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Inter-comparison of NO₂ column densities measured by Pandora and OMI over Seoul, Korea

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Abstract : Total Vertical Column Density (VCD) of NO₂, a key component in air quality and tropospheric chemistry was measured using a ground-based instrument, Pandora, in Seoul from March 2012 to October 2013. The NO₂ measurements using Pandora were compared with those obtained by satellite remote sensing from Ozone Monitoring Instrument (OMI) where the intercomparison characteristics were analyzed as a function of measurement geometry, cloud amount and aerosol loading. The negative biases of the OMI NO₂ VCD were larger when cloud amount and Aerosol Optical Depth (AOD) were higher. The correlation coefficient between NO₂ VCDs from Pandora and OMI was 0.53 for the entire measurement period, whereas the correlation coefficient between the two was 0.74 when the cloud amount and AOD were low (cloud amount<3, AOD<0.4). The low bias of OMI data was associated with the shielding effect of the cloud and the aerosols.

Key Words : NO₂ VCD, Pandora, OMI, Validation, Seoul

1. Introduction

Nitrogen dioxide (NO₂) emissions from fossil fuel combustion and biomass burning affects global air quality and tropospheric chemistry (Seinfeld and Pandis, 2006). NO₂ is formed by anthropogenic source such as high-temperature combustion of fossil fuel, and comes mainly from motor vehicle exhaust and stationary sources such as power plant. It is also

produced naturally by soil, undersea microorganism, and lightning. NO₂ plays an important role in atmosphere chemistry as it is a strong oxidizing agent that reacts in the air to form corrosive nitric acid, as well as toxic organic nitrates. NO₂ also plays an important role in the photochemical smog to produce ground-level ozone. High levels of NO₂ affect the public health by respiratory and cardiovascular problems. In East Asia, top-down emission inventory, which is based on

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satellite measurements, suggested that NO₂ emission from China increased substantially during the period of 1996-2004. Han *et al.* (2011) compared model-predicted NO₂ column densities with OMI measurements to assess the current emission inventory over Korea (Han *et al.*, 2011). Mijling *et al.* (2013) estimated NO₂ emission trend over East Asia by using satellite measurement of Global Ozone Monitoring Experiment (GOME-2) (Mijling *et al.*, 2013). However, satellite based measurements has relatively high uncertainties compared to the ground-based measurements due to its different sensitivity with respect to altitude, even though satellite measurements provide large spatial coverage (Boersma *et al.*, 2007).

Thus, it is important to validate the satellite based measurements via comparison with ground-based measurements such as Pandora (Herman *et al.*, 2009) and MAX-DOAS (Irie *et al.*, 2008; Lee *et al.*, 2011). The previous study (Herman *et al.*, 2009) has shown that NO₂ Vertical Column Density (VCDs) retrieved from satellite-based Ozone Monitoring Instrument (OMI) and ground-based Pandora were well correlated ($R = 0.73$, slope = 0.98) in Eastern U.S. However, the validation of OMI NO₂ total VCD products has not been performed in East Asia where the emissions are persistently high and the characteristics of atmospheric states are different from the Eastern USA. In this study, The NO₂ VCD products of OMI are compared with those obtained from the ground-based Pandora measurement at Seoul, a site in East Asia. The spatio-temporal characteristics of NO₂ VCD measured by OMI and Pandora are also shown to analyze the difference.

2. Measurements

Pandora is located on the rooftop of Science Hall at Yonsei University in Seoul (37.56°N, 126.94°E) 70 m above the sea level, as shown in Fig. 1(a). The location

is more than 300 m far from the main traffic load, thus the effect of near local emission from the load can be negligible. Pandora is a passive system which measures direct sunlight from 270 nm to 530 nm with 0.5 nm spectral resolution. Its field of view is 1.6°, and the pointing precision is 0.01°. From the measured solar radiance, the trace gases total column densities are retrieved using the Differential Optical Absorption Spectroscopy (DOAS) technique (Herman *et al.*, 2009). The NO₂ fitting window of Pandora is between 370 nm and 500 nm. The temporal resolution of Pandora measurement is about 2 minutes. The precision of Pandora NO₂ VCD is 0.01 DU and that of accuracy is ± 0.05 DU (Herman *et al.*, 2009). The more information of Pandora was described in Herman *et al.* (2009). Pandora measurements have been carried out in Seoul from March 2012 to October 2013. The data with error less than 0.05 DU (1 DU = 2.67×10^{16} molecules/cm²) are used for the inter-comparison.

OMI onboard Earth Observing System (EOS) Aura satellite was launched on July 15, 2004 following the mission of Total Ozone Mapping Spectrometer (TOMS). OMI measures the ultraviolet and visible radiance between 270 nm and 500 nm with the spectral resolution of 0.5 nm. OMI has wide field of view of 114°, to have swath as wide as 2600 km, so that it can measure the whole globe within a day (Levelt *et al.*, 2006). The measurement principle of OMI is described in Fig. 1(b). Operational base-line product of NO₂ OMI algorithm employs direct fitting method (BOAS) (Levelt *et al.*, 2006). The fitting window of NO₂ is between 365 nm and 500 nm where average spectrum resolution is 0.63 nm. The spatial resolution of OMI is 13 × 24 km² in normal mode and 13 × 12 km² in zoom mode (Levelt *et al.*, 2006). The local overpass time of OMI over Seoul is at around 13:30.

In this study, the OMI level 2G products (OMNO2G) were used from National Aeronautics and Space Administration (NASA) website (<http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI>). For the

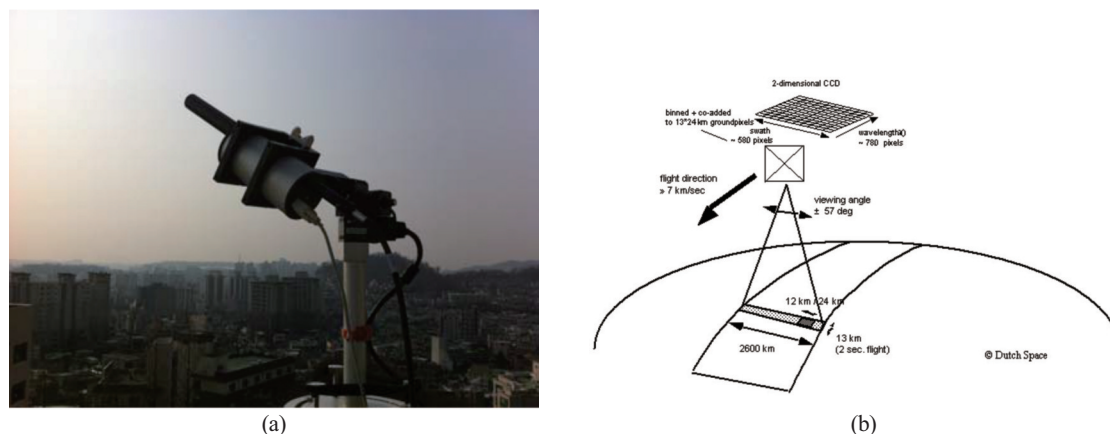


Fig. 1. (a) Pandora at Yonsei University, Seoul, Korea and (b) the OMI measurements (Levelt *et al.*, 2006).

comparison, Pandora data were averaged in ± 30 minutes overpass time of OMI. OMI data was spatially averaged within 20 km from Yonsei University considering the OMI spatial resolution. In order to avoid uncertainties caused by the cloud contaminations, the OMI data is used with cloud fraction less than 0.2.

3. Results

The retrieved NO₂ VCDs from Pandora were compared with the OMI values as shown in Fig. 2. The correlation coefficient between NO₂ VCD from Pandora and OMI was 0.53, with the number of coincident data of 166. This overall comparison showed the correlation coefficient between the OMI and the Pandora in Seoul, Korea lower than the results of Herman *et al.* (2009), which were carried out in the U.S. and Greece. This implies a possibility for the effect of different environment between the East Asia and U.S./Europe, for example high aerosol loading and cloud characteristics. The slope obtained from the regression equation in Fig.2 is 0.33, showing the OMI NO₂ VCD values are underestimated compared to the Pandora data.

Fig. 3 shows the difference between NO₂ VCD from Pandora and OMI measurements at various cloud

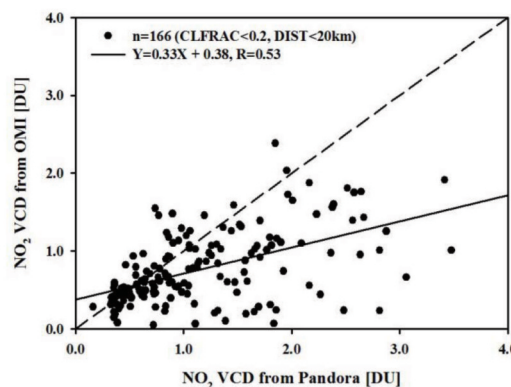


Fig. 2. Correlation between NO₂ VCDs from OMI and Pandora measurements.

amounts at nearest overpass time of OMI in Seoul. The cloud amount data was obtained from Korean Meteorological Administration (KMA) station in Seoul, which is located 2.5 km to east of Yonsei University. The difference between NO₂ VCD from Pandora and OMI was larger when cloud amount was higher. These differences can be attributed to shielding effect of cloud on the column density retrieval of OMI. As shown in the figure, the cloud amount between the OMI (closed square) and ground observation of KMA (abscissa) shows good correlation but large difference due to the different observation geometry such as viewing zenith angle, and corresponding spatial resolution.

Similar tendency is also shown in the relationship between the differences and Aerosol Optical Depth

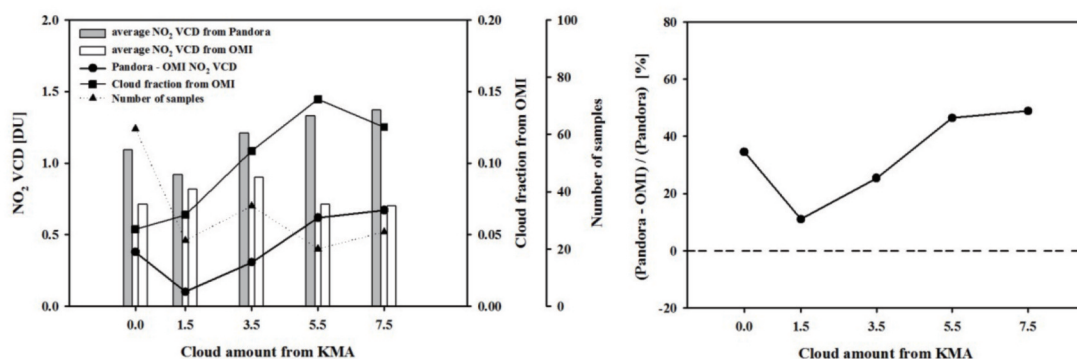


Fig. 3. Difference between NO₂ VCDs from Pandora and OMI measurements for different cloud amounts.

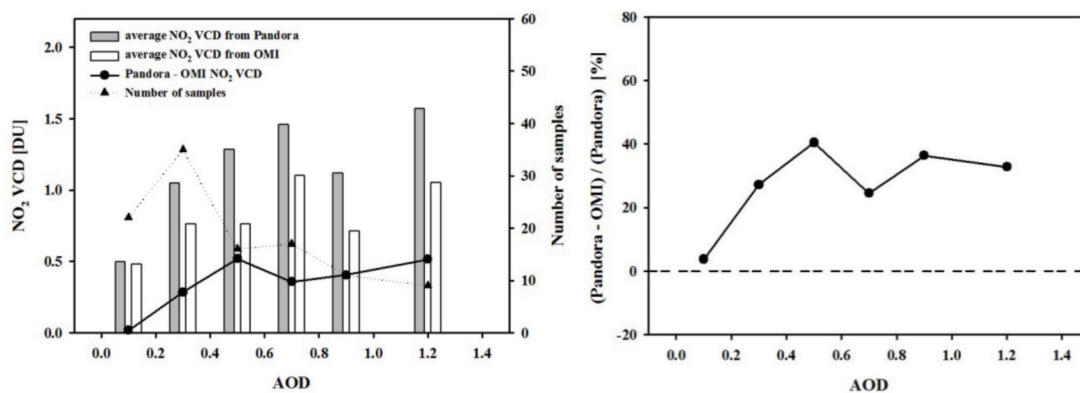


Fig. 4. Difference between NO₂ VCDs from Pandora and OMI measurements at various AOD.

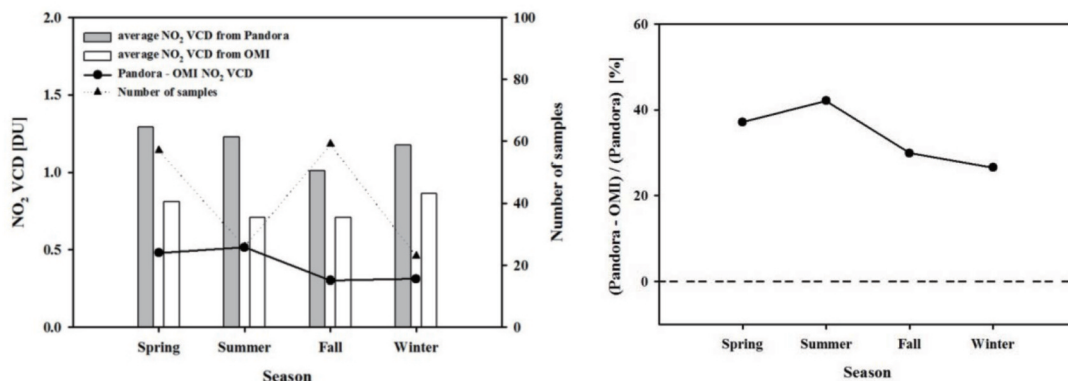


Fig. 5. Seasonal differences between NO₂ VCDs obtained from Pandora and OMI.

(AOD). Fig. 4 shows the difference between NO₂ VCD from Pandora and OMI measurements as a function of AOD at 440 nm at the same site of Yonsei University, one of the AEROSOL ROBOTIC NETWORK (AERONET) site (<http://aeronet.gsfc.nasa.gov/>). For the comparison, AERONET data at Yonsei University were averaged

for ± 30 minutes of the OMI overpass time. The difference between NO₂ VCD from Pandora and OMI was nearly zero when AOD interval is between 0 and 0.2. As AOD becomes larger, the biases became higher which also might be associated with the shielding effect of the aerosols.

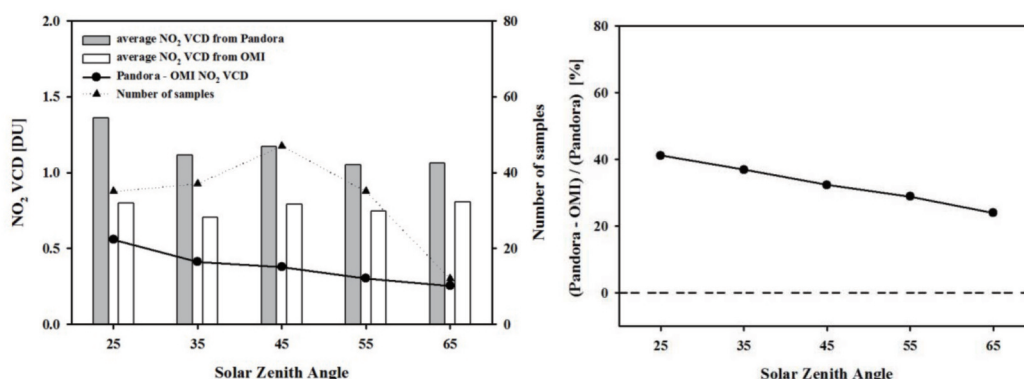


Fig. 6. Difference between NO₂ VCD from Pandora and OMI measurements at various solar zenith angles.

Fig. 5 shows the difference of NO₂ VCDs between the Pandora and the OMI in each season. The mean NO₂ VCDs from Pandora were 1.30, 1.23, 1.01, and 1.18 DU in spring, summer, fall, and winter, respectively, whereas those from OMI were 0.81, 0.71, 0.71, and 0.86 DU, respectively. NO₂ VCD of OMI was systematically smaller than those of Pandora by 0.49, 0.52, 0.30, and 0.32 DU in spring, summer, fall, and winter, respectively. The difference of NO₂ total VCDs from Pandora and OMI were larger in spring and summer than those in fall and winter.

Fig. 6 shows the difference between Pandora and OMI NO₂ VCD measurements as a function of solar zenith angle (SZA). SZAs from Pandora and OMI products were very close, thus averaged for the coincide measurements. The difference between NO₂ VCDs from Pandora and OMI was larger when SZA was low. Table 1 shows the correlation between retrieved NO₂ VCDs from Pandora and OMI at different SZAs. The correlation coefficient between NO₂ VCD from Pandora and OMI was the highest ($R = 0.82$) when SZA interval is between 30° and 40°, while it was the lowest when SZA is larger than 60° as shown in Fig. 7. Since Pandora uses Geometric Air Mass Factor (GAMF) for conversion of Slant Column Density (SCD) into VCD, it is likely to have small errors in the Pandora data. Thus, the biases can be attributed to the uncertainties in the AMF calculations

Table 1. Relationship between NO₂ VCDs obtained from Pandora and OMI measurements at different solar zenith angles

	Slope	Intercept	R	Number of data
SZA<30°	0.28	0.42	0.50	35
30°<SZA<40°	0.45	0.21	0.82	37
40°<SZA<50°	0.35	0.38	0.51	47
50°<SZA<60°	0.31	0.42	0.40	35
60°<SZA	0.17	0.62	0.28	12

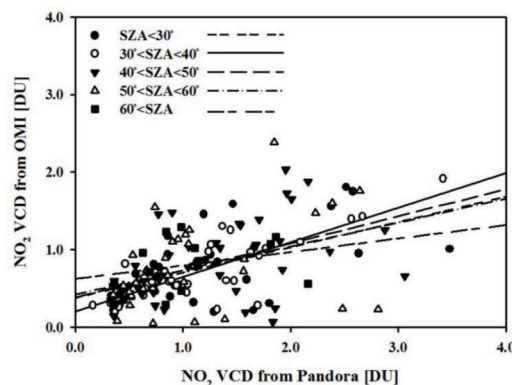
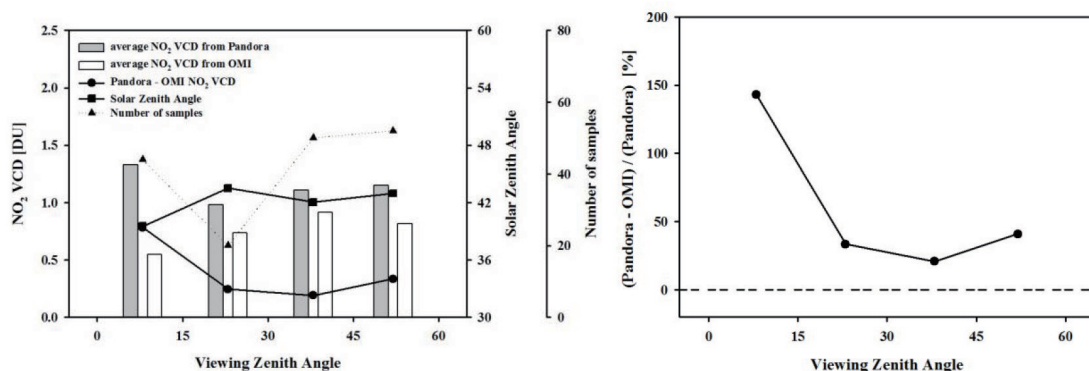
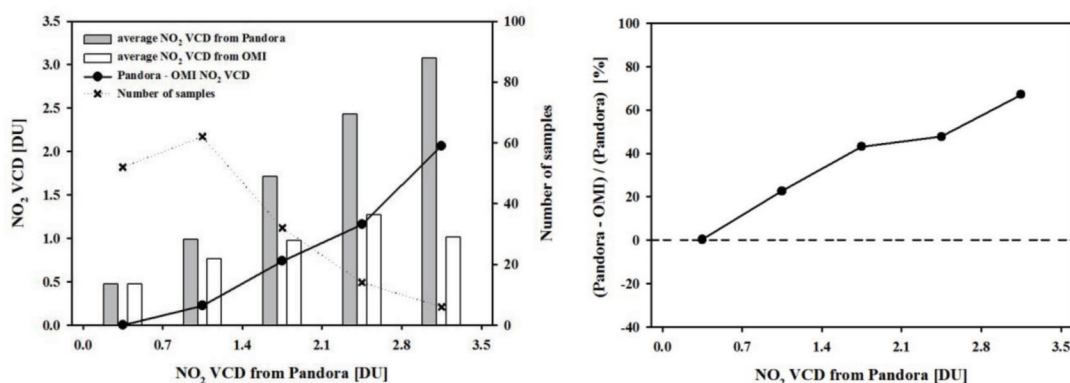


Fig. 7. Relationship between NO₂ VCDs obtained from Pandora and OMI measurements at various solar zenith angles.

for the OMI data. The differences in the two methods, aerosol loading, cloud characteristics and the spatial variability of NO₂ in Seoul with complicated NO_x emission locations are thought to cause larger difference in NO₂ VCD obtained from the two methods than those found at the previous investigation (Herman *et al.*, 2009).

Fig. 8 shows the variations of difference in NO₂

Fig. 8. Difference between NO₂ VCDs obtained from Pandora and OMI measurements at various viewing zenith angles.Fig. 9. Difference of NO₂ VCD between Pandora and OMI as a function of Pandora VCD.

VCDs obtained from Pandora and OMI depending on various Viewing Zenith Angles (VZA) of OMI. The difference between NO₂ VCDs from Pandora and OMI was larger when VZA was low, although the opposite trends are expected in general. This may be explained with the different geometry between the Pandora and OMI for the intercomparison. As the OMI is in sunsynchronous orbit, the SZA for the OMI measurements at Seoul changes by season only thus remains within 40° and 43°, while the viewing zenith angle may change widely depending on the viewing geometry of the satellite.

Fig. 9 shows the variations of difference in NO₂ VCDs obtained from Pandora and OMI depending on the Pandora NO₂ VCD. The difference between the two NO₂ VCDs tends to be larger both in the absolute values and relative (%) when the NO₂ VCD of Pandora

measurements are large. This tendency can be explained with the high concentrations of NO₂ usually indicate heavily polluted condition, thus the aerosol loading is expected to be high, as shown in Fig. 4. Thus, it is likely that the large aerosol contamination increase the uncertainty in NO₂ measurements.

In order to avoid the contamination by aerosol and clouds for the NO₂ measurements, the retrieved NO₂ VCDs from Pandora and OMI are compared when the cloud amount is less than 3 and AOD is less than 0.4, as shown in Fig. 10. The correlation coefficient between NO₂ VCD from Pandora and OMI was increased to 0.74 with the number of coincident data of 40. The slope and y-intercept between Pandora and OMI measurements were 0.49 and 0.25, respectively. The regression line slope of 0.49 shows that the OMI NO₂ VCD values are still underestimated compared to

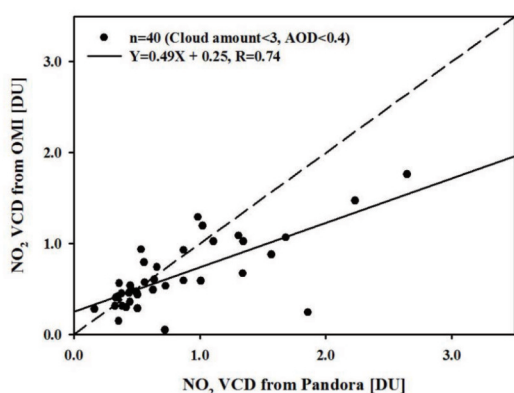


Fig. 10. Correlation between NO₂ VCDs from OMI and Pandora measurements for conditions where the cloud amount and AOD were low.

the Pandora data. However, the correlation coefficient ($R = 0.74$) between OMI and Pandora measurement was higher when the cloud amount and AOD were low, than the value ($R = 0.53$) between the two NO₂ VCDs for the entire measurement period. Thus, it can be inferred that the morphology and condition for clouds and aerosols increase the uncertainty of the retrieved OMI NO₂ VCD, since the shielding effect of the cloud and the aerosols may result in high uncertainty for the contaminated radiance fraction thus the air mass factor.

4. Summary and Conclusion

NO₂ VCD was measured using the ground-based Pandora from March 2012 to October 2013 in Seoul, Korea, and was compared with the coincident NO₂ VCD obtained from OMI. The correlation coefficient between the NO₂ VCDs from Pandora and OMI was 0.53. It was found that the correlation coefficient between the NO₂ VCD from OMI and Pandora was lower than the results of Herman *et al.* (2009) for the U.S. and Greece. The NO₂ VCD of OMI is underestimated compared to the Pandora measurements with the regression line slope of 0.33. For conditions where the cloud amount and AOD were low, the correlation coefficient between the NO₂ VCDs from

Pandora and OMI was increased to 0.74, with the slope and y-intercept of 0.49 and 0.25, respectively. The underestimation of OMI data was associated with cloud amount and AOD, which can be attributed to the different geometry and thus the uncertainties in the AMF calculations for the OMI data. However, the NO₂ VCD difference between the two measurements decreased as SZA increased. Thus, the differences in the geometry and spatial coverage of the two methods cause the difference in NO₂ VCD obtained from the two measurements. In general, the tropospheric NO₂ often causes the enhancement in NO₂ VCD due to the less variability of stratospheric NO₂, the further investigations need to be taken with measurements of the same spatial coverage and tropospheric NO₂ to identify the sources for such underestimation in NO₂ VCD in Seoul measured by OMI.

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