shows a GEOS-Chem simulation over Israel of the diurnal variation in the NO<sub>2</sub> column and in the chemical loss rate constant  $k$  for a winter and a summer month in cloud-free conditions.  $k$  includes the chemical loss of NO<sub>x</sub> to HNO<sub>3</sub> through the gas-phase reaction of NO<sub>2</sub> with OH and the hydrolysis of N<sub>2</sub>O<sub>5</sub> in aerosols. The GEOS-Chem model incorporating diurnally varying NO<sub>x</sub> emissions and photochemistry simulates up to 5× higher values and a much more pronounced diurnal cycle for  $k$  in August than in February 2006. In winter, the absence of a daytime maximum in NO<sub>x</sub> loss is expected to lead to an increase of NO<sub>x</sub> over the course of the day, because emissions are higher in the day than at night. The seasonal differences in  $k$  are consistent with higher OH concentrations in summer reflecting higher water vapour concentrations and more UV flux in that season (Spivakovsky et al., 2000). It is this strong daytime change in  $k$  (OH) in summer that is responsible for the distinct decrease in the NO<sub>2</sub> columns between 10:00 and 13:45 in summer. In winter, the chemical loss rate constant is generally too small throughout the day (low OH) to yield a net chemical loss, implying that NO<sub>x</sub> emissions may offset chemical loss during the daylight hours in that season. It is this mechanism that likely explains the observed wintertime 10:00–13:45 increases (expressed as ratios <1.0) in Fig. 7.

## 5 Conclusions

We showed that NO<sub>2</sub> concentration data from urban monitoring networks can provide useful validation for NO<sub>2</sub> column measurements from space. Previous validations of satellite retrievals relied primarily on profile measurements from aircraft, but these do not sample the lowest part of the atmosphere, where most of the NO<sub>2</sub> resides and strong gradients exist, and provide little statistics needed to overcome difficulties in vertical extrapolation and horizontal representativity. Ground-based measurements on the other hand sample NO<sub>2</sub> close to the source and offer the benefit of large, continu-

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ous datasets.

Our validation focused on urban locations in Israel in 2006. In situ measurements (10:00 and 13:45 h) of NO<sub>2</sub> concentrations show significant correlation with collocated SCIAMACHY and OMI tropospheric NO<sub>2</sub> column retrievals. We converted surface concentrations into columns representative for the boundary layer (BL) by assuming a well-mixed BL, and a climatology of observed Israeli BL depths. Afternoon surface NO<sub>2</sub> has been corrected for potential interference from oxidized nitrogen compounds (NO<sub>x</sub>). This correction leads to 5–15% smaller NO<sub>2</sub> concentrations. The collocated 13:45 h BL and OMI NO<sub>2</sub> columns are in agreement ( $r=0.64$ ,  $n=542$ , slope= $0.93\pm 0.07$ ). A similar agreement is apparent in 10:00 h BL and SCIAMACHY NO<sub>2</sub> columns, provided they were collocated within 0.1°.

The observed seasonal cycles in ground-based measurements and OMI NO<sub>2</sub> are consistent. BL and OMI NO<sub>2</sub> columns are 1.6–2.7× higher in winter than in summer, reflecting the strong seasonal variation in photochemistry and NO<sub>2</sub> lifetime. OMI observes a strong weekly cycle with approximately 50% smaller NO<sub>2</sub> columns on the Saturdays relative to the weekday mean. Ground-based techniques observe 46% lower NO<sub>2</sub> on Saturdays, similar as from space.

Outside the winter season, collocated satellite and ground-based measurements show higher NO<sub>2</sub> columns at 10:00 than at 13:45. In summer, the diurnal variation is strongest, with 10:00–13:45 ratios up to 1.4. In winter, the observed ratios are close to 1.0, and there is often a (small) increase in tropospheric NO<sub>2</sub> between mid-morning and early afternoon. Simulations with the global 3-D chemical transport model GEOS-Chem are consistent with the observed seasonal variation in the 10:00 vs. 13:45 difference. The simulations suggest that the high summertime and low wintertime ratios can be understood from a much stronger photochemical sink from oxidation by OH in summer than in winter. In winter, the photochemical sink is sufficiently small that continuous NO<sub>x</sub> emissions may offset chemical loss during the daylight hours, explaining the observed 10:00–13:45 increase in NO<sub>2</sub>.

The quality of the satellite retrievals at the urban scales shown here provides some

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confidence in top-down constraints on  $\text{NO}_x$  emissions from the satellite data. But retrievals should be improved by using forward model parameters (surface albedo's, a priori profile shapes, and surface pressures) from data bases with horizontal resolutions similar to the satellite footprints. Aerosols contribute to retrieval uncertainty because they affect retrieved cloud fractions, and this complex interaction should be investigated further in order to reduce retrieval errors.

*Acknowledgements.* This work was funded by the NASA Atmospheric Composition Modeling and Analysis Program. The OMI project is managed by NIVR and KNMI in The Netherlands. The ground level data was provided by the Israel Ministry of Environmental Protection. Yinon Rudich acknowledges support by the Helen and Martin Kimmel Award for Innovative Investigation.

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**Table 1.** Summary of the comparison between surface NO<sub>2</sub> concentrations and OMI tropospheric NO<sub>2</sub> columns<sup>1</sup> at 8 Israeli cities in 2006.

Station	Lat. (°N)	Lon. (°E)	<i>r</i>	<i>n</i>	slope (molecules cm <sup>-2</sup> /ppb)	intercept (molecules cm <sup>-2</sup> )
Carmiel	32.93	35.30	0.52	97	1.33±0.29	-2.62±0.59
Haifa	32.82	34.99	0.65	137	0.30±0.03	-2.23±0.42
Afula	32.65	35.20	0.13	59	0.60±2.75	-0.09±0.82
Modiin	31.92	34.99	0.65	106	1.06±0.11	-1.11±0.91
Rehovot	31.90	34.80	0.77	100	1.13±0.13	0.26±0.60
Ashdod	31.80	34.65	0.54	105	0.59±0.11	-3.21±0.87
Beit Shemesh	31.25	34.75	0.47	96	0.84±0.24	-2.30±0.50
Beer Sheva	31.38	35.01	0.76	84	1.26±0.16	-2.52±0.76

<sup>1</sup> OMI tropospheric NO<sub>2</sub> columns (v1.02) had a pixel center within ±0.1° latitude/longitude of the station location, and were measured under mostly-clear situations (cloud radiance fraction <50%). Only OMI observations with viewing zenith angles <35° were selected, ensuring that the satellite and surface observations coincide within 15 min. The OMI pixel centers were on average within 8 km of the station locations.

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**Table 2.** Summary of the comparison between surface NO<sub>2</sub> concentrations and SCIAMACHY tropospheric NO<sub>2</sub> columns<sup>1</sup> at 8 Israeli cities in 2006.

Station	<i>r</i>	<i>n</i>	slope (molecules cm <sup>-2</sup> /ppb)	intercept (molecules cm <sup>-2</sup> )
Carmiel	0.69	38	1.34±0.11	-2.43±0.92
Haifa	0.43	28	0.45±0.21	-4.31±1.57
Afula	0.34	19	0.60±0.60	-0.88± 1.09
Modiin	0.36	48	0.94±0.44	0.09±1.12
Rehovot	0.54	41	0.70±0.18	-0.32±0.96
Ashdod	0.61	43	0.67±0.14	-5.08±1.88
Beit Shemesh	0.49	21	1.29±0.54	-2.38±1.47
Beer Sheva	0.72	12	0.41±0.08	0.43±0.64

<sup>1</sup> Comparison between uncorrected surface NO<sub>2</sub> concentrations and SCIAMACHY tropospheric NO<sub>2</sub> (v1.1) columns for 8 Israeli stations. We selected SCIAMACHY columns with a pixel center within ±0.25° latitude/longitude of the stations, measured under mostly-clear situations. The center location of the SCIAMACHY pixels (*n*=176) was on average within 20 km of the station location.

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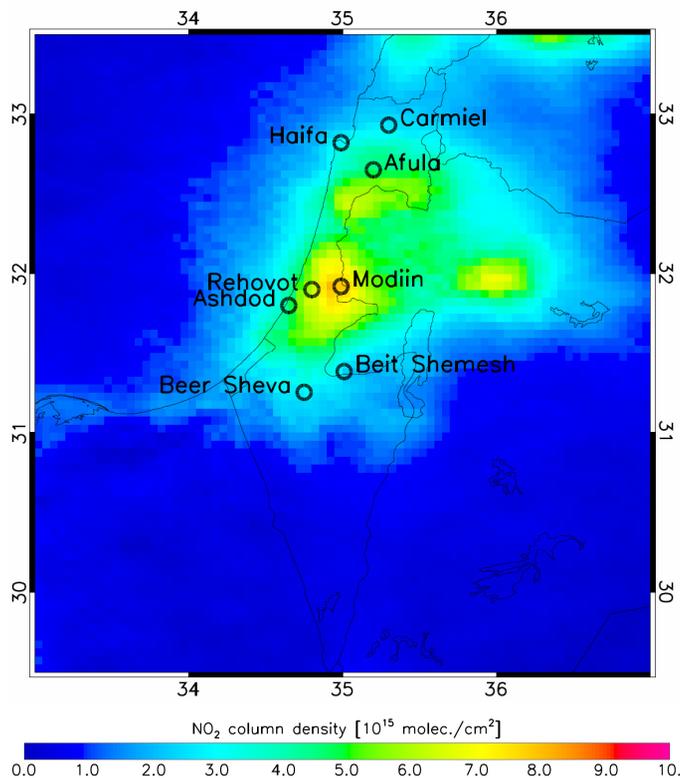
**Table 3.** The 10:00–13:45 ratios<sup>1</sup> of tropospheric NO<sub>2</sub> columns for source regions in the Middle East.

Region	Corner coordinates	winter	spring	summer	autumn
Israel	31.0–33.0°N, 34.5–35.5°E	0.77	1.00	1.29	0.88
Cairo	29.0–30.5°N, 30.5–32.0°E	0.91	1.16	1.16	1.12

<sup>1</sup> Ratios calculated as geometrical means shown in Fig. 6a–d.[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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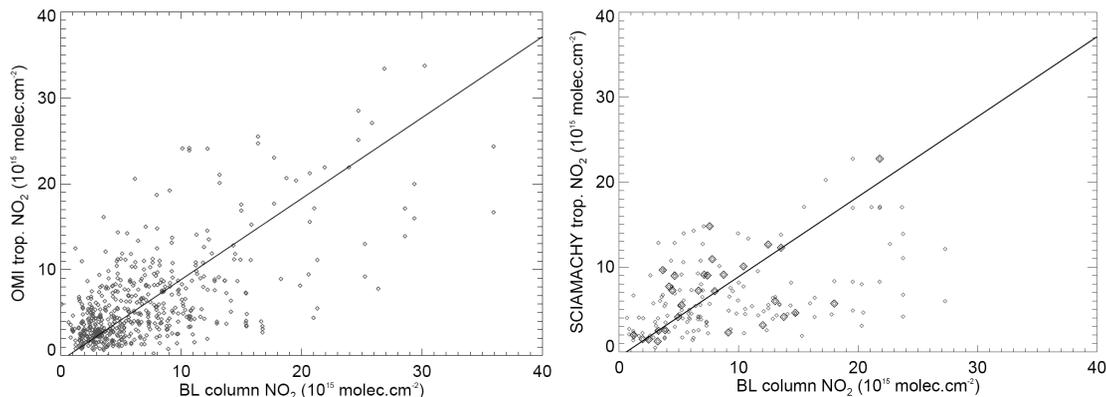


**Fig. 1.** Annual mean tropospheric NO<sub>2</sub> column in 2006 from OMI (DOMINO v1.02) for mostly-clear situations (cloud radiance fraction <50%). The circles indicate the location of surface stations.

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**Fig. 2.** Left panel: OMI tropospheric versus interference-corrected boundary layer NO<sub>2</sub> columns (10<sup>15</sup> molecules cm<sup>-2</sup>) at 13:30–14:00 h at 6 Israeli stations. The solid line indicates the result of a RMA regression ( $r=0.63$ , slope=0.93). OMI measurements have been taken under mostly clear conditions (cloud radiance fraction <50%) and with pixel centres within 0.1° of the stations. Right panel: same, but now for SCIAMACHY and boundary layer NO<sub>2</sub> columns at 10:00 h. The solid line indicates the RMA regression to SCIAMACHY (cloud radiance fraction <50%) observations within 0.1° of the stations, indicated by the larger diamonds ( $r=0.54$ , slope=0.94). The smaller diamonds indicate coincidences where SCIAMACHY pixel centers were within 0.25° of the stations.

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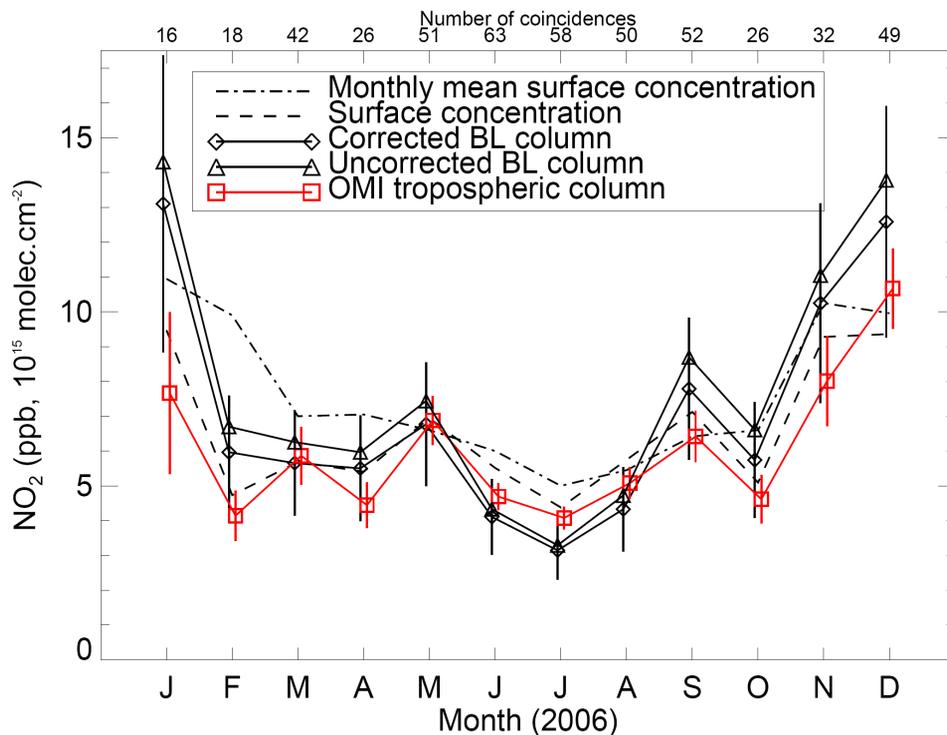
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**Fig. 3.** Seasonal variation of NO<sub>2</sub> (2006) observed in Israeli cities. The dashed-dotted line indicates the monthly mean near-surface NO<sub>2</sub> concentration for all conditions (including cloudy). The dashed line indicates the subset for mostly-clear satellite-coincidences only (cloud radiance fractions <50%). The solid black lines indicate the boundary layer NO<sub>2</sub> columns inferred from the surface concentrations with (diamonds) and without (triangles) interference correction. OMI tropospheric NO<sub>2</sub> columns in red. The error bars represent the standard deviation of the mean values. The numbers in the upper x-axis refer to the number of cloud-free coincidences found in each month.

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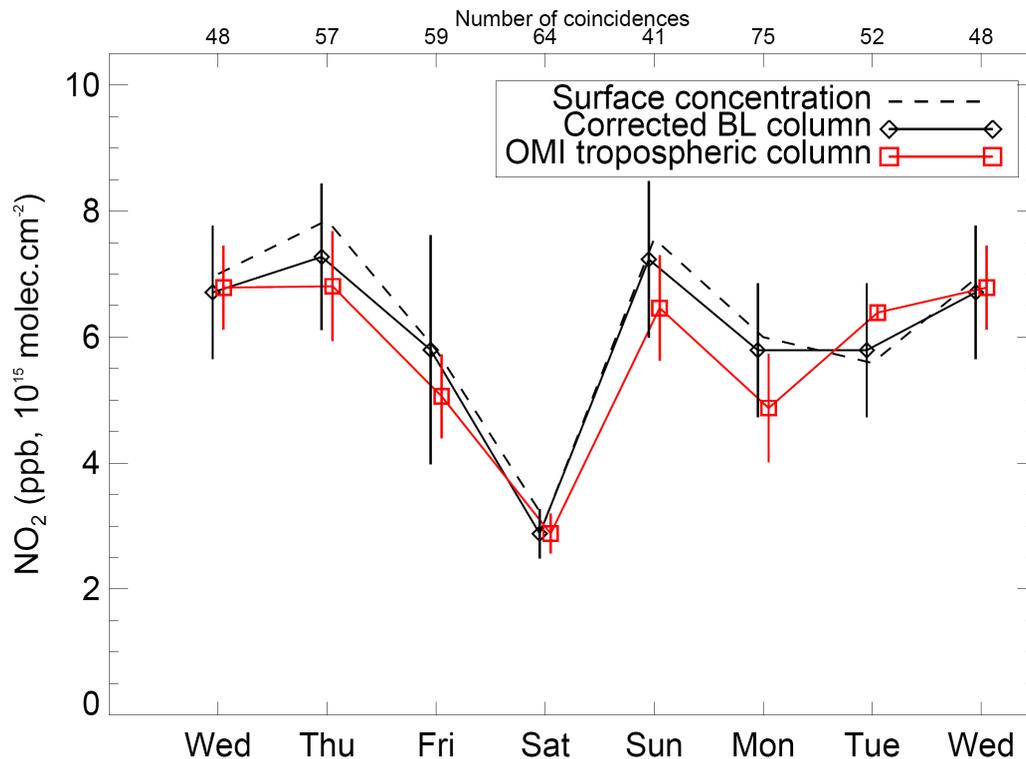
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**Fig. 4.** Weekly variation of NO<sub>2</sub> over Israeli cities, March–November 2006. The dashed line indicates the mean NO<sub>2</sub> observed near-surface, the black diamonds represent interference-corrected surface measurements, and OMI observations are in red squares. All curves for the Israeli stations of Beer Sheva, Beit Shemesh, Carmiel, Rehovot, and Modiin. Winter measurements have been excluded to avoid sampling biases (some weekdays had no winter measurements). The numbers in the upper x-axis refer to the number of cloud-free coincidences found for each day.

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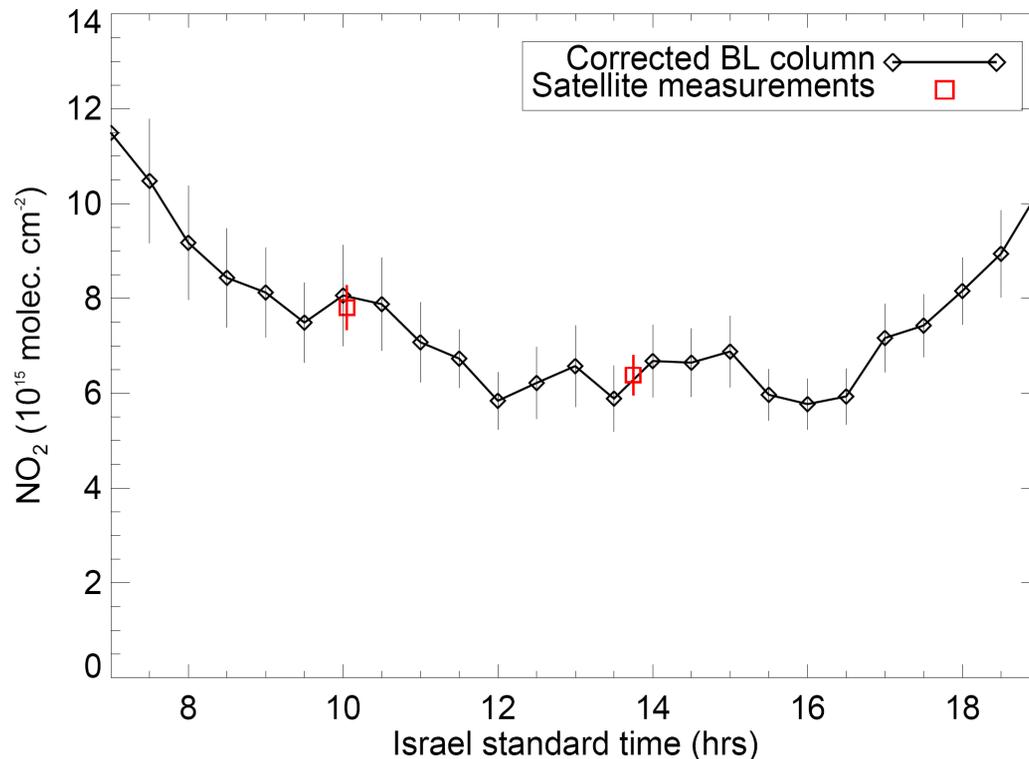
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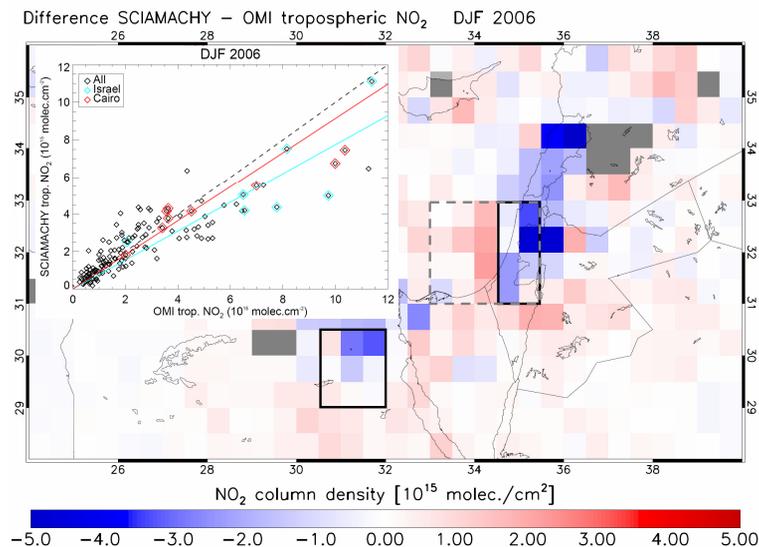


**Fig. 5.** Diurnal variation of NO<sub>2</sub> in Israeli cities in March–November 2006. The black diamonds indicate the mean ( $n=35$ ) boundary layer NO<sub>2</sub> columns observed with 30-min intervals, with coincident and collocated SCIAMACHY and OMI NO<sub>2</sub> columns in red. All columns have been observed on the same cloud-free days at the locations of Israeli surface stations. The pixel centre latitudes and longitudes were required to be within 0.1° (OMI), 0.25° (SCIAMACHY) of the station locations.

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**Fig. 6a.** Absolute difference between SCIAMACHY and OMI tropospheric NO<sub>2</sub> columns over the Middle East in winter 2006. Red colors indicate higher retrievals from SCIAMACHY than from OMI, and vice versa for blue colors. The measurements have been taken under mostly clear conditions. The inset shows the corresponding scatter plot. The light blue diamonds indicate the grid cells over Israel, and the red ones over the greater Cairo region. The dashed line in the inset represents  $y=x$ . The solid light blue and red lines illustrate the corresponding geometrical mean SCIAMACHY:OMI ratio over Israel and Cairo. Both regions are enclosed by the black rectangles in the map. The region enclosed by the grey dashed rectangle represents the spatial extent of the GEOS-Chem grid cell over Israel.

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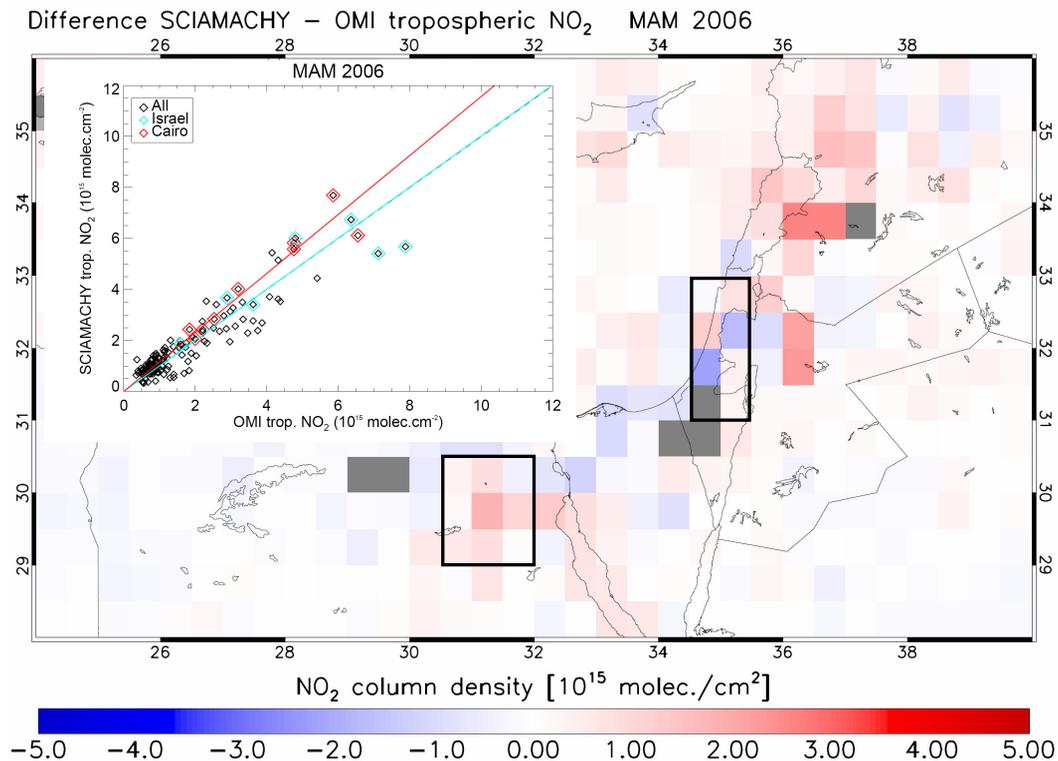
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**Fig. 6b.** Same as Fig. 6a, but now for spring (March, April, May) 2006.

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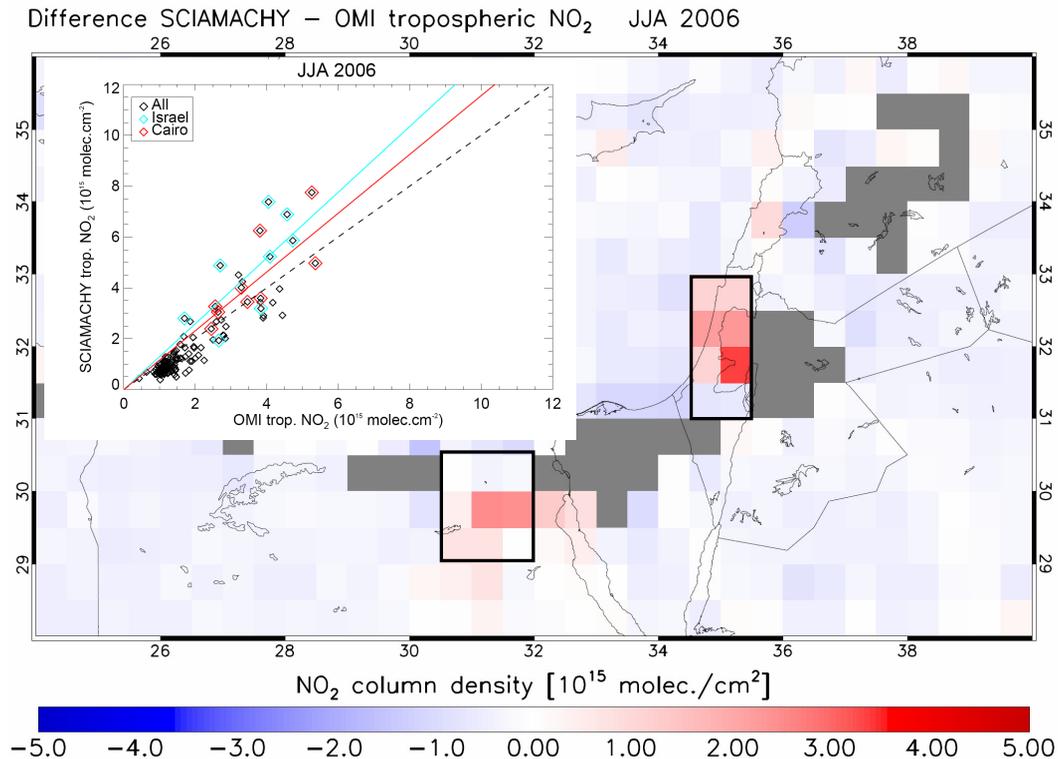
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**Fig. 6c.** Same as Fig. 6a, but now for summer (June, July, August) 2006.

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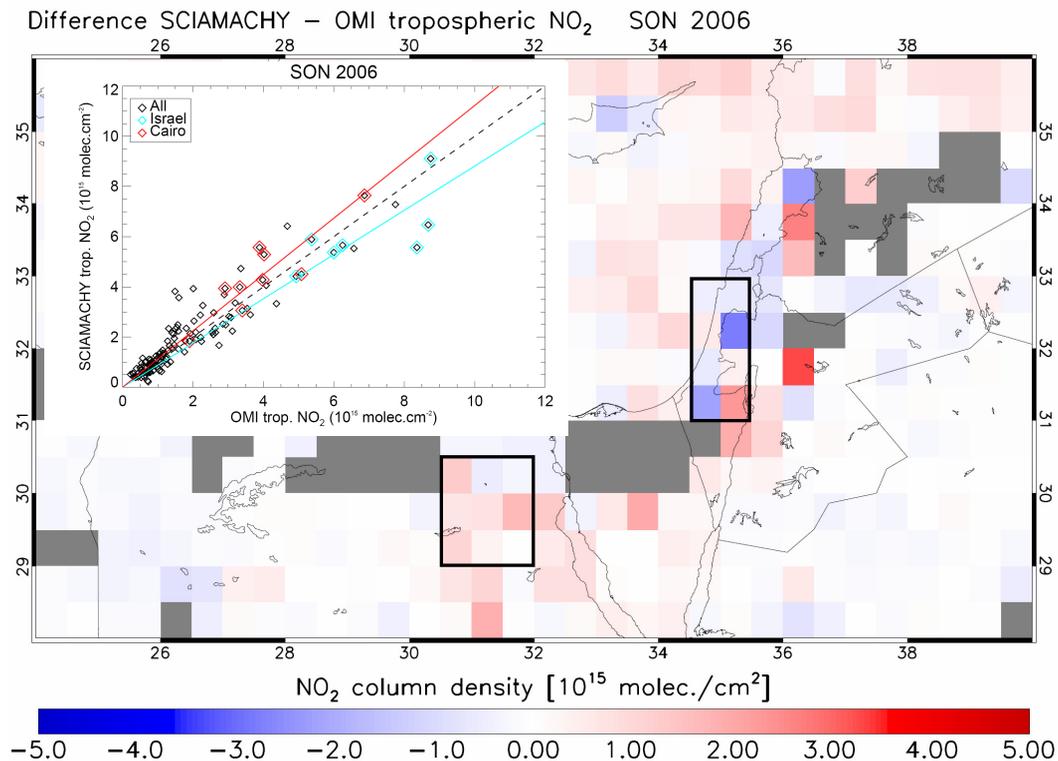
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**Fig. 6d.** Same as Fig. 6a, but now for autumn (September, October, November) 2006.

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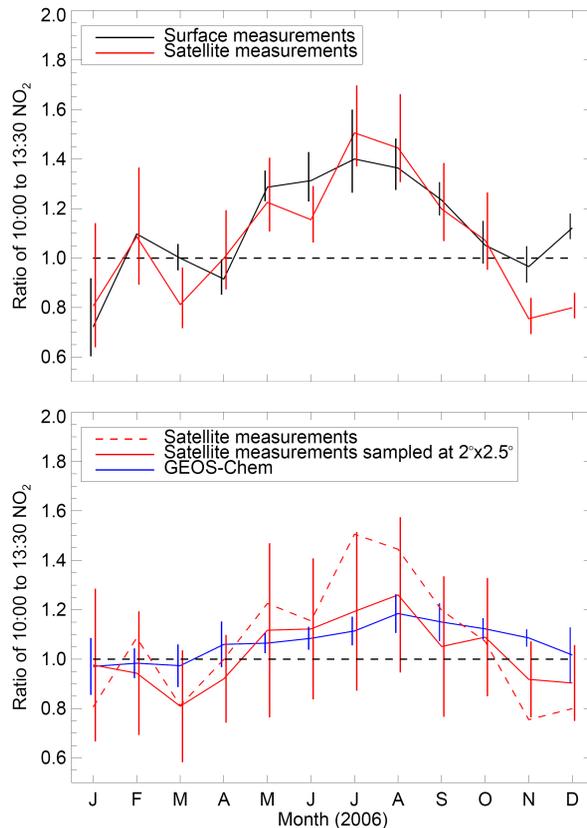
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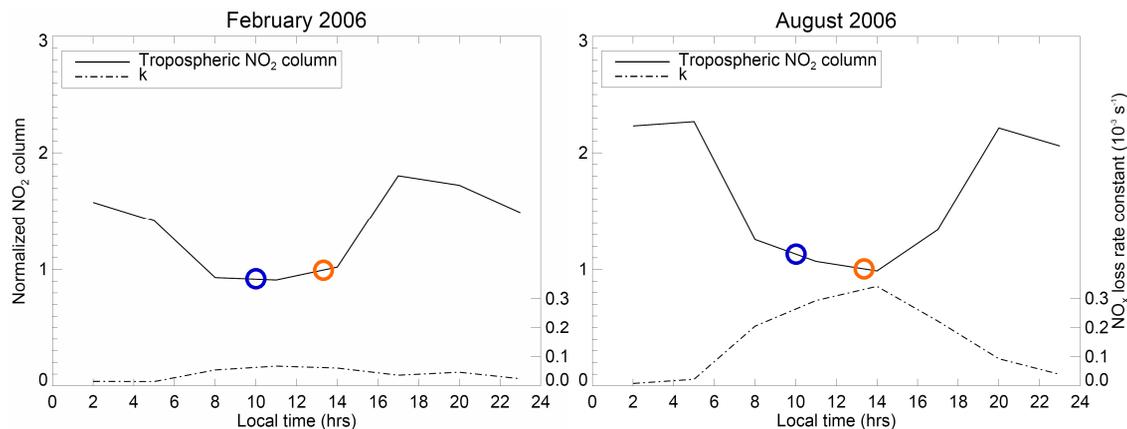


**Fig. 7.** Seasonal cycle in the diurnal cycle of tropospheric NO<sub>2</sub> columns. Upper panel: cycle over the Israel source region from surface measurements (black line), and from SCIAMACHY and OMI measurements (red line). Lower panel: cycle over the 2°×2.5° area of the GEOS-Chem grid cell from satellite measurements (solid red line) and from the GEOS-Chem model sampled at 10:00 and 13:30 h (solid blue line).

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**Fig. 8.** Diurnal cycle in tropospheric NO<sub>2</sub> columns (solid line) and NO<sub>x</sub> chemical loss rate constant *k* (dashed line) over Israel, simulated by GEOS-Chem for mostly-clear conditions in February 2006 (left panel), and August 2006 (right panel). The open circles indicate the value of the simulated tropospheric NO<sub>2</sub> column at the SCIAMACHY (blue) and OMI (orange) overpass times.

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