



Underestimation of column NO₂ amounts from the OMI satellite compared to diurnally varying ground-based retrievals from multiple PANDORA spectrometer instruments

Jay Herman¹, Nader Abuhassan¹, Jhoon Kim², Jae Kim³, Manvendra Dubey⁴, Marcelo Raponi⁵, and Maria Tzortziou⁶

¹University of Maryland Baltimore County JCET, Baltimore, MD, USA

²Department of Atmospheric Sciences, Yonsei National University, Seoul, South Korea

³Department of Atmospheric Science, Pusan National University, Busan, South Korea

⁴Earth Systems Observations, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

⁵Departamento de Investigaciones en Láseres y Aplicaciones (DEILAP), Instituto de Investigaciones Científicas y Técnicas para la Defensa (CITEDEF), Ministerio de Defensa (MINDEF), Buenos Aires, Argentina

⁶City College of New York, New York City, NY, USA

Correspondence: Jay Herman (jay.r.herman@nasa.gov)

Received: 1 April 2019 – Discussion started: 14 May 2019

Revised: 20 August 2019 – Accepted: 11 September 2019 – Published: 23 October 2019

Abstract. Retrievals of total column NO₂ (TCNO₂) are compared for 14 sites from the Ozone Measuring Instrument (OMI using OMNO2-NASA v3.1) on the AURA satellite and from multiple ground-based PANDORA spectrometer instruments making direct-sun measurements. While OMI accurately provides the daily global distribution of retrieved TCNO₂, OMI almost always underestimates the local amount of TCNO₂ by 50 % to 100 % in polluted areas, while occasionally the daily OMI value exceeds that measured by PANDORA at very clean sites. Compared to local ground-based or aircraft measurements, OMI cannot resolve spatially variable TCNO₂ pollution within a city or urban areas, which makes it less suitable for air quality assessments related to human health. In addition to systematic underestimates in polluted areas, OMI's selected 13:30 Equator crossing time polar orbit causes it to miss the frequently much higher values of TCNO₂ that occur before or after the OMI overpass time. Six discussed Northern Hemisphere PANDORA sites have multi-year data records (Busan, Seoul, Washington DC, Waterflow, New Mexico, Boulder, Colorado, and Mauna Loa), and one site in the Southern Hemisphere (Buenos Aires, Argentina). The first four of these sites and Buenos Aires frequently have high TCNO₂ (TCNO₂ > 0.5 DU). Eight additional sites have shorter-term data records in the US and South Korea. One of these is a

1-year data record from a highly polluted site at City College in New York City with pollution levels comparable to Seoul, South Korea. OMI-estimated air mass factor, surface reflectivity, and the OMI 24 km × 13 km FOV (field of view) are three factors that can cause OMI to underestimate TCNO₂. Because of the local inhomogeneity of NO_x emissions, the large OMI FOV is the most likely factor for consistent underestimates when comparing OMI TCNO₂ to retrievals from the small PANDORA effective FOV (measured in m²) calculated from the solar diameter of 0.5°.

1 Introduction

Retrieval of total column NO₂ (TCNO₂) from the Ozone Monitoring Instrument (OMI) has been a scientific success story for the past 14 years. Near-total global coverage from the well-calibrated OMI has enabled observation of all the regions where NO₂ is produced and has permitted monitoring of the changes during the 2004 to 2019 period, especially in regions where there is heavy and growing industrial activity (e.g., China and India). TCNO₂ amounts (data used: OMNO2-NASA v3.1) retrieved from OMI over various specified land locations show a strong local underestimate compared to co-located PANDORA spectrometer in-

struments (the abbreviation PAN is used for graph and table labels). The underestimate of OMI TCNO₂ at the overpass time compared to ground-based measurements has previously been reported at a few specific locations (Bechle, 2013; Lamsal et al., 2014; Ialongo et al., 2016; Kollonige et al., 2018; Goldberg et al., 2019; Herman et al., 2018). The accuracy and precision of PANDORA TCNO₂ measurements have been previously discussed (Herman et al., 2009, 2018). For any location, the OMI overpass local standard time consists of the central overpass near the 13:30 Equator crossing solar time and occasionally a side-viewing overpass from adjacent orbits within ± 90 min of the central overpass time. Independently of instrument calibration and retrieval errors, there are two specific aspects to the underestimation of TCNO₂ pollution levels. Because of OMI's selected polar orbit, it is not possible for the midday OMI observations to see the large diurnal variation of TCNO₂ that usually occur after the 13:30 overpass time, and second, because of spatial inhomogeneity the large OMI field of view (FOV) footprint $13 \text{ km} \times 13 \text{ km}$ at OMI nadir view tends to average regions of high NO₂ amounts (Nowlan et al., 2016; Judd et al., 2018) with those from lower pollution areas. An analysis by Judd et al. (2019, their Fig. 9) shows the effect of decreasing satellite spatial resolution on improving agreement with PANDORA, with the best agreement occurring with an airborne instrument, GEO-TASO (resolution $3 \text{ km} \times 3 \text{ km}$), followed by TropOMI ($5 \text{ km} \times 5 \text{ km}$) and then OMI ($18 \text{ km} \times 18 \text{ km}$). Both OMI and TropOMI show an underestimate of TCNO₂ compared to PANDORA.

There are other possible systematic retrieval errors with OMI TCNO₂. The largest of these is determining the air mass factor (AMF) needed to convert slant column measurements into vertical column amounts followed by the surface reflectivity R_S (Boersma et al., 2011; Lin et al., 2015; Nowlan et al., 2016; Lorente et al., 2018). Accurately determining the AMF for TCNO₂ requires a priori knowledge of the NO₂ profile shape (Krotkov et al., 2017), which is estimated from coarse-resolution model calculations (Boersma et al., 2011) and using the correct R_S . Currently R_S is found using a statistical process of sorting through years of data to find relatively clear-sky scenes for each location (Kleipool et al., 2008; O'Byrne et al., 2010). Boersma et al. (2004) gave a detailed error analysis for the various components contributing OMI TCNO₂ retrievals, resulting in an estimated "retrieval precision of 35 %–60 %" in heavily polluted areas dominated by determining the AMF. An improved V2.0 DOMINO retrieval (Boersma et al., 2011) algorithm reduced the retrieval errors while increasing the estimated air mass factor, which reduces the retrieved TCNO₂ by up to 20 % in winter and 10 % in summer. The current versions of OMNO2-NASA (Krotkov et al., 2017) and v2.0 DOMINO (Boersma et al., 2011) are generally in good agreement (Marchenko et al., 2015; Zara et al., 2018). However, the OMNO2-NASA TCNO₂ retrievals are 10 % to 15 % lower than the v2.0 DOMINO retrievals and with Quality

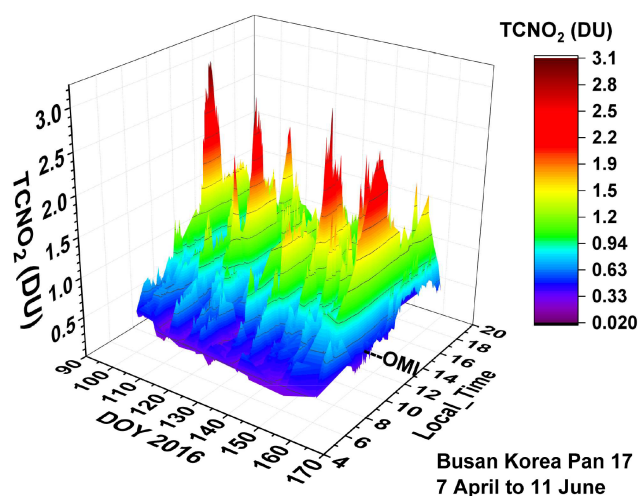


Figure 1. Diurnal variation of TCNO₂ measured at Pusan University in Busan, South Korea.

Assurance for Essential Climate Variables (QA4ECV) retrievals. A subsequent detailed analysis of surface reflectivity (Vasilkov et al., 2017) shows that retrieval of TCNO₂ in highly polluted areas (e.g., some areas in China) can increase by 50 % with the use of geometry-dependent reflectivities but only increase about 5 % in less polluted areas. For PANDORA, calculation of the solar-viewing AMF is a simple geometric problem (AMF is approximately proportional to the cosecant of the solar zenith angle SZA) and is independent of R_S (Herman et al., 2009). For a highly polluted region with TCNO₂ = 5.34×10^{16} molecules cm^{-2} or 2 DU, the PANDORA error is expected to be less than 2 ± 0.05 DU (± 2.5 %), with the largest uncertainty coming from an assumed nominal amount of stratospheric TCNO₂ = 0.1 DU.

Accurate satellite TCNO₂ retrievals (and for other trace gases) are important in the estimate of the effect of polluted air containing NO₂ on human health (Kim and Song, 2017, and references therein), especially from the viewpoint of NO₂ as a respiratory irritant and precursor to cancer (Choudhari et al., 2013). Since NO₂ is largely produced by combustion, satellite observations of NO₂ serve as a proxy for changing industrial activity. Another important application requiring accurate measurements of the amount of TCNO₂ and its diurnal variation is atmospheric NO₂ contribution to nitrification of coastal waters (Tzortziou et al., 2018).

We show that the use of OMI TCNO₂ for estimating local air quality and coastal nitrification on a global basis is misleading for most polluted locations, and especially on days when the morning or afternoon amounts are higher than those occurring at the OMI overpass time near 13:30 standard time. OMI TCNO₂ data are extremely useful for estimating regional pollution amounts and for assessing long-term changes in these amounts. Modeling studies (Lamsal et al., 2017, Fig. 1) based on the Global Modelling Initiative model (Strahan et al., 2007) simulating TCNO₂ diurnal

variation over Maryland, USA (37–40° N, 74–79° W), show a late afternoon peak and show that the stratospheric component does not substantially contribute to this peak. Boersma et al. (2016) show that sampling strategy can cause systematic errors between OMI TCNO₂ and model TCNO₂, with satellite results being up to 20 % lower than models. Duncan et al. (2014) review the applicability of satellite TCNO₂ data to represent air quality and note that TCNO₂ correlates well with surface levels of NO₂ in industrial regions, and state that the portion of TCNO₂ in the boundary layer could be over 75 % of the total vertical column, depending on the NO₂ altitude profile shape.

This paper presents 14 different site comparisons between retrieved OMI TCNO₂ overpass values that are co-located with PANDORA TCNO₂ amounts from various locations in the world. Six of the comparisons are where PANDORA has long-term data (1-year or longer) records. The comparisons are done using 80 s cadence data matched to the OMI overpass times averaged over ± 6 min and with monthly running averages calculated using a lowess (*f*) locally weighted least squares fit to a fraction *f* of the data points (Cleveland, 1981) of OMI-PANDORA time matched TCNO₂. OMI overpass data, <https://avdc.gsfc.nasa.gov/index.php?site=666843934&id=13> (last access: 15 October 2019), are filtered for the row anomaly and cloudy pixels. The selection of a ± 6 min window represents 720 s or nine PANDORA measurements averaged together around the OMI overpass time to reduce the effect of outlier points. The specific value of ± 6 min is arbitrary but increases the already high effective signal-to-noise ratio by a factor of 3. PANDORA data are filtered for significant cloud cover by examining the effective variance in sub-interval (20 s) measurements. Each PANDORA-listed measurement is the average of up to 4000 (clear-sky) individual measurements made over 20 s.

This paper gives a discussion and presentation of data on the effects of diurnal variation that are always missed at the local OMI midday overpass times. We show that OMI TCNO₂ values are also systematically lower than PANDORA values at sites with significant pollution (TCNO₂ > 0.3 DU). We present a unique view of a year of fully time resolved diurnal variation of TCNO₂ at two sites, Washington DC and New York City, which are similar to other polluted locations.

2 Brief instrument descriptions

For the purposes of TCNO₂ retrievals, both OMI and PANDORA are spectrometer-based instruments using nearly the same spectral range and similar spectral resolution (about 0.5 nm). Both use spectral fitting retrieval algorithms that differ (Boersma et al., 2011; Herman et al., 2009) because of the differences between direct-sun viewing retrievals (PANDORA) and above the atmosphere downward-viewing re-

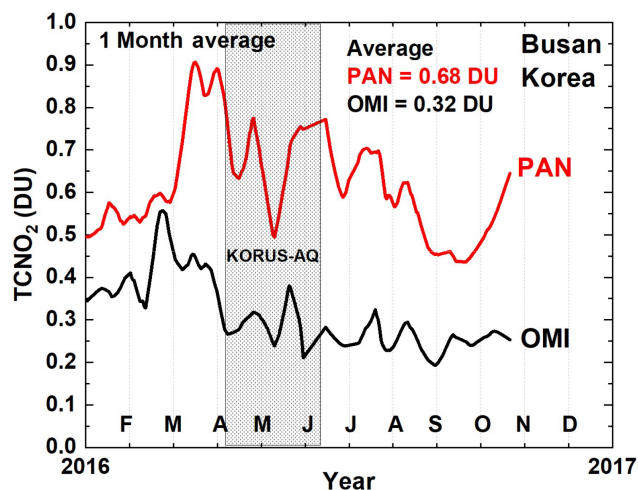


Figure 2. Monthly average values of TCNO₂ for OMI and PANDORA at OMI overpass times.

trievals (OMI). The biggest difference is with the respective fields of view, 13 km × 13 km at OMI nadir view and larger off-nadir FOV compared to the much smaller PANDORA FOV (1.2°) measured in m² with the precise value depending on the NO₂ profile shape and the solar zenith angle. For example, if most of the TCNO₂ is located below 2 km, then the PANDORA FOV is approximately given by $(1.2\pi/180)(2/\cos(\text{SZA}))$, which for SZA = 45° is about 59 m × 59 m. If the solar disk (0.5°) is used as the limiting factor, then the effective FOV is smaller (25 m × 25 m).

2.1 OMI

OMI is an east–west side (2600 km) and nadir-viewing polar-orbiting imaging spectrometer that measures the earth's backscattered and reflected radiation in the range 270 to 500 nm with a spectral resolution of 0.5 nm. The polar-orbiting side-viewing capabilities produce a pole-to-pole swath that is about 2600 km wide displaced in longitude every 90 min by the earth's rotation to provide coverage of nearly the entire sunlit Earth once per day at a 13:30 solar hour Equator crossing time with spatial gaps at low latitudes. OMI provides full global coverage every 2 to 3 d. Additional gaps are caused by a problem with the OMI CCD “row anomaly” (Torres et al., 2018) that effectively reduces the number of near-nadir overpass views. A detailed OMI instrument description is given in Levelt et al. (2006). TCNO₂ is determined in the visible spectral range from 405 to 465 nm where the NO₂ absorption spectrum has the maximum spectral structure and where there is little interference from other trace gas species (there is a weak water feature in this range). OMI TCNO₂ overpass data are available for many ground sites (currently 719) from the following NASA website: <https://avdc.gsfc.nasa.gov/index.php?site=666843934&id=13> (last access: 16 July 2019).

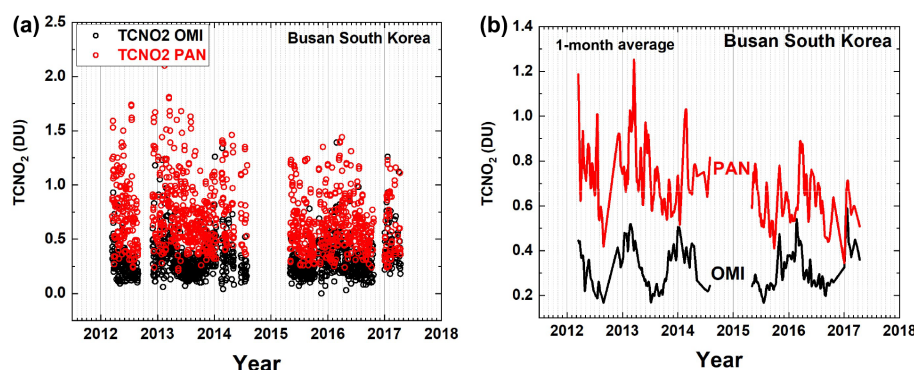


Figure 3. Extended time series for Busan. (a) Individual matching PANDORA and OMI data points for the overpass time ± 6 min. (b) Monthly averages.

2.2 PANDORA

PANDORA is a sun-viewing instrument for $\text{SZA} < 80^\circ$ that obtains about 4000 spectra for clear-sky views of the sun in 20 s for each of two ranges, UV (290–380 nm using a UV340 bandpass filter) and visible plus UV (280–525 nm using no filter). The overall measurement time is about 80 s, including 20 s dark-current measurements between each spectral measurement throughout the day. About 4000 clear-sky spectra for the UV and visible portions are separately averaged together to achieve very high signal-to-noise ratios (SNRs). The UV340 filter for the UV portion of the spectra reduces stray light effects from the visible wavelength range. A detailed description of PANDORA and its SNR is given in Herman et al. (2009, 2015). The effect of moderate cloud cover (reduction of the observed signal by a factor of 8) in the PANDORA FOV on TCNO₂ retrievals is small (Herman et al., 2018). Cloud cover also reduces the number of measurements possible in 20 s, which potentially increases the noise level. PANDORA is driven by a highly accurate sun tracker that points an optical head at the sun and transmits the received light to an Avantes 2048 \times 32 pixel CCD spectrometer (AvaSpec-ULS2048 from 280 to 525 nm with 0.6 nm resolution) through a 50 μm diameter fiber optic cable. The estimated TCNO₂ error is approximately 0.05 DU ($1 \text{ DU} = 2.69 \times 10^{16} \text{ molecules cm}^{-2}$) out of a typical value of 0.3 DU in relatively clean areas and over 3 DU in highly polluted areas. PANDORA data are available for 250 sites. Some sites have multi-year data sets, but many of these sites are short-term campaign sites (https://avdc.gsfc.nasa.gov/pub/DSCOVER/Pandora/DATA_01/, last access: 16 July 2019).

2.3 Overpass comparisons and diurnal variation of TCNO₂

The contribution of NO₂ to air quality at the earth's surface is usually a proportional function of TCNO₂ that varies with the time of day and with the altitude profile shape (Lamsal

et al., 2013; Bechle et al., 2013). Most of the NO₂ amount is usually located between 0 and 3 km altitude with a small amount of about $0.1 \pm 0.05 \text{ DU}$ (Dirksen et al., 2011) in the upper troposphere and stratosphere. Because of the relatively short chemical lifetime, 3–4 h (Liu et al., 2016), in the lower atmosphere, most of the NO₂ is located near (0 to 20 km) its sources (industrial activity, power generation, and automobile traffic). At higher altitudes or in the winter months, the lifetime of NO₂ is longer, permitting transport over larger distances from its sources.

During the South Korean campaign (KORUS-AQ) in the spring of 2016 the diurnal variations of TCNO₂ vs. days of the year DOY were determined for six sites (Herman et al., 2018), one of which is reproduced here (Fig. 1) for the city of Busan, showing relatively low values of TCNO₂ in the morning (0.5 DU), moderately high values during the middle of the day (1.3 DU), and very high values on some of the afternoons (2 to 3 DU). Of these data, OMI only observes midday values near the 13:30 time marked on the Local_Time axis of Fig. 1, thereby missing very high values (2 to 3 DU) that frequently occur later in the afternoon coinciding with times when people are outdoors returning from work.

In addition to not being designed to observe the TCNO₂ diurnal variation, the OMI values are about half those observed by PANDORA (Fig. 2) at the OMI overpass time, so that using OMI values to estimate NO₂ pollution seriously underestimates the air quality problem even at midday. The shaded area in Fig. 2 corresponds to the period covered in the KORUS-AQ campaign of 7 April to 11 June 2016 shown in Fig. 1. An extended time series for the Busan location is shown in Fig. 3.

Because of the different effective NO₂ FOV of PANDORA (measured in m^2) while tracking the moving sun position located in the heart of Busan (FOV distance $d < 5 \text{ km}$ for an $\text{SZA} < 70^\circ$ used for TCNO₂ retrievals), both the daily (Fig. 3a) and PANDORA monthly average variations (Fig. 3b), obtained at the OMI overpass time, differ from the variation in the OMI TCNO₂ caused by the much larger OMI

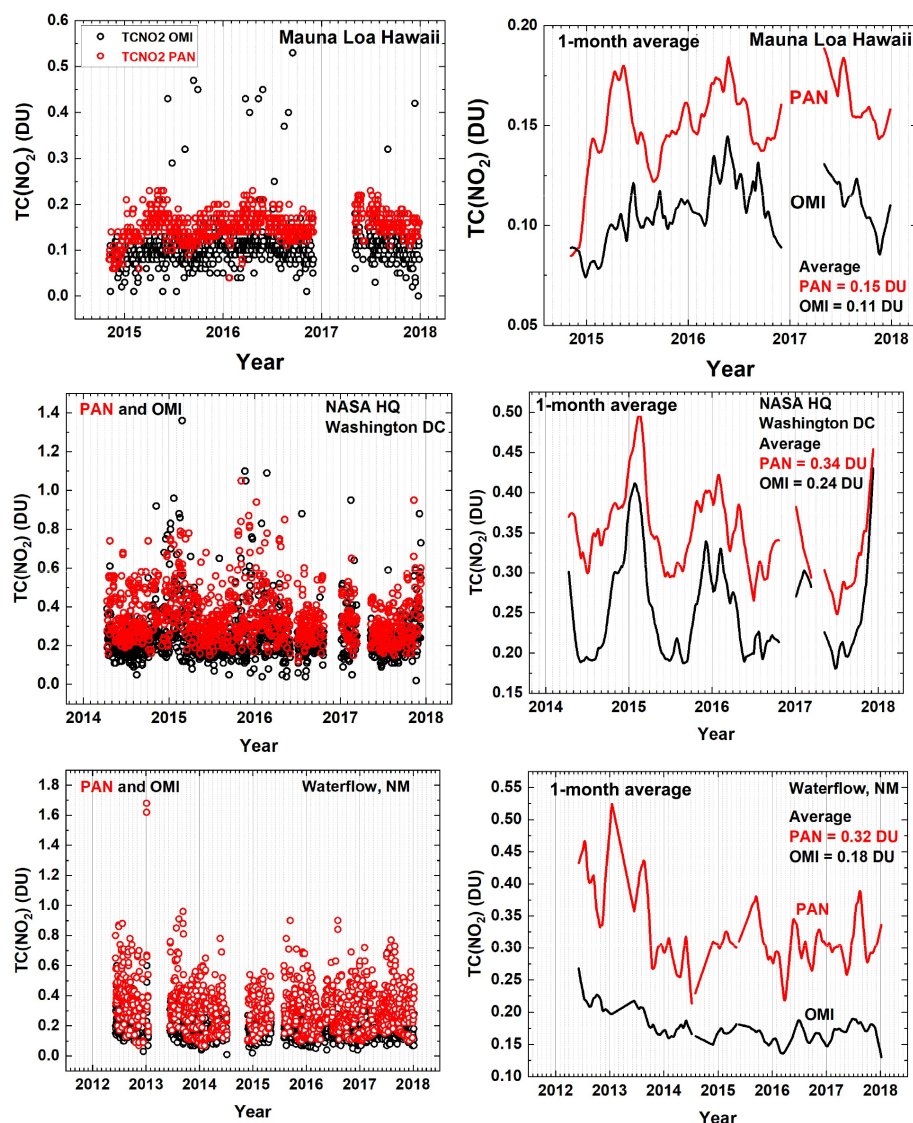


Figure 4. PANDORA compared to OMI. Extended TCNO₂ overpass time series for Mauna Loa Observatory, Hawaii, NASA Headquarters, Washington DC, and Waterflow, New Mexico.

FOV (13 km × 13 km at OMI nadir view) retrieval. Because of this, the OMI time series has low correlation ($r^2 = 0.1$) with the PANDORA time series.

The extended OMI vs. PANDORA time series from 2012 to 2017 for Busan (Fig. 3) shows the same magnitude of differences seen during the KORUS-AQ period. A similar OMI vs. PANDORA plot for total column ozone TCO₃ (Appendix Fig. A1) shows good agreement between PANDORA and OMI, indicating that the PANDORA instrument was operating and tracking the sun properly. Because the spatial variability of TCO₃, which is mostly in the stratosphere, is much less than for TCNO₂, the effect of different FOVs is minimized for ozone.

The same type of differences, TCNO₂(PAN) > TCNO₂(OMI), are seen at a wide vari-

ety of sites (e.g., see Figs. 4 and 5) for Northern Hemisphere sites and one site in the Southern Hemisphere where PANDORA has an extended time series. Comparing extended Busan multi-year time series, some broad-scale correlation can be seen with peaks in February 2013, in January 2014, and in 2016. The OMI data from Busan are different than data from many sites, since Busan is located very near the ocean, causing a portion of the OMI FOV to be over the relatively unpolluted ocean areas, whereas PANDORA is located inland (Pusan University) in an area of dense automobile traffic and quite near mountains capable of trapping air.

Figures 4 and 5 show a variety of different sites, ranging from the Mauna Loa Observatory location at 3.4 km (11 161 feet) on a relatively clean Hawaiian island surrounded by

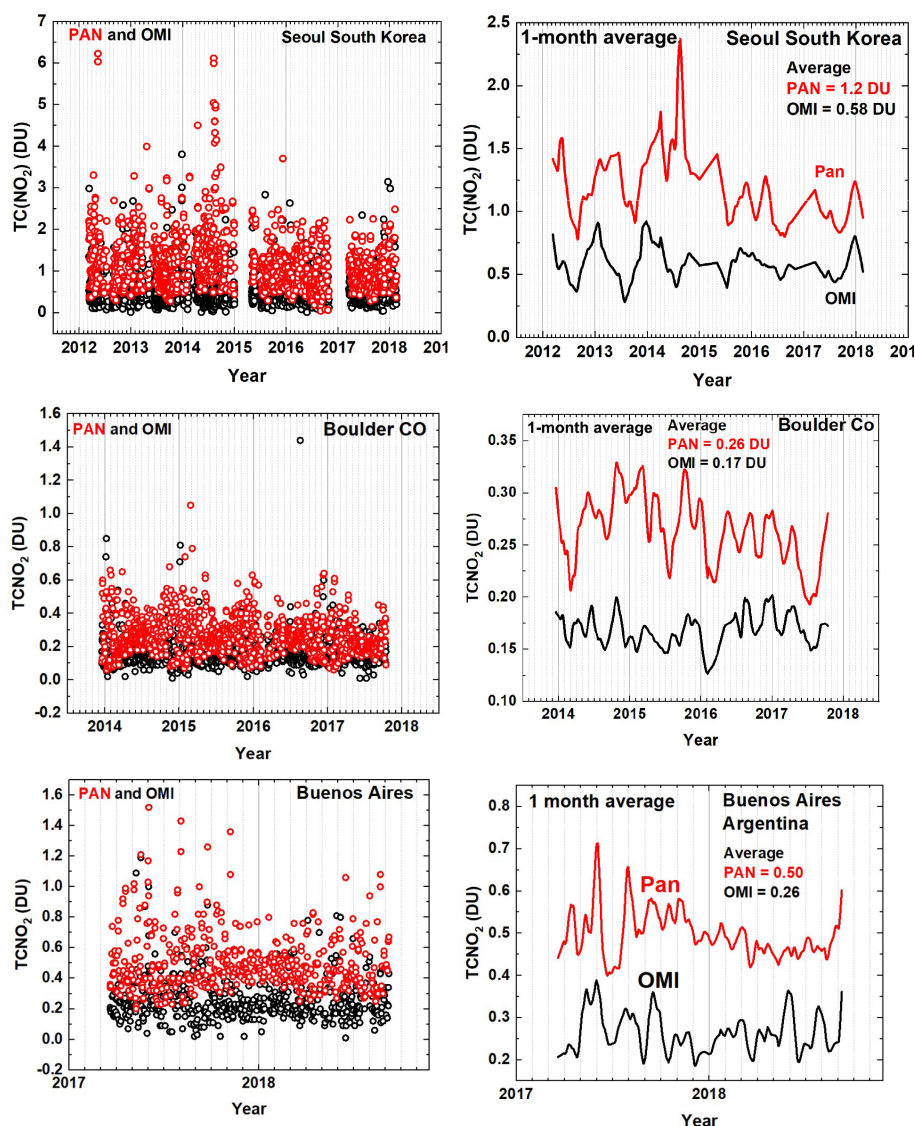


Figure 5. PANDORA compared to OMI. Extended TCNO₂ overpass time series for Seoul, South Korea, Boulder, Colorado, and Buenos Aires, Argentina (Raponi et al., 2018).

ocean to a polluted landlocked semi-arid site at Waterflow, New Mexico, near a power plant. All the sites considered show a significant underestimate of OMI TCNO₂. A summary of the monthly average underestimates is given in Tables 1 and 2. For some sites there is evident correlation between the two offset measurements. For example, the PANDORA at NASA Headquarters in Washington DC tracks the OMI measurement quite well on a monthly average basis, with a correlation coefficient of r^2 (mn) = 0.7, even though the daily correlation is low (r^2 (d) = 0.17). Other sites have only short periods of correlation and overall weak correlation (Table 1 showing daily, d, and monthly, mn, correlation coefficients for the graphs in Figs. 4 and 5).

TCNO₂(PAN) comparisons with TCNO₂(OMI) from Mauna Loa Observatory MLO (Fig. 4) are not those that

might be expected, since the PANDORA observations are in an area where there are almost no automobile emissions and certainly no power plants, yet PAN > OMI and TCNO₂(PAN) values are large enough so that the pollution values (0.18 DU) are well above the stratospheric values (approximately 0.1 DU). OMI, which mainly measures values over the clean ocean, has an average value of about 0.1 DU (see Appendix Fig. A2). Since there are no emission or combustion sources of NO₂ at high altitudes near MLO at 3.4 km, the PANDORA values suggest upward airflow from the near-sea-level circumferential ring road, Keahole oil power plant, and resort areas. The Mauna Loa TCNO₂ values do not show any correlation with the recent increased volcanic activity at Mt. Kilauea after 2016. A graph showing the midday values of TCNO₂ at MLO is given in the Appendix. Recently, the

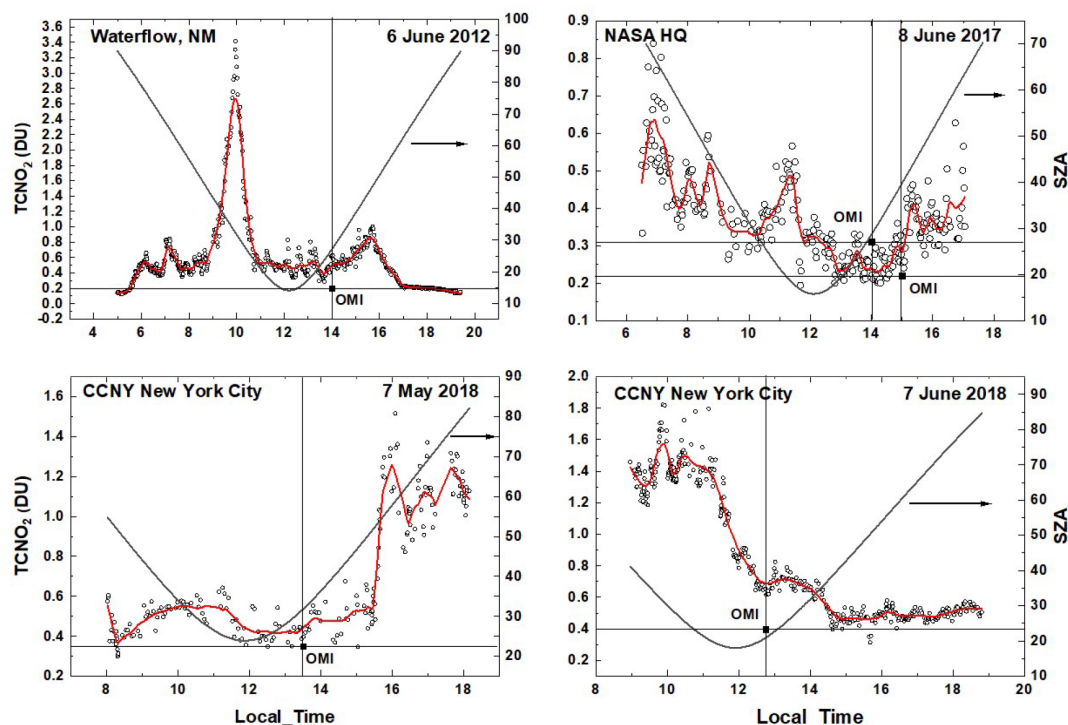


Figure 6. Diurnal variation of TCNO₂ on a single day (1) 2 km north of Waterflow, NM, near a power plant, (2) on the roof of NASA Headquarters in Washington DC, and (3) on the roof of a building at CCNY City College of New York, New York City.

original Mauna Loa PANDORA was replaced. The new instrument's calibration will be reviewed before being added to the time series as part of a general data quality assurance program that starts with the most recently deployed or upgraded PANDORA instruments at about 100 locations.

An interesting inland site is near the very small town of Waterflow, New Mexico (Figs. 4 and 6), where two power plants located near the PANDORA site ceased operation on 30 December 2013 (Lindenmaier et al., 2014). According to a quote from AZCentral Newspaper (Tuesday 31 December 2013), “Three coal-fired generators that opened in the 1960s near Farmington, N.M., closed Monday as part of a \$182 million plan for Arizona Public Service Co. to meet environmental regulations, the utility reported”. The TCNO₂ data suggest that the actual shutdown occurred near 15 October 2013. After the shutdown, air quality improved in the area, with TCNO₂ decreasing from 0.4 to 0.28 DU. The remaining more efficient generators continued to produce smaller NO₂ emissions. These were shut down at the end of 2016 with little additional observed change in TCNO₂, since these boilers used NO₂ scrubbers (Mavendra Dubey, personal communication, 2018; Fenton, 2015). A nearby highway (Route 64) about 2 km from the PANDORA site has little automobile traffic. An example of the diurnal behavior of TCNO₂ at Waterflow, New Mexico, on 6 June 2012 is shown in Fig. 6 to illustrate the behavior of PANDORA TCNO₂ retrievals at a wide range of SZAs. The terrain surrounding

the Waterflow PANDORA site is flat, with no obstructions (buildings) permitting observations to very high SZAs. Almost every day the power plant briefly puts out very high emissions of NO₂ as part of its daily boiler cleaning cycle. This can be seen in the very high peak value of TCNO₂ of 3.4 DU compared to the nominal value of 0.5 DU occurring for most of the day. The value from the FOV-averaged OMI retrieval at 21:01 GMT (14:01 local standard time) is about 0.2 DU compared to the PANDORA value of about 0.5 DU. Figure 6 also illustrates TCNO₂ diurnal behavior at two other sites, NASA HQ in Washington DC and City College of New York, and compares the values to the OMI-retrieved TCNO₂.

Both Figs. 6 and 2A show the PANDORA TCNO₂ retrieval with the values of the SZA plotted on the same graph showing that the direct-sun retrievals are good out to SZA = 70°. Depending on atmospheric conditions, retrievals using Beer's law absorption attenuation and spectral fitting for SZA > 75° begin to yield non-physical values (TCNO₂ too small). During midday measurements, the signal-to-noise ratio is very high since over 4000 clear-sky measurements are averaged together to produce one data point every 20 s. Even with aerosol loading (no spectral features) or moderate cloud cover blocking the sun, the retrievals are still accurate (Herman et al., 2018).

Table 2 contains a summary of some sites that were part of short-term Discover-AQ campaigns in Maryland, Texas, California, and Colorado, two longer-term sites in South Korea,

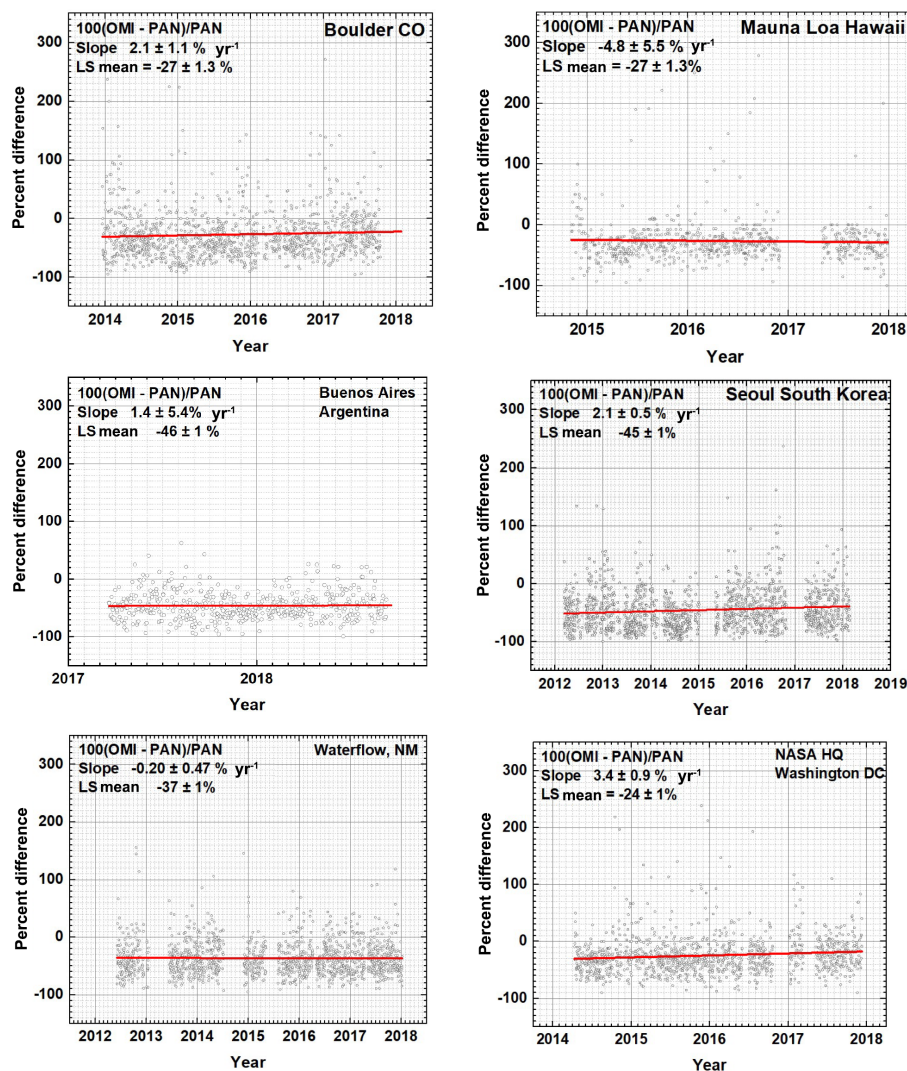


Figure 7. Percent differences between OMI and PANDORA. The slopes are the absolute change in the percent difference. For example, the Boulder percent difference goes from -31% to -23% over 4 years. The LS means are least squares means with the corresponding error estimates.

Table 1. Values of TCNO₂ for PANDORA and OMI from monthly averages in Figs. 4 and 5.

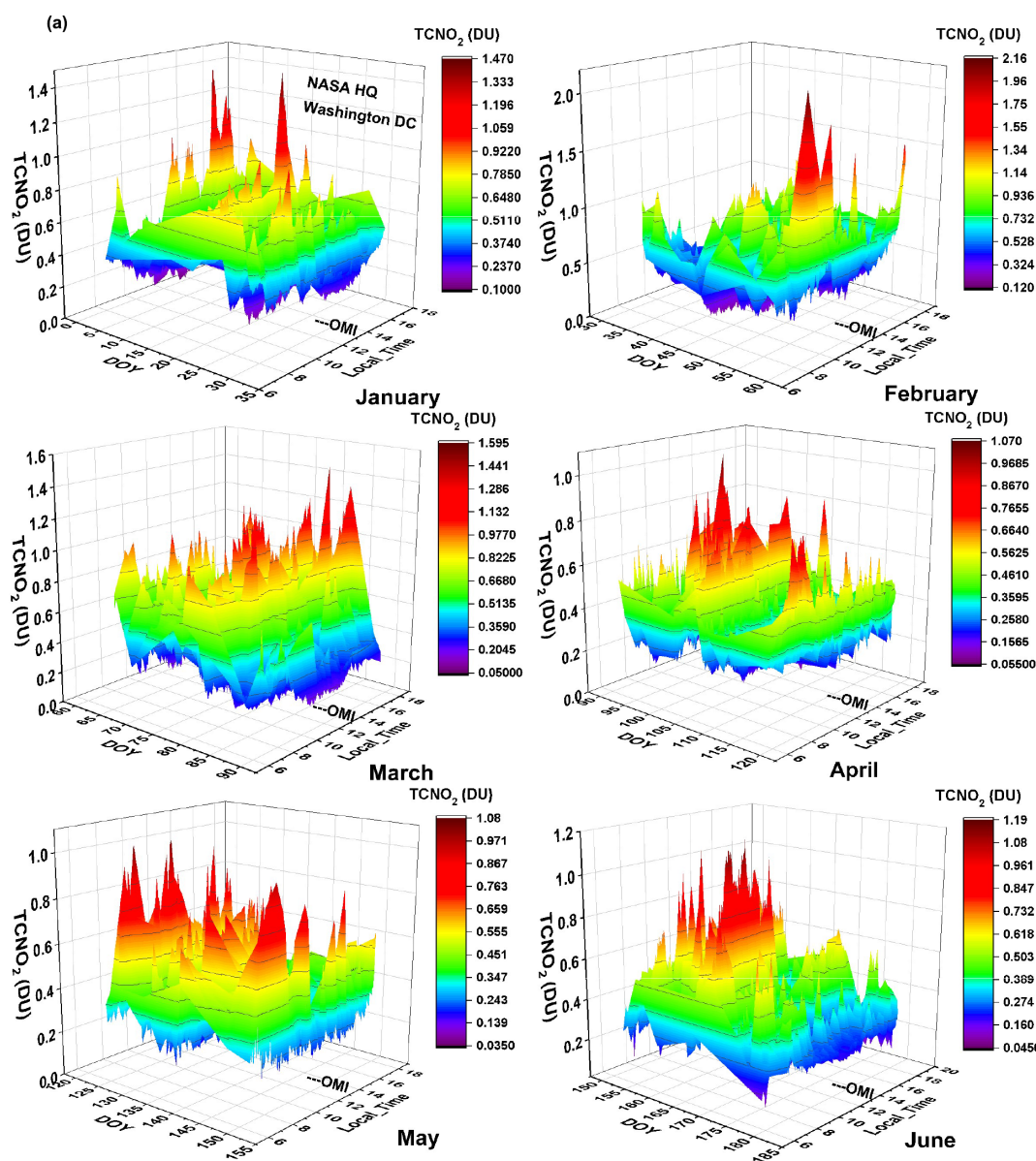
Name	Location (lat, long)	PAN (DU)	OMI (DU)	r^2 (d, mn)
Mauna Loa, Hawaii	$19.536^\circ, -155.5762^\circ$	0.16	0.11	0.01, 0.30
NASA HQ, Washington DC	$38.882^\circ, -77.01^\circ$	0.34	0.25	0.17, 0.70
Waterflow, New Mexico*	$36.797^\circ, -108.48^\circ$	0.32	0.18	0.13, 0.52
Seoul, South Korea	$37.5644^\circ, 126.934^\circ$	1.2	0.58	0.11, 0.06
Busan, South Korea	$35.2353^\circ, 129.0825^\circ$	0.68	0.32	0.09, 0.10
Boulder, Colorado	$39.9909^\circ, -105.2607^\circ$	0.27	0.17	0.04, 0.09
Buenos Aires, Argentina	$-34.5554^\circ, -58.5062^\circ$	0.50	0.26	0.16, 0.08
Average		0.49	0.27	

* Waterflow, NM, is listed for OMI data as Four Corners, NM, a nearby landmark.

Table 2. Average values of TCNO₂ for PANDORA and OMI for additional sites.

Name	Location (lat, long)	PAN (DU)	OMI (DU)
Essex, Maryland	39.31083°, −76.47444°	0.30	0.28
Baltimore, Maryland	39.29149°, −76.59646°	0.45	0.27
Fresno, California	36.7854°, −119.7731°	0.42	0.17
Denver La Casa, Colorado	39.778°, −105.006°	0.68	0.19
GIST ^a	35.226°, 126.843°	0.42	0.20
HUFS ^b	37.338°, 127.265°	0.61	0.51
City College, New York City	40.8153°, −73.9505°	0.60	0.40
Average		0.50	0.29

^a Gwangju Institute of Science and Technology, South Korea. ^b Hankuk University of Foreign Studies, South Korea.

**Figure 8.**

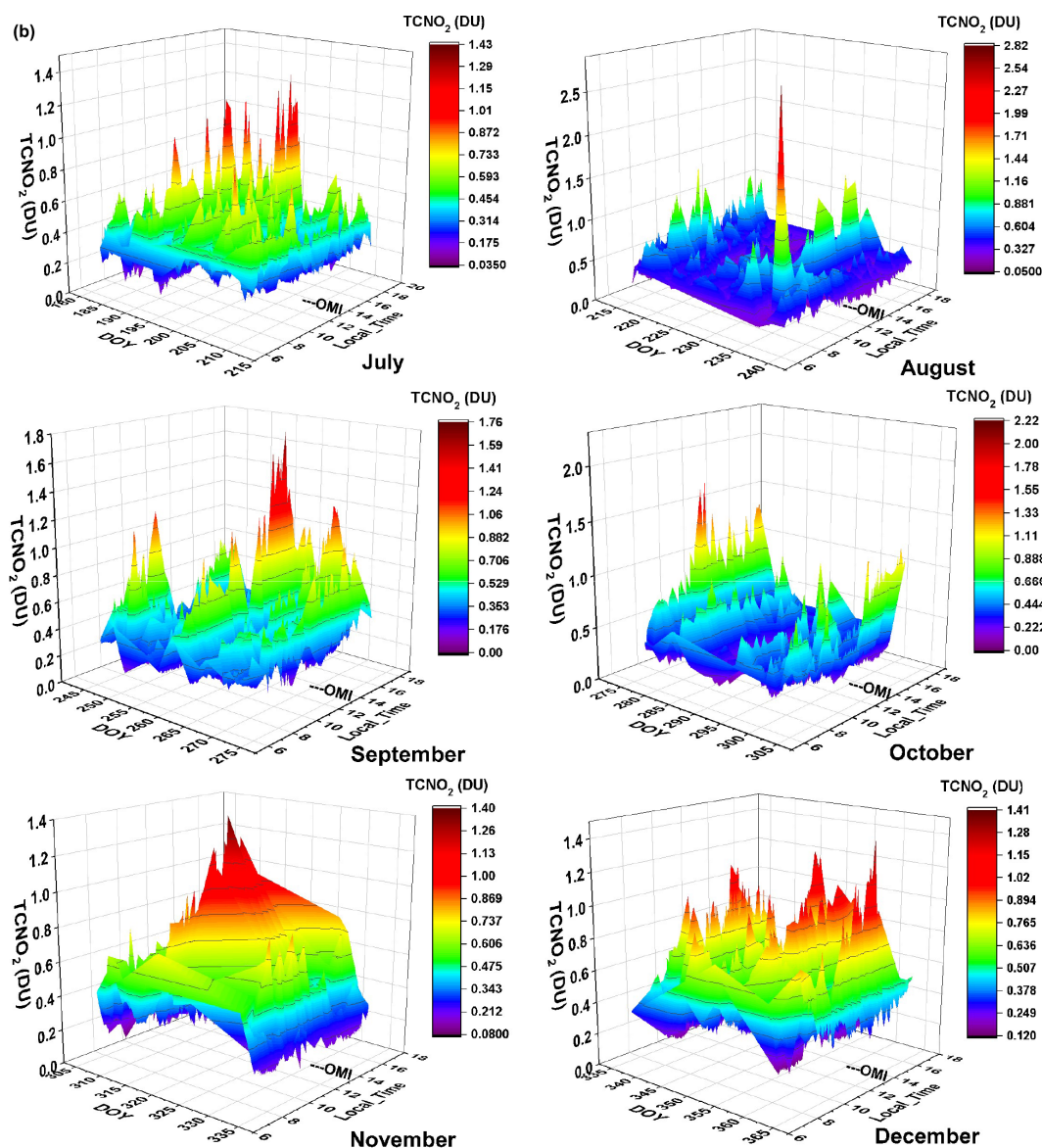


Figure 8. (a) TCNO₂ diurnal variation (DU) from January to June, NASA Headquarters, Washington DC, from January to June 2015. The approximate OMI overpass time near 13:30 is marked. (b) TCNO₂ diurnal variation (DU) from July to December, NASA Headquarters, Washington DC, from July to December 2015. The approximate OMI overpass time near 13:30 is marked.

and one in New York City. Essex, Maryland, is located on the Chesapeake Bay 10 km east of the center of Baltimore. The site is relatively clean ($PAN = 0.3$ DU) compared to the center of Baltimore ($PAN = 0.45$ DU), while OMI measures about the same amounts for both sites (0.28 and 0.27 DU) because the OMI FOV is larger than the distance between the two sites. The Houston, Texas, site contains 7 months of data from January to July 2013, with widespread NO₂ pollution permitting PANDORA and OMI to measure the same average values even though PANDORA observes episodes on many days when TCNO₂ exceeds 1.5 DU for short periods at times not observed by OMI. Observations in the small city of Fresno, California, were during January when

agricultural sources of NO₂ were at a minimum (Almaraz, 2018), but automobile traffic in the center of Fresno was significant. In this situation, PANDORA recorded the effect of automobile traffic, while OMI averaged the city of Fresno and surrounding fallow agricultural areas. The Denver La Casa location is in the center of the city in an area with high amounts of local automobile traffic and near the Cherokee power-generating plant. The result is a high level of average pollution (0.42 DU), while OMI measures both the city center and the surrounding relatively clean plains areas. The HUFs South Korean site is southeast of Seoul in a fairly isolated valley. However, Seoul and its surrounding areas are a widespread transported source of pollution

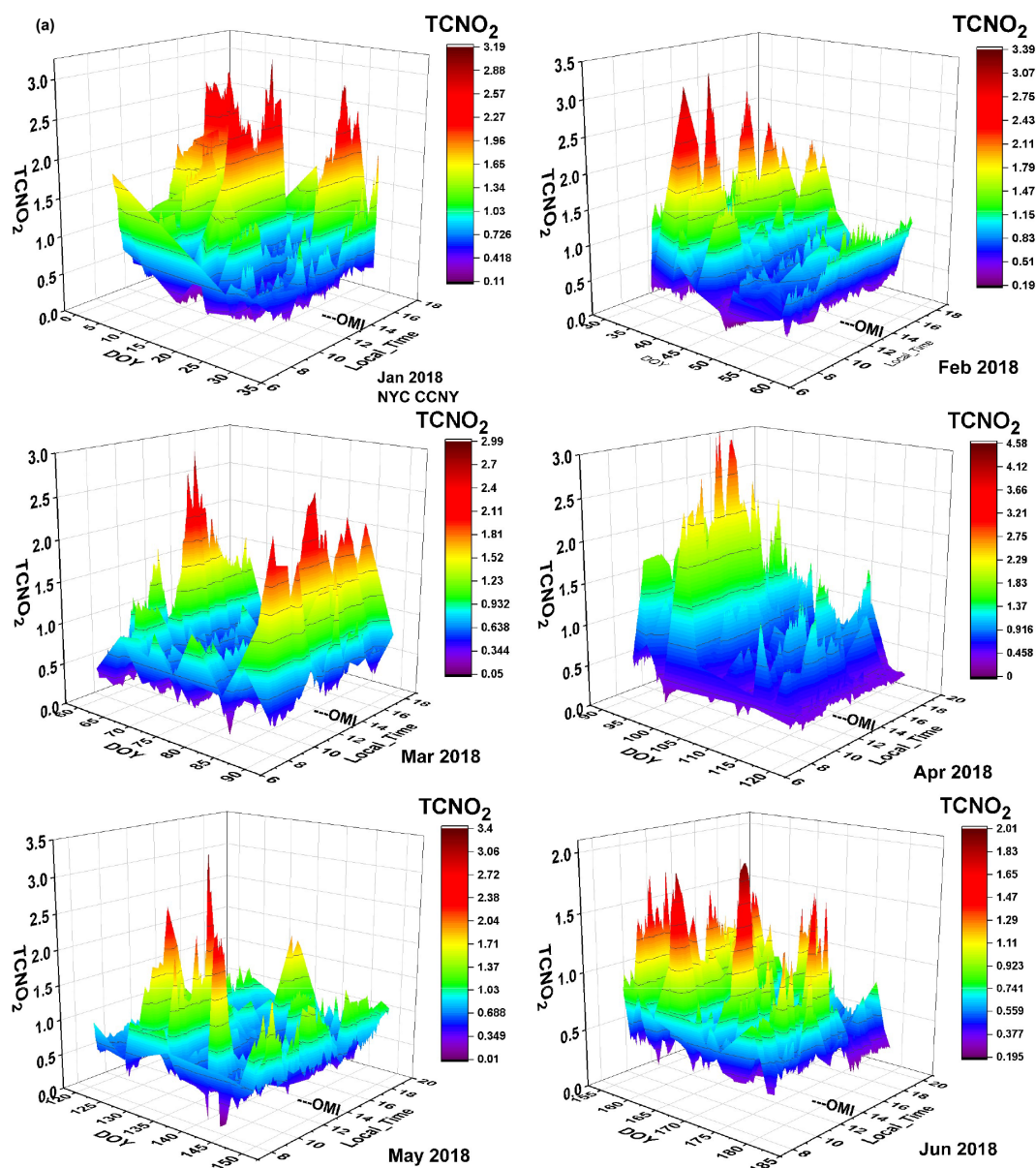


Figure 9.

so that both PANDORA and OMI measure elevated TCNO₂ amounts. In contrast, the PANDORA Gwangju Institute of Science and Technology (GIST) site is on the outskirts of a small city in southwestern South Korea with significant traffic. The result is significant amounts of localized TCNO₂ (PANDORA = 0.42) surrounded by areas that produce little NO₂ leading to OMI observing a very clean 0.2 DU. The averages of sites in the two tables are similar, leading to ratios of PAN/OMI of 1.8 and 1.7, respectively. The estimated 50 % increase in OMI retrievals of TCNO₂ from using the geometry-dependent reflectivity (Vasilkov et al., 2017) for the most polluted sites will narrow the disagreement with PANDORA. For example, OMI Seoul TCNO₂ may become

0.87 DU (PANDORA = 1.2 DU) and Buenos Aires 0.39 DU (PANDORA = 0.5 DU), still underestimating the amount of NO₂ pollution and missing the significant diurnal variation.

For the six sites shown, the average OMI underestimate of TCNO₂ is approximately a factor of 1.8 at the overpass time on a monthly average basis with occasional spikes that exceed this amount. The bias values range from 1.1 to 3.6, with higher biases tending to be associated with higher TCNO₂ values. The factor of 1.8 underestimate ignores the frequent large values of TCNO₂ at other times during the day (Fig. 7). In addition, averaging TCNO₂ (PAN) over each entire day yields average values for the whole period that are 10 % to 20 % higher than just averaging over midday values that

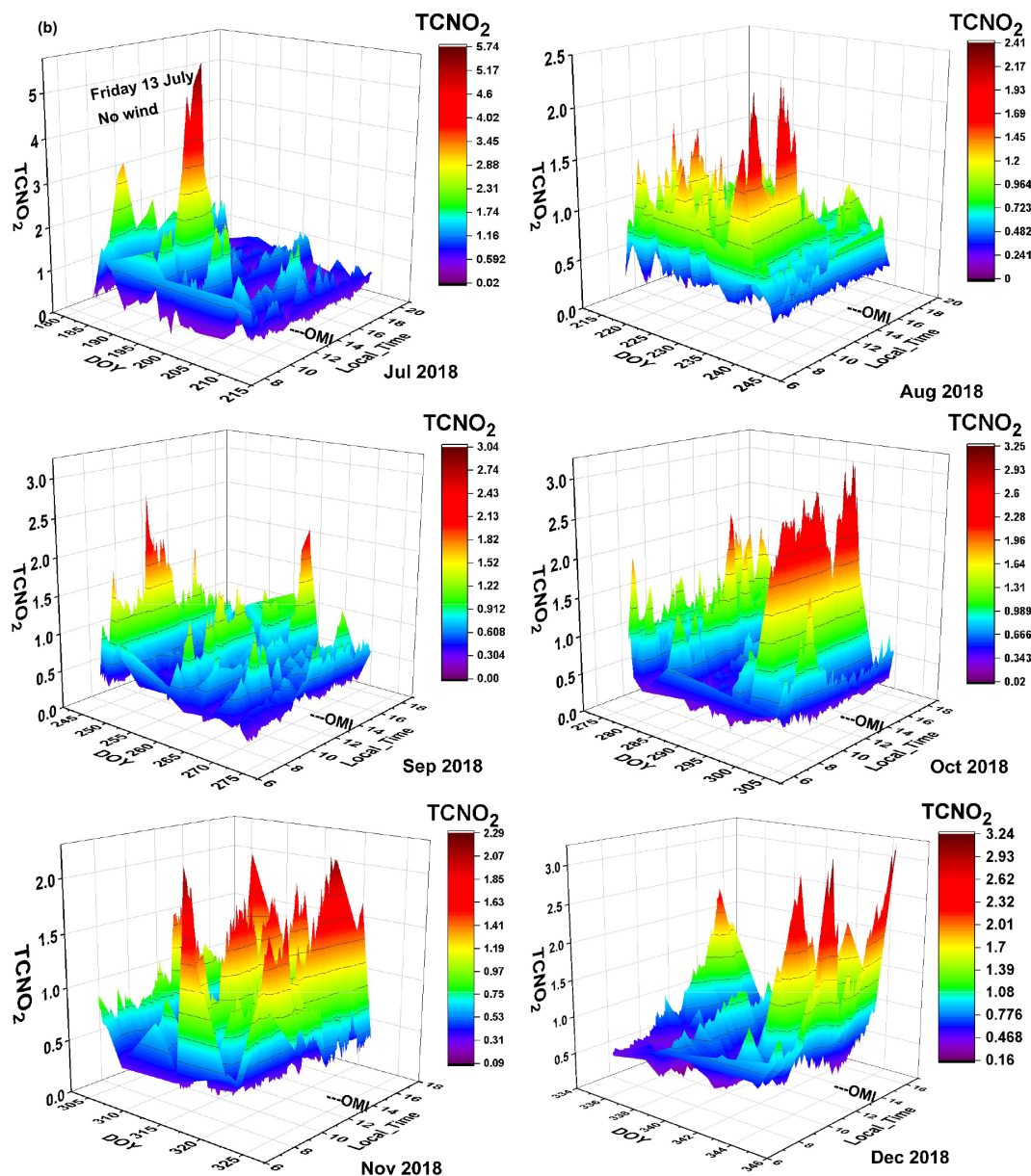


Figure 9. (a) TCNO₂ diurnal variation (DU) at CCNY in New York City for January to June 2018. The approximate OMI overpass time near 13:30 is marked. (b) TCNO₂ diurnal variation at CCNY in New York City for July to December 2018. The peak near 5 DU occurs on 13 July 2018 between 11:20 and 12:30 EST. The approximate OMI overpass time near 13:30 is marked.

matched the OMI overpass time. Aside from the absolute magnitude, the short-term variations (over several months) are similar for both OMI and PANDORA although mostly not correlated. If correlation coefficients r^2 are generated from linear fits to scatter plots of TCNO₂ from OMI vs. PANDORA, the correlation is mostly poor (examples: r^2 =: Seoul 0.06, Mauna Loa 0.3, and NASA HQ 0.7; see Figs. 4 and 5). Additional sites with shorter PANDORA time series of TCNO₂ show similar behavior.

Duncan et al. (2016) estimated trends from OMI TCNO₂ time series and found that the Seoul metropolitan area had a

decrease of $-1.5 \pm 1.3 \text{ \% yr}^{-1}$ (2005–2014) consistent with an OMI-estimated change of $-1.4 \pm 1 \text{ \% yr}^{-1}$ (2012–2018) in this paper. However, for the small area near Yonsei University, the decrease estimated from PANDORA is $-5.8 \pm 0.75 \text{ \% yr}^{-1}$. Park (2019) estimates that metropolitan Seoul has decreased in population even as surrounding areas have increased in population.

The average percent differences between OMI and PANDORA shown in Fig. 7 are relatively constant over time for each site, with small changes over each multi-year observation period. The differences between OMI and PANDORA

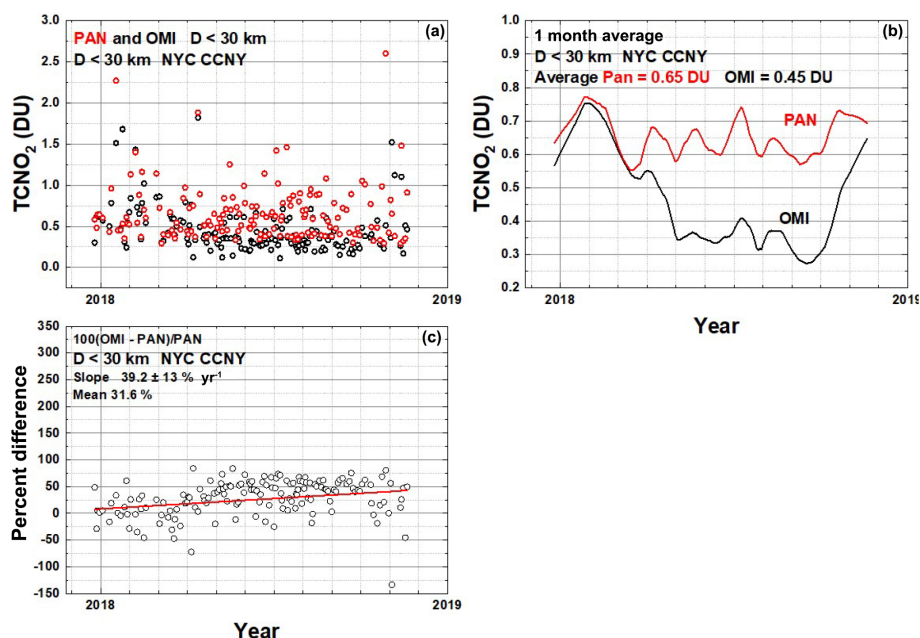


Figure 10. TCNO₂ overpass time series for CCNY in Manhattan, New York City. (a) OMI overpass TCNO₂ (black) compared with OMI (red). (b) Monthly lowestess (0.08) fit to the daily overpass data. (c) Percent difference $100(\text{OMI}-\text{PAN})/\text{PAN}$ calculated from the data in (a).

are provided by forming the percent differences of the daily TCNO₂ values (Fig. 7) in the form $100(\text{OMI}-\text{PAN})/\text{PAN}$. Also shown are the average percent differences and the linear fit slopes in percent change per year of the percent differences over the multi-year period. For example, the Boulder percent difference goes from -31 % to -23 % over 4 years. Of the six sites in shown in Fig. 7, two have statistically significant slopes, Seoul, South Korea ($2.1 \pm 0.5 \text{ \% yr}^{-1}$) and NASA Headquarters in Washington DC ($3.4 \pm 0.9 \text{ \% yr}^{-1}$), at the 2σ level, suggesting a significant area average increase in pollution compared to PANDORA's local values.

For some sites (see Fig. 7), PANDORA and OMI trends are the same within statistical uncertainty (Waterflow, NM, Buenos Aires, and Mauna Loa), while the other three sites show significantly different trends (Boulder, NASA HQ, and Seoul).

The results for Busan (from Fig. 3) show a least squares average for the percent difference of $-48 \pm 0.8 \text{ \%}$ for the 2012–2018 period with a slope of $6.8 \pm 1 \text{ \% yr}^{-1}$. There is a decrease in the percent difference after October 2015 (Fig. 3) that is mainly from PANDORA seeing less TCNO₂ than during the 2012–2014 period. There is a gap in the Busan time series from July 2014 until April 2015, when the original PANDORA was replaced with a new instrument. The calibrations of both PANDORAs appear to be correct. Because of the break in the time series it is not clear whether there was a change in local conditions around Pusan University compared to the wide area observed by OMI.

2.4 Diurnal variation of TCNO₂ compared to OMI retrievals

Figure 8 shows details of the daily diurnal variation of TCNO₂ on the roof of NASA Headquarters, Washington DC, adjacent to a major cross-town highway (I695) for every day during each month of 2015 for local time vs. DOY. The mid-day observing local standard time for OMI is marked for each graph. Displaying an entire year of daily (2 min time resolution) PANDORA data shows that the high values of TCNO₂ are a frequent occurrence but do not occur every day.

The amount of TCNO₂ is mostly from the adjacent highway and the surrounding urban area with heavy traffic. The relatively moderate TCNO₂ values (0.4 to 0.8 DU) are probably a testament to the effectiveness of catalytic converters mandatory on all US automobiles in such a high traffic area (Bishop and Steadman, 2015). The same data are plotted in Fig. 6 for 8 June 2017, showing that OMI reasonably matched the values seen by PANDORA at 14:00 and 15:00 but was not available to observe high values that occurred in the morning.

Figure 9 contains the daily TCNO₂ diurnal variability vs. DOY for each month measured by a PANDORA from the roof of a building on the CCNY (City College of New York) campus in the middle of Manhattan in New York City (NYC). From the values shown, the pollution levels are quite high, rivaling the pollution levels in Seoul, South Korea (see Fig. 5). OMI at its midday overpass time would detect some of the high-level pollution events but miss many others occurring mostly in the afternoon. There are a signifi-

icant number of days in all the months where the TCNO₂ levels appear to be low (e.g., blue color in July and October), but the blue color still represents significant pollution levels (TCNO₂(PAN) > 0.5 DU) that are small only compared to the peak values during the month (TCNO₂(PAN) > 1 DU). The highest amount of TCNO₂ recorded during 2018 was about 5 DU on 13 July 2018 from 11:20 and 12:30 EST, a time with very light winds (1 km h⁻¹) and moderate temperature (25 °C). There were many smaller peaks between 2 and 3 DU throughout the year. Extreme cases of high NO₂ amounts are frequently associated with the local meteorology indications of stagnant air (Harkey et al., 2015). The same data are shown in Fig. 6 for two days, 7 May and 7 June 2018, showing the comparison with OMI and the occurrence of much higher values of TCNO₂ in the morning and afternoon.

For both Washington DC (Fig. 8) and New York City (Fig. 9) there is strong day-to-day and month-to-month variability that depends on the local meteorological conditions (Seo et al., 2018; Zheng et al., 2015) and the amount of automobile traffic in the area (Andersen et al., 2011; Amin et al., 2017). High TCNO₂ events occur most often in the afternoon such that the OMI overpass near 13:30 would miss most high TCNO₂ events. Poor air quality affecting respiratory health would be improperly characterized by both the OMI average values being too low (Fig. 4) and by missing the extreme pollution events that occur frequently in the late afternoon. The high value of TCNO₂ that occurred on 5 August (2.2 DU) at 07:45 EST for Washington DC is not a retrieval error (SZA less than 70°), but is a one-time anomaly in 2015 compared to more usual high values of 1.5 DU with an occasional spike to 2 DU. It should be noted that TCNO₂ does not accurately represent the NO₂ concentration at the surface, since it is mostly a measure of the amount in the lower 2 km. However, it is roughly proportional to the surface measurements close to the pollution sources (Bechle et al., 2013; Knepp et al., 2014), with the exact proportionality dependent on the profile shape near the ground.

Similar daily diurnal variation graphs of TCNO₂ (Figs. 8 and 9) could be shown for each site. However, the basic idea is the same for each site. OMI underestimates the amount of TCNO₂ because of its large FOV and misses most of the peak events at other times of the day. For some sites, such as Busan and Seoul, the peak values can reach 3 DU and above late in the afternoon, which are never seen by OMI (Herman et al., 2018).

Figure 10 for CCNY is similar to the graphs in Figs. 4–6 showing the relative behavior between PANDORA and OMI but including only OMI pixels that are at a distance $D < 30$ km from CCNY. The results are almost identical to those when $D < 80$ km. There is a period in March 2018 when OMI TCNO₂ slightly exceeded that measured by PANDORA. OMI with its large FOV may be seeing part of the chemically driven seasonal variation, while PANDORA is seeing a nearly constant source driven amount mostly from automobile traffic. For most days during 2018,

PAN(TCNO₂) > OMI(TCNO₂), with the average value for PAN = 0.65 DU and for OMI = 0.45 DU (Fig. 10b). The percent difference plot shows that there is a systematic increase between PANDORA and OMI TCNO₂ from a value of 10 % to a value of 50 %.

3 Summary

Examination of long-term TCNO₂ monthly average time series from the OMI satellite and PANDORA ground-based observations shows that OMI systematically underestimates the amount of NO₂ in the atmosphere by an average factor of 1.5 to 2 at the local OMI overpass time near the Equator crossing time of 13:30 ± 01:30. As shown in Fig. 7 for TCNO₂, 100(OMI–PAN)/PAN least squares mean underestimates are much larger than error estimates. These differences are reduced for the smaller pixel size TropOMI TCNO₂ values (Judd et al., 2019). In addition, the PANDORA diurnal time series for every day during a year at each site (only two typical sites are shown in this paper, NYC and NASA-HQ) shows peaks in TCNO₂ that are completely missed by only observing at midday (see Figs. 6, 8, 9, and A2). The result is that estimates of air quality related to health effects from OMI observations are strongly underestimated almost everywhere, as shown at all the sites with a long PANDORA record. In comparisons to PANDORA, OMI data are mostly uncorrelated or weakly correlated (e.g., Seoul correlation coefficient $r^2 = 0.06$, Mauna Loa $r^2 = 0.3$), while NASA HQ in Washington DC shows a correlation on a seasonal basis (NASA HQ $r^2 = 0.7$), suggesting a wide area coordinated source of NO₂ (most likely automobile traffic). The data from CCNY show some correlation between the locations of the peaks and troughs. Seven short-term TCNO₂ time series were examined, showing similar results (Table 1), except when the pollution region is widespread as in the Seoul, South Korea, region. The conclusion is that while OMI satellite TCNO₂ data are uniquely able to assess regional long-term trends in TCNO₂ and provide a measure of the regional distribution of pollutants, the OMI data cannot properly assess local air quality or the effect on human health over extended periods in urban or industrial areas. This will continue to be the case, but to a lesser degree, when the OMI TCNO₂ data are improved by reprocessing with a new geometry-dependent reflectivity (Vasilkov et al., 2017) and by the smaller FOV of TropOMI. The analysis shows that locating PANDORAs at polluted sites could provide quantitative corrections for spatial and temporal biases that affect the determination of local air quality from satellite data. Satellite detection of diurnal variation of TCNO₂ will be improved with the upcoming launch of three planned geostationary satellites over Korea, the US, and Europe to verify the proper operation of the various PANDORA instruments. A similar analysis for total column ozone (TCO) was performed (see Appendix) and shows close agreement between OMI and PANDORA, with

the largest difference occurring for Mauna Loa Observatory at 3.4 km altitude, where PANDORA misses the ozone between the surface and 3.4 km.

Data availability. The data used in this paper can be accessed from a NASA website Pandora Data on <https://avdc.gsfc.nasa.gov/pub/DSCOVER/Pandora/DATA/> (last access: 15 October 2019) and OMI Data on <https://avdc.gsfc.nasa.gov/index.php?site=666843934&id=13> (last access: 15 October 2019).

Appendix A

Ozone: this section shows the corresponding PANDORA total column ozone (TCO) values compared to OMI TCO for Busan, South Korea (Fig. A1), that shows close agreement for the entire 2012–2017 period. The different fields of view for OMI and PANDORA have a much smaller effect because of the greater spatial uniformity of stratospheric ozone compared to tropospheric NO₂. Additional sites are summarized in Table A1. The largest TCO difference (15 DU or 5.6 %) occurs for Mauna Loa Observatory (altitude = 3.4 km) compared to OMI (average altitude = sea level). The close results show that the PANDORA was working properly and pointing accurately at the sun. The PANDORA TCO data shown here use a mid-latitude effective ozone temperature correction from model calculations that may not be accurate for each individual site (Herman et al., 2017). The ozone retrievals shown here use an average effective ozone temperature instead of a locally measured ozone temperature (Herman et al., 2015, 2017).

Table A1. Average values of TCO₃ for PANDORA and OMI.

Location	PAN (DU)	OMI (DU)	Percent difference
Mauna Loa Observatory, Hawaii (3.394 km)*	254	269	5.6
NASA HQ, Washington DC (0.02 km)	308	314	1.9
Waterflow, New Mexico (1.64 km)	293	292	0.3
Yonsei University, Seoul, South Korea (0.07 km)	317	325	2.5
Busan University, Busan, South Korea (0.03 km)	313	315	0.6
Boulder, Colorado (NOAA Building) (1.617 km)	299	302	1.0
Buenos Aires, Argentina (0.025 km)	279	284	1.8
Essex, Maryland (0.012 km)	299	301	0.7
Baltimore, Maryland (0.01 km)	296	296	0.0
Fresno, California (0.939 km)	306	309	1.0
Denver La Casa, Colorado (1.6 km)	292	294	0.7
Gwangju Institute of Science and Technology (GIST), South Korea (0.021 km)	302	307	1.6
Hankuk University Foreign Studies (HUFS), South Korea (0.04 km)	318	326	2.5
City College, Manhattan, New York City (0.04 km)	316	325	2.8
Average	299	304	1.6

* Mauna Loa TCNO₂: Fig. A2 shows the diurnal variation of TCNO₂ at MLO on specific days 3, 4, 7, and 8 June 2016 along with the variation in SZA. This shows that the MLO is polluted by NO₂ with column amounts in excess of stratospheric amounts (approximately 0.1 DU) even though there are no local sources. OMI retrievals of TCNO₂ on each day are much lower (about 0.12 DU) because of the averaging over OMI's large FOV that includes very clean ocean areas.

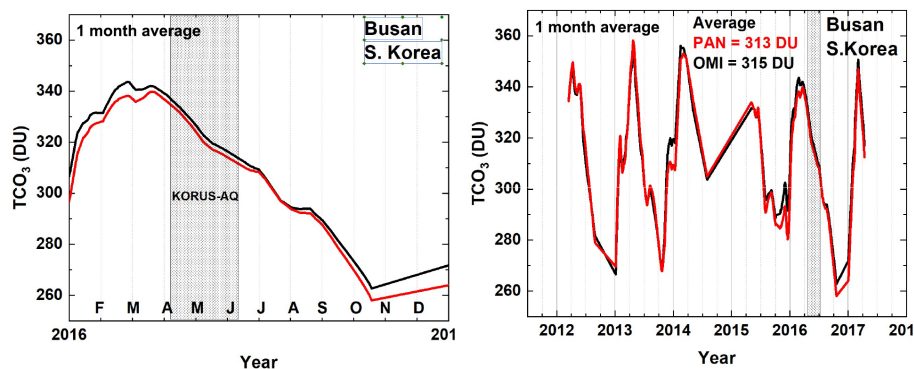


Figure A1. Monthly average values of TCO for OMI and PANDORA at OMI overpass times for Busan, South Korea. Shaded area represents the KORUS-AQ campaign period.

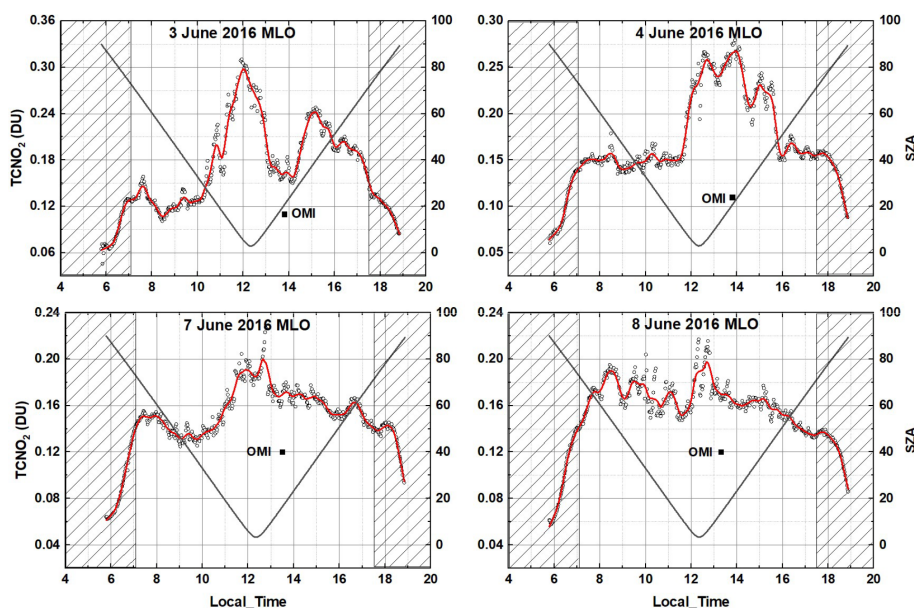


Figure A2. The diurnal variation of TCNO₂ at MLO on 4 d during June 2016 compared to OMI TCNO₂ (small square). Shaded areas represent high SZA conditions where the PANDORA retrievals are not accurate.

Author contributions. JH produced all of the figures and text, JhK and JaK contributed the Korean PANDORA data, MD contributed the data from Waterflow, New Mexico, and the CO₂ analysis, MR contributed the Buenos Aires PANDORA data, and MT contributed the PANDORA data from CCNY.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This project is supported by the Korean Ministry of Environment (MOE) as a Public Technology Program based on Environmental Policy (2017000160001), by the Los Alamos National Laboratory's Laboratory Directed Research and Development program, and by the NASA PANDORA project managed by Robert Swap.

Financial support. This research has been supported by the NASA PANDORA project supported by the NASA Tropospheric Composition Program.

Review statement. This paper was edited by Folkert Boersma and reviewed by two anonymous referees.

References

- Almaraz, M., Bai, E., Wang, C., Trousdell, J., Conley, S., Faloon, I., and Houlton, B. Z.: Agriculture is a major source of NO_x pollution in California, *Sci. Adv.*, 31, 1–8, <https://doi.org/10.1126/sciadv.aao3477>, 2018.
- Amin, S. R., Tamima, U., and Jimenez, L. A.: Understanding Air Pollution from Induced Traffic during and after the Construction of a New Highway: Case Study of Highway 25 in Montreal, *J. Adv. Transport.*, 2017, 5161308, <https://doi.org/10.1155/2017/5161308>, 2017.
- Andersen, Z. J., Hvidberg, M., Jensen, S. S., Ketzel, M., Loft, S., Sørensen, M., Tjønneland, A., Overvad, K., and Raaschou-Nielsen, O.: Chronic obstructive pulmonary disease and long-term exposure to traffic-related air pollution: A cohort study, *Am. J. Respir. Crit. Care Med.*, 183, 455–461, <https://doi.org/10.1164/rccm.201006-0937OC>, 2011.
- Bechle, M. J., Millet, D. B., and Marshall, J. D.: Remote sensing of exposure to NO₂: Satellite versus ground-based measurement in a large urban area, *Atmos. Environ.*, 69, 345–353, 2013.
- Bishop, G. A. and Stedman, D. H.: Reactive Nitrogen Species Emission Trends in Three Light-/Medium-Duty United States Fleets, *Environ. Sci. Technol.*, 49, 11234–11240, <https://doi.org/10.1021/acs.est.5b02392>, 2015.
- Boersma, K. F., Eskes, H. J., and Brinksma, E. J.: Error analysis for tropospheric NO₂ retrieval from space, *J. Geophys. Res.-Atmos.*, 1–20, <https://doi.org/10.1029/2003JD003962>, 2004.
- Boersma, K. F., Eskes, H. J., Dirksen, R. J., van der A, R. J., Veefkind, J. P., Stammes, P., Huijnen, V., Kleipool, Q. L., Sneep, M., Claas, J., Leitão, J., Richter, A., Zhou, Y., and Brunner, D.: An improved tropospheric NO₂ column retrieval algorithm for the Ozone Monitoring Instrument, *Atmos. Meas. Tech.*, 4, 1905–1928, <https://doi.org/10.5194/amt-4-1905-2011>, 2011.
- Boersma, K. F., Vinken, G. C. M., and Eskes, H. J.: Representativeness errors in comparing chemistry transport and chemistry climate models with satellite UV-Vis tropospheric column retrievals, *Geosci. Model Dev.*, 9, 875–898, <https://doi.org/10.5194/gmd-9-875-2016>, 2016.
- Choudhary, S. K., Chaudhary, M., Bagde, S., Gadhai, A. R., and Joshi, V.: Nitric oxide and cancer: a review, *W. J. Surg. Oncol.*, 11, 118, 2013.
- Cleveland, W. S.: LOWESS: A program for smoothing scatterplots by robust locally weighted regression, *The American Statistician*, JSTOR, 35, 54, <https://doi.org/10.2307/2683591>, 1981.
- Dirksen, R. J., Boersma, K. F., Eskes, H. J., Ionov, D. V., Bucsela, E. J., Levelt, P. F., and Kelder, H. M.: Evaluation of stratospheric NO₂ retrieved from the Ozone Monitoring Instrument: Intercomparison, diurnal cycle, and trending, *J. Geophys. Res.*, 116, 1–22, <https://doi.org/10.1029/2010JD014943>, 2011.
- Duncan, B. N., Lamsal, L. N., Thompson, A. M., Yoshida, Y., Lu, Z., Streets, D. G., Hurwitz, M. M., and Pickering, K. E.: A space-based, high-resolution view of notable changes in urban NO_x pollution around the world (2005–2014), *J. Geophys. Res.-Atmos.*, 121, 976–996, <https://doi.org/10.1002/2015JD024121>, 2016.
- Fenton, J.: Power plants install emissions controls, *Farmington Daily Times*, available at: <http://www.daily-times.com/story/news/local/four-corners/2015/10/12/power-plants-install-emissions-controls/73823014/> (last access: 13 October 2015), 2015.
- Goldberg, D. L., Saide, P. E., Lamsal, L. N., de Foy, B., Lu, Z., Woo, J.-H., Kim, Y., Kim, J., Gao, M., Carmichael, G., and Streets, D. G.: A top-down assessment using OMI NO₂ suggests an underestimate in the NO_x emissions inventory in Seoul, South Korea, during KORUS-AQ, *Atmos. Chem. Phys.*, 19, 1801–1818, <https://doi.org/10.5194/acp-19-1801-2019>, 2019.
- Harkey, M., Holloway, T., Oberman, J., and Scotty, E.: An evaluation of CMAQ NO₂ using observed chemistry-meteorology correlations, *J. Geophys. Res.-Atmos.*, 120, 11775–11797, <https://doi.org/10.1002/2015JD023316>, 2015.
- Herman, J., Cede, A., Spinei, E., Mount, G., Tzortziou, M., and Abuhassan, N.: NO₂ column amounts from ground-based Pandora and MFDOAS spectrometers using the direct-sun DOAS technique: Intercomparisons and application to OMI validation, *J. Geophys. Res.*, 114, D13307, <https://doi.org/10.1029/2009JD011848>, 2009.
- Herman, J., Evans, R., Cede, A., Abuhassan, N., Petropavlovskikh, I., and McConville, G.: Comparison of ozone retrievals from the Pandora spectrometer system and Dobson spectrophotometer in Boulder, Colorado, *Atmos. Meas. Tech.*, 8, 3407–3418, <https://doi.org/10.5194/amt-8-3407-2015>, 2015.
- Herman, J., Evans, R., Cede, A., Abuhassan, N., Petropavlovskikh, I., McConville, G., Miyagawa, K., and Noiro, B.: Ozone comparison between Pandora #34, Dobson #061, OMI, and OMPS in Boulder, Colorado, for the period December 2013–December 2016, *Atmos. Meas. Tech.*, 10, 3539–3545, <https://doi.org/10.5194/amt-10-3539-2017>, 2017.
- Herman, J., Spinei, E., Fried, A., Kim, J., Kim, J., Kim, W., Cede, A., Abuhassan, N., and Segal-Rozenhaimer, M.: NO₂ and HCHO

- measurements in Korea from 2012 to 2016 from Pandora spectrometer instruments compared with OMI retrievals and with aircraft measurements during the KORUS-AQ campaign, *Atmos. Meas. Tech.*, 11, 4583–4603, <https://doi.org/10.5194/amt-11-4583-2018>, 2018.
- Ialongo, I., Herman, J., Krotkov, N., Lamsal, L., Boersma, K. F., Hovila, J., and Tamminen, J.: Comparison of OMI NO₂ observations and their seasonal and weekly cycles with ground-based measurements in Helsinki, *Atmos. Meas. Tech.*, 9, 5203–5212, <https://doi.org/10.5194/amt-9-5203-2016>, 2016.
- Judd, L. M., Al-Saadi, J. A., Valin, L. C., Pierce, R. B., Yang, K., Janz, S. J., Kowalewski, M. G., Szykman, J. J., Tiefengraber, M., and Mueller, M.: The Dawn of Geostationary Air Quality Monitoring: Case Studies From Seoul and Los Angeles, *Environ. Sci.*, 1–17, <https://doi.org/10.3389/fenvs.2018.00085>, 2018.
- Judd, L. M., Al-Saadi, J. A., Janz, S. J., Kowalewski, M. G., Pierce, R. B., Szykman, J. J., Valin, L. C., Swap, R., Cede, A., Mueller, M., Tiefengraber, M., Abuhassan, N., and Williams, D.: Evaluating the impact of spatial resolution on tropospheric NO₂ column comparisons within urban areas using high-resolution airborne data, *Atmos. Meas. Tech. Discuss.*, <https://doi.org/10.5194/amt-2019-161>, in review, 2019.
- Kim, S.-Y. and Song, I.: National-scale exposure prediction for long-term concentrations of particulate matter and nitrogen dioxide in South Korea, *Environ. Pollut.*, 226, 21–29, <https://doi.org/10.1016/j.envpol.2017.03.056>, 2017.
- Kleipool, Q. L., Dobber, M. R., De Haan, J. F., and Levelt, P. F.: Earth Surface Reflectance Climatology from Three Years of OMI Data, *J. Geophys. Res.*, 113, 1–22, <https://doi.org/10.1029/2008JD010290>, 2008.
- Knepp, T., Pippin, M., Crawford, J., Szykman, J., Long, R., Cowen, L., Cede, A., Abuhassan, N., Herman, J., Delgado, R., Compton, J., Berkoff, T., Fishman, J., Martins, D., Stauffer, R., Thompson, A., Weinheimer, A., Knapp, D., Montzka, D., Lenschow, D., and Neil, D.: Estimating Surface NO₂ and SO₂ Mixing Ratios from Fast-Response Total Column Observations and Potential Application to Geostationary Missions, *J. Atmos. Chem.*, Springer, New York, NY, 1–26, 2014.
- Kollonige, D. E., Thompson, A. M., Josipovic, M., Tzortziou, M., Beukes, J. P., Burger, R., Martins, D. K., van Zyl, P. G., Vakkari, V., and Laakso, L.: OMI satellite and ground-based Pandora observations and their application to surface NO₂ estimations at terrestrial and marine sites, *J. Geophys. Res.-Atmos.*, 123, 1441–1459, <https://doi.org/10.1002/2017JD026518>, 2018.
- Krotkov, N. A., Lamsal, L. N., Celarier, E. A., Swartz, W. H., Marchenko, S. V., Bucsela, E. J., Chan, K. L., Wenig, M., and Zara, M.: The version 3 OMI NO₂ standard product, *Atmos. Meas. Tech.*, 10, 3133–3149, <https://doi.org/10.5194/amt-10-3133-2017>, 2017.
- Lamsal, L., Randall, M., Parrish, D., and Krotkov, N.: Scaling Relationship for NO₂ Pollution and Urban Population Size: A Satellite Perspective, *Environ. Sci. Technol.*, 47, 12707–12716, <https://doi.org/10.1021/es400744g>, 2013.
- Lamsal, L. N., Krotkov, N. A., Celarier, E. A., Swartz, W. H., Pickering, K. E., Bucsela, E. J., Gleason, J. F., Martin, R. V., Philip, S., Irie, H., Cede, A., Herman, J., Weinheimer, A., Szykman, J. J., and Knepp, T. N.: Evaluation of OMI operational standard NO₂ column retrievals using in situ and surface-based NO₂ observations, *Atmos. Chem. Phys.*, 14, 11587–11609, <https://doi.org/10.5194/acp-14-11587-2014>, 2014.
- Lamsal, L. N., Janz, S. J., Krotkov, N. A., Pickering, K. E., Spurr, R. J. D., Kowalewski, M. G., Loughner, C. P., Crawford, J. H., Swartz, W. H., and Herman, J. R.: High-resolution NO₂ observations from the Airborne Compact Atmospheric Mapper Retrieval and validation, *J. Geophys. Res.-Atmos.*, 122, 1953–1970, <https://doi.org/10.1002/2016JD025483>, 2017.
- Levelt, P. F., Van den Oord, G. H. J., Dobber, M. R., Malkki, A., Visser, H., de Vries, J., Stammes, P., Lundell, J. O. V., and Saari, H.: The Ozone Monitoring Instrument, *IEEE T. Geosci. Remote.*, 44, 1093–1101, <https://doi.org/10.1109/tgrs.2006.872333>, 2006.
- Lin, J.-T., Martin, R. V., Boersma, K. F., Snee, M., Stammes, P., Spurr, R., Wang, P., Van Roozendaal, M., Clémer, K., and Irie, H.: Retrieving tropospheric nitrogen dioxide from the Ozone Monitoring Instrument: effects of aerosols, surface reflectance anisotropy, and vertical profile of nitrogen dioxide, *Atmos. Chem. Phys.*, 14, 1441–1461, <https://doi.org/10.5194/acp-14-1441-2014>, 2014.
- Lindenmaier, R., Dubey, M. K., Henderson, B. G., Butterfield, Z. T., Herman, J. R., Rahn, T., and Lee, S.-H.: Multiscale observations of CO₂, (CO₂)-C-13, and pollutants at Four Corners for emission verification and attribution, *P. Natl. Acad. Sci. USA*, 111, 8386–8391, <https://doi.org/10.1073/pnas.1321883111>, 2014.
- Liu, F., Beirle, S., Zhang, Q., Dörner, S., He, K., and Wagner, T.: NO_x lifetimes and emissions of cities and power plants in polluted background estimated by satellite observations, *Atmos. Chem. Phys.*, 16, 5283–5298, <https://doi.org/10.5194/acp-16-5283-2016>, 2016.
- Lorente, A., Boersma, K. F., Stammes, P., Tilstra, L. G., Richter, A., Yu, H., Kharbouche, S., and Muller, J.-P.: The importance of surface reflectance anisotropy for cloud and NO₂ retrievals from GOME-2 and OMI, *Atmos. Meas. Tech.*, 11, 4509–4529, <https://doi.org/10.5194/amt-11-4509-2018>, 2018.
- Marchenko, S., Krotkov, N. A., Lamsal, L. N., Celarier, E. A., Swartz, W. H., and Bucsela, E. J.: Revising the slant column density retrieval of nitrogen dioxide observed by the Ozone Monitoring Instrument, *J. Geophys. Res.-Atmos.*, 120, 5670–5692, <https://doi.org/10.1002/2014JD022913>, 2015.
- Nowlan, C. R., Liu, X., Leitch, J. W., Chance, K., González Abad, G., Liu, C., Zoogman, P., Cole, J., Delker, T., Good, W., Murcray, F., Ruppert, L., Soo, D., Follette-Cook, M. B., Janz, S. J., Kowalewski, M. G., Loughner, C. P., Pickering, K. E., Herman, J. R., Beaver, M. R., Long, R. W., Szykman, J. J., Judd, L. M., Kelley, P., Luke, W. T., Ren, X., and Al-Saadi, J. A.: Nitrogen dioxide observations from the Geostationary Trace gas and Aerosol Sensor Optimization (GeoTASO) airborne instrument: Retrieval algorithm and measurements during DISCOVER-AQ Texas 2013, *Atmos. Meas. Tech.*, 9, 2647–2668, <https://doi.org/10.5194/amt-9-2647-2016>, 2016.
- O’Byrne, G., Martin, R. V., van Donkelaar, A., Joiner, J., and Celarier, E. A.: Surface reflectivity from the Ozone Monitoring Instrument using the Moderate Resolution Imaging Spectroradiometer to eliminate clouds: Effects of snow on ultraviolet and visible trace gas retrievals, *J. Geophys. Res.*, 115, D17305, <https://doi.org/10.1029/2009JD013079>, 2010.
- Park, S. H.: Seoul, *The Wiley Blackwell Encyclopedia of Urban and Regional Studies*, edited by: Orum, A., John Wiley & Sons Ltd.,

- Hoboken, <https://doi.org/10.1002/9781118568446.eurs0283>, 2019.
- Raponi, M. M., Cede, A., Santana Diaz, D., Sánchez, R., Otero, L. A., Salvador, J. O., Ristori, P. R., and Quel, E. J.: Total Column Ozone Measured In Buenos Aires Between March And November 2017, Using A Pandora Spectrometer System, *Anales AFA*, 29, 46–50, <https://doi.org/10.31527/analesafa.2018.29.2.46>, 2018.
- Seo, J., Park, D.-S. R., Kim, J. Y., Youn, D., Lim, Y. B., and Kim, Y.: Effects of meteorology and emissions on urban air quality: a quantitative statistical approach to long-term records (1999–2016) in Seoul, South Korea, *Atmos. Chem. Phys.*, 18, 16121–16137, <https://doi.org/10.5194/acp-18-16121-2018>, 2018.
- Strahan, S. E., Duncan, B. N., and Hoor, P.: Observationally derived transport diagnostics for the lowermost stratosphere and their application to the GMI chemistry and transport model, *Atmos. Chem. Phys.*, 7, 2435–2445, <https://doi.org/10.5194/acp-7-2435-2007>, 2007.
- Torres, O., Bhartia, P. K., Jethva, H., and Ahn, C.: Impact of the ozone monitoring instrument row anomaly on the long-term record of aerosol products, *Atmos. Meas. Tech.*, 11, 2701–2715, <https://doi.org/10.5194/amt-11-2701-2018>, 2018.
- Tzortziou, M., Parker, O., Lamb, B., Herman, J. R., Lamsal, L., Stauffer, R., and Abuhassan, N.: Atmospheric Trace Gas (NO₂ and O₃) Variability in South Korean Coastal Waters, and Implications for Remote Sensing of Coastal Ocean Color Dynamics, *Remote Sens.*, 10, 1587, <https://doi.org/10.3390/rs10101587>, 2018.
- Vasilkov, A., Qin, W., Krotkov, N., Lamsal, L., Spurr, R., Haffner, D., Joiner, J., Yang, E.-S., and Marchenko, S.: Accounting for the effects of surface BRDF on satellite cloud and trace-gas retrievals: a new approach based on geometry-dependent Lambertian equivalent reflectivity applied to OMI algorithms, *Atmos. Meas. Tech.*, 10, 333–349, <https://doi.org/10.5194/amt-10-333-2017>, 2017.
- Zara, M., Boersma, K. F., De Smedt, I., Richter, A., Peters, E., van Geffen, J. H. G. M., Beirle, S., Wagner, T., Van Roozendael, M., Marchenko, S., Lamsal, L. N., and Eskes, H. J.: Improved slant column density retrieval of nitrogen dioxide and formaldehyde for OMI and GOME-2A from QA4ECV: intercomparison, uncertainty characterisation, and trends, *Atmos. Meas. Tech.*, 11, 4033–4058, <https://doi.org/10.5194/amt-11-4033-2018>, 2018.
- Zheng, G. J., Duan, F. K., Su, H., Ma, Y. L., Cheng, Y., Zheng, B., Zhang, Q., Huang, T., Kimoto, T., Chang, D., Pöschl, U., Cheng, Y. F., and He, K. B.: Exploring the severe winter haze in Beijing: the impact of synoptic weather, regional transport and heterogeneous reactions, *Atmos. Chem. Phys.*, 15, 2969–2983, <https://doi.org/10.5194/acp-15-2969-2015>, 2015.