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Seasonal Variation of Total Column Formaldehyde, Nitrogen Dioxide, and Ozone Over Various Pandora Spectrometer Sites with a Comparison of OMI and Diurnally Varying DSCOVR-EPIC Satellite Data

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Abstract

Both The OMI (Ozone Monitoring Instrument) satellite and the Pandora ground-based instruments operate with spectrometers that have similar characteristics in wavelength range and spectral resolution that enable them to retrieve total column amounts of formaldehyde TCHCHO, and nitrogen dioxide TCNO2, and ozone TCO at 13:30 ± 0:45 local time. At most sites, Pandora shows a strong seasonal dependence for TCO and TCHCHO and little seasonal dependence for TCNO2, while OMI sees little seasonal dependence for TCHCHO and TCNO2 but does see the seasonal dependence for TCO. The seasonal behavior of TCHCHO is caused by plant growth and emissions from lakes that peak in the summer suggesting that OMI is not correctly retrieving TCHCHO all the way to the Earth's boundary layer. Since the OMI retrieval is around 13:30 local equator crossing time ± 0:45 and tends to occur near the frequent minimum of the daily TCNO2 time series, OMI underestimates the amount of air-pollution that occurs during each year. Better TCNO2 agreement occurs when the Pandora data is averaged between 13:00 and 14:00 hours local time. Comparisons of OMI total column NO_2 and HCHO with Pandora daily time series show both agreement and disagreement at various sites and days. Similar comparisons of OMI TCO with those retrieved by Pandora show good agreement in most cases. Additional comparisons are shown of Pandora TCO with hourly retrievals during a day from EPIC (Earth Polychromatic Imaging Camera) spacecraft instrument orbiting the Earth-Sun Lagrange point L_1.

1.0 Introduction

Formaldehyde, HCHO, is ubiquitous in the atmosphere and as with other VOCs (Volatile Organic Compounds) are emitted from natural and anthropogenic sources, such as plants, animals, biomass burning, fossil fuel combustion, and industrial processes (Zhang et al., 2019; Morfopoulos et al., 2021). Formaldehyde is mainly produced from the oxidation of VOCs such as isoprene, methane, and anthropogenic emissions (Wittrock, 2006). Formaldehyde can also be directly emitted from some sources, such as vehicle exhaust, tobacco smoke, building materials, and wood burning affecting pollution levels both indoors and outdoors. The majority of gaseous and atmospheric formaldehyde derive from microbial and plant decomposition (Peng et al., 2022). HCHO concentrations in the first few kilometers of the atmosphere vary depending on the location, time of day, season, and meteorological conditions. Some of the factors that influence total atmospheric column amounts of HCHO are:

- **Solar radiation**: Formaldehyde is photolyzed by solar ultraviolet radiation, which means it is broken down into smaller molecules and radicals. The photolysis rate of formaldehyde depends on the solar zenith angle, the cloud cover, and the atmospheric composition. Generally, formaldehyde photolysis is faster during mid-day and in the summer.
- **Temperature**: The thermal decomposition rate of formaldehyde increases with temperature, which means it is faster in warmer regions and seasons.
- **Humidity**: Formaldehyde reacts with water vapor in the atmosphere, forming formic acid and hydroxyl radicals. The reaction rate of formaldehyde with water vapor depends on the relative humidity, which varies with the temperature and the precipitation. Generally, formaldehyde reaction with water vapor is faster in humid regions and seasons.

The largest sources of NO_2 are obtained from fossil fuel burning from various types of automobiles truck emissions and power generation (Van der A, 2008; Stavrakou et al. 2020) followed by industrial

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processes and oil and gas production. Additional sources are soils under natural vegetation and the oceans, agriculture and the use of nitrogen rich fertilizers, forest fires, and lightning. In populated areas, anthropogenic sources of lower tropospheric NO_2 are larger than natural sources. Nitrogen oxides play a major role in atmospheric chemistry and the production and destruction of ozone in both the troposphere and stratosphere. In the boundary layer high concentrations of both HCHO and NO_2 are health hazards for humans.

HCHO, NO_2 and O_3 in the atmosphere are typically measured by several types of instruments.

- Airborne: The GeoTASO instrument is a spectrometer that measures formaldehyde and other trace gases from an aircraft. The GeoTASO data can be used to validate and improve the satellite retrievals of formaldehyde and to study the emission sources and transport processes of formaldehyde in the atmosphere (Judd et al., 2018).
- Satellite: The Ozone Monitoring Instrument (OMI) is a satellite sensor launched in July 2004 that measures HCHO, NO_2, O_3, and other atmospheric constituents from space. The OMI data can be used to monitor their global distribution and long-term trends, and to investigate the role of NO_2 and HCHO in atmospheric chemistry and air quality (Boeke et al., 2011). For ozone, DSCOVR (Deep Space Climate Observatory), located at the Earth-Sun gravitational balance Lagrange point L_1, contains a filter-based instrument EPIC (Earth Polychromatic Imaging Camera) capable of obtaining TCO once per hour (90 minutes in Northern hemisphere winter) simultaneously at 18 x 18 km^2 resolution for the entire sunlit globe at the Earth rotates (Herman et al., 2018). Other current satellite instruments also detect NO_2 and HCHO, such as The TROPOspheric Monitoring Instrument (TROPOMI).
- Ground-based Spectrometer: The Pandora spectrometer system forms a worldwide network of 67 direct sun observing instruments that match atmospheric observations with known laboratory spectra of HCHO, NO_2, and O_3 to obtain the total vertical column above the Pandora instrument every 2 minutes. Pandora uses a single-grating spectrometer and a charge-coupled device (CCD) 2048 x 64-pixel detector to record the direct-sun spectra in the ultraviolet and visible wavelength range, 280 – 525 nm with an oversampled 0.5 nm spectral resolution. The retrieval algorithm is based on a spectral fitting technique to retrieve the slant column densities of HCHO, NO_2 and other gases, and then convert them to vertical column densities using geometric air mass factors appropriate for direct-sun observations. Pandora spectrometers have been deployed in various field campaigns and locations to monitor the spatial and temporal variability of TCHCHO and TCNO2 to validate and improve the satellite observations of TCHCHO (Herman et al., 2009, Tzortziou et al., 2015, Spinei et al., 2018).

This study will examine the seasonal cycles of total column NO_2, HCHO, and O_3 seen by the Pandora instruments by examining multi-year (2021 – 2024) time series for seasonal and daily behavior at various sites and will compare with observations made from the OMI satellite overpass measurements of the Pandora sites. Pandora ozone measurements will be additionally compared to hourly data obtained from EPIC. All of the Pandora data used in this study are after the upgrade of the instruments to eliminate internal sources of HCHO (Spinei, et al., 2021). Part of this study (TCNO2 and TCO) is an extension of Herman et al. (2019) using Pandora data (2012 – 2017) before the internal upgrade. A difference is that Pandora TCO is now compared with hourly TCO retrieved by DSCOVR-EPIC.

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2.0 Examples of Seasonal and Daily Variation of HCHO and NO_2

Worldwide Pandora data for 147 sites can be downloaded from the Austrian Pandonia website https://data.pandonia-global-network.org/ or from a NASA backup site updated every week. https://avdc.gsfc.nasa.gov/pub/DSCOVR/Pandora/DATA_02/. Of interest for this study are the Level-2 (L2) time series ASCII files. For example, the Bronx New York City files for Pandora instrument 180 for TCNO2 data are in Pandora180s1_BronxNY_L2_rnvs3p1-8.txt, TCHCHO in Pandora180s1_BronxNY_L2_rfus5p1-8.txt, and TCO data in Pandora180s1_BronxNY_L2_rout2p1-8.txt. The data are arranged in irregular columns that are identified in the metadata header for each file. In the current version, column 1 contains the date and time for each measurement and column 39 contains measured column density in moles m^{-2} (multiply by $6.02214076 \times 10^{23}/2.6867 \times 10^{20} = 2241.4638$ to convert to DU where 1 DU = 2.6867×10^{20} molecules m^{-2}). Pandora data also contain measurements of water vapor, and SO_2 total column amounts.

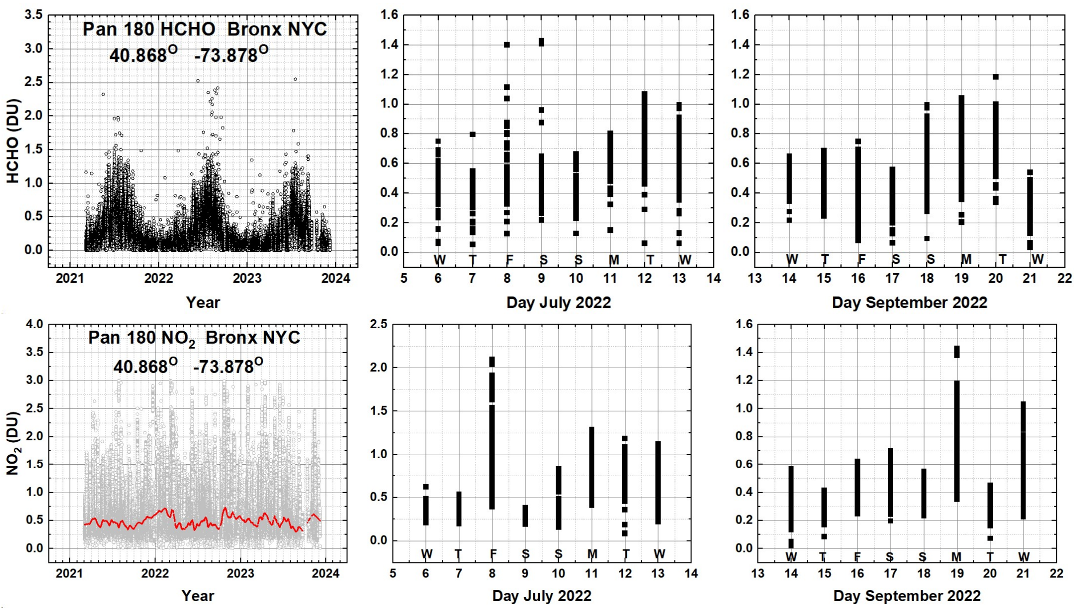

Fig. 01 Seasonal and daily behavior of HCHO and NO_2 from Pan 180 located in the Bronx, NYC at 40.868°N, -73.878°W. The red line is a Lowess(0.03) fit to the data, which is approximately a 1-month local least-squares average. The Local principal investigator for Pan 180 is Dr. Luke Valin.

Figure 1 shows the seasonal and daily variation of total column HCHO (TCHCHO) and NO_2 (TCNO2) using all of the Pandora data obtained during each day in Bronx, New York. The daily data for 1 week in July and September shows the range of values for both weekdays and weekends. When all the TCHCHO data are plotted as an aggregate for 3 years, there is a strong seasonal pattern with a maximum in July and a minimum near the end of December. The summer seasonal dependence of TCHCO is consistent with the surface HCHO values observed by the ground-based Air-Quality System AQS (Wang et al., 2022). For TCNO2, there is only a weak seasonal pattern with small maxima in January-February, since the sources of NO_2 are largely from the nearly constant flow of cars and trucks.

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Figure 2 shows the daily average of Pandora data obtained from diurnal variation of TCHCHO and $TCNO_2$ from 09:00 to 15:00 local standard time (GMT – 5) (Pandora180s1_BronxNY_L2_rfus5p1-8.txt). The primary emission sources of atmospheric HCHO include direct emission from vegetation, the soil, biomass burning, and decaying plant and animal matter. This is consistent with the Bronx location that is adjacent to a large, vegetated park with a small lake near Fordham University. The same seasonal dependence and magnitude occurs when the Pandora sampling is restricted to 13:00 to 14:00 local standard time similar to the OMI overpass time.

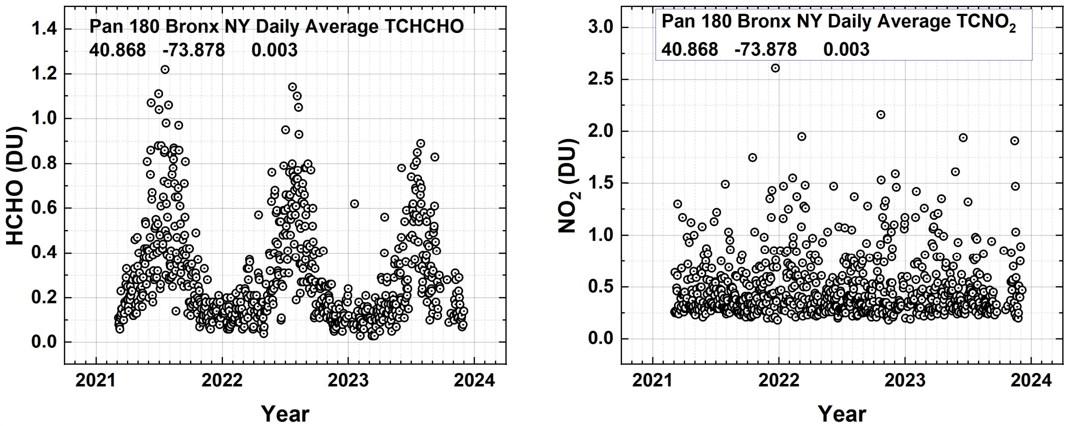

Fig. 02 The daily average seasonal variation of HCHO and NO_2 over Fordham University in Bronx, New York City from Pandora 180 at 40.868° latitude and -73.878° longitude. Each point is a daily average of the data in Fig.1. Local principal investigator: Dr. Luke Valin

There are 3 Pandora sites in New York City and one in nearby Bayonne, New Jersey. The NYC sites are in the Bronx-Fordham University, Manhattan-City College NY (CCNY), Queens-Queens College. All four successfully measure NO_2 in the period 2021 – 2023. A strong seasonal cycle in TCNO2 is not seen (Figs. 1 and 2) in the traffic driven production of NO_2.in the Bronx, New York. The mean values of total column NO_2 (TCNO2) for each the 3 New York sites are 0.5 DU while the TCNO2 for the port city of Bayonne, NJ is substantially higher at 0.7 DU. None of the four sites show any seasonal TCNO2 pattern. For TCHCHO, all four sites show an annual seasonal cycle with three of the sites having a 3-year average of 0.3 DU except for the Queens site at 0.45 DU. The Queens site may be anomalous because of many missing points affecting the average.

Similar behavior is seen at other sites such as the one from New Haven Connecticut located in a vegetated area adjacent to two rivers (Fig.3). TCHCHO has a clear summer peak in June – July and a suggestion of a winter TCNO2 peak in December – January coinciding with the maximum heating season.

The seasonal variation of TCHCHO could not be studied prior to the internal upgrade of Pandora after 2019 that was needed because of the release of HCHO from polyoxymethylene (POM-H Delrin) out-gassing as a function of daytime temperature within the Pandora sun-pointing head (Spinei et al., 2021)

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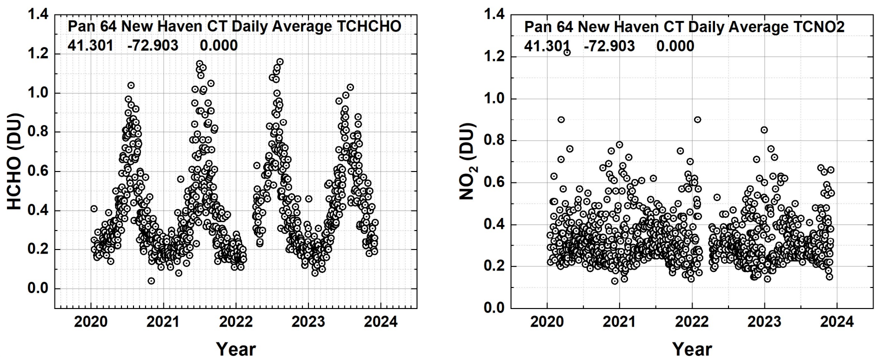

Fig. 03 The seasonal variation of TCHCHO and TCNO2 over New Haven Connecticut from Pandora 64 at 41.301^{O}N latitude and -72.903^{O}W longitude. Each point is a daily average. Local principal investigator: Dr. Nader Abuhassan

An equatorial Pandora site (Fig. 4) with a sufficiently long data record is located in Bangkok, Indonesia near a small park and lake. Bangkok has a tropical monsoon climate with three main seasons: hot season from March to June, rainy season from July to October, and cool season between November and February. TCHCHO has a seasonal cycle peaking in March – April when the sun is nearly overhead and a minimum during the rainy season. TCNO2 has a clear seasonal cycle peaking in December – January and a minimum during the rainy season.

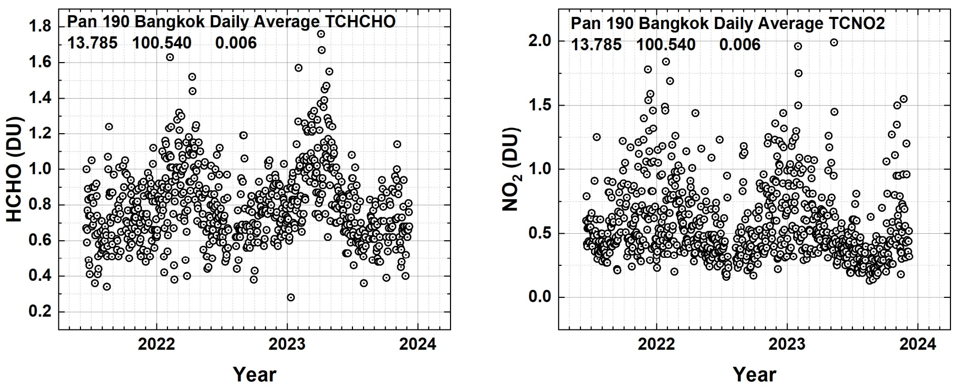

Fig. 04 The seasonal variation of TCHCHO and TCNO2 over equatorial Bangkok Indonesia at 13.785^{O}N and 100.540^{O}E. The local principal investigator is Surassawadee Phoompanit.

An unusual counter example to the typical seasonal cycle is for the Pandora site located in Tel Aviv Israel. Tel Aviv has significant amounts of HCHO but does not show seasonal variation in TCHCHO because of a coastal location in a warm climate even at midlatitudes located at 32.113^{O}N, 34.085^{O}E that has essentially two seasons, a cool, rainy winter: October – April and a dry, hot summer: May – September. The result is there is limited seasonal increase in vegetational activity and no seasonal

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variation in HCHO (Fig. 5). However, TCNO2 shows a clear seasonal increase in the December - January months frequently reaching over 0.5DU. The TCNO2 seasonality is similar to that of the near-surface concentrations reported by Boersma et al., (2009). The Pandora instrument 182 is located at Tel Aviv University about 1 km from a major highway. Tel Aviv has frequent episodes of smog associated with heavy automobile and truck traffic (Newmark, 2001).

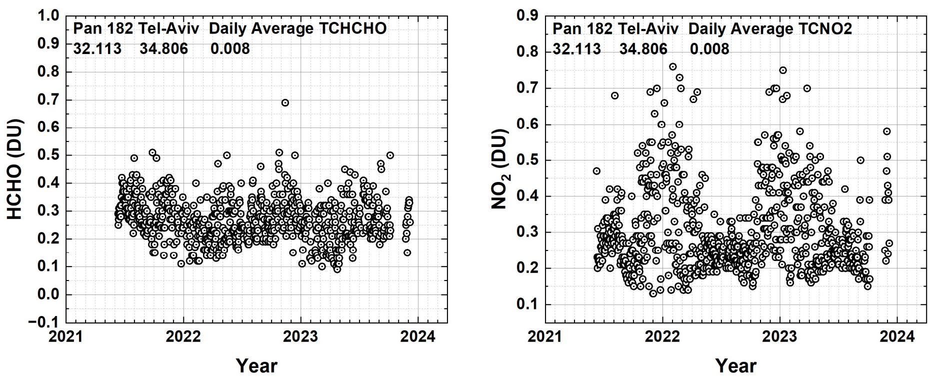

Fig. 05 Seasonal variation in daily average TCHCHO and TCNO2 in Tel Aviv Israel from Pandora 182 located at 32.113^{O}N, 34.085^{O}E at a height of 8 meters. The local principal investigator for Pan 182 is Dr. Michal Rozenhaimer.

Finally, a Pandora example from the Southern Hemisphere SH from Wakkerstroom, South Africa located in a rural area near the ocean a few degrees outside of the equatorial zone at -27.359^{O}S and 30.144^{O}E.

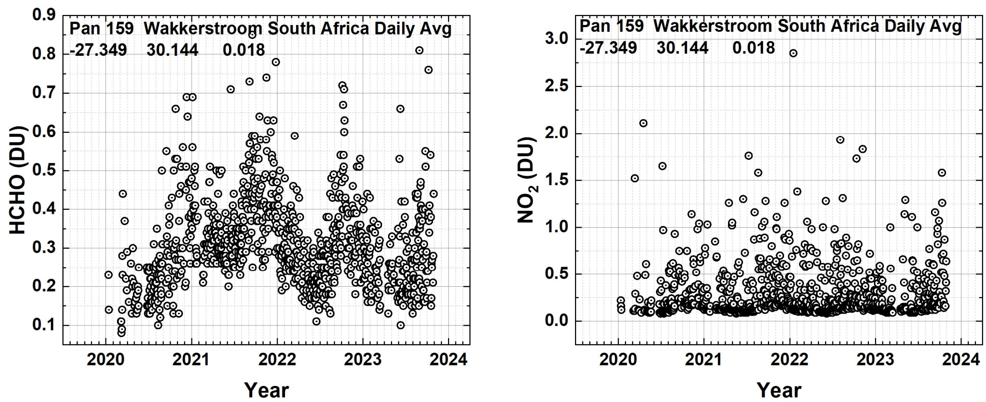

Fig. 06 Seasonal variation in daily average HCHO and NO_2 in Wakkerstroom South Africa from Pandora 159 located at -27.359^{O}S and 30.144^{O}E. Local principal investigator: B. Scholes

As expected, the peak value of TCHCHO occurs near the SH summer in November – December, while TCNO2 has no significant seasonal dependence.

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2.1 Comparisons Between Pandora and OMI Retrievals of NO_2 and HCHO

In this section two types of comparisons of Pandora with OMI satellite data are considered. The first is the long-term TCNO2 time series consisting of the data record of Pandora and OMI from 2020 – 2023. The second looks at a few selected days and compares Pandora values with the mid-afternoon OMI overpass at times near 13:30 hours equator crossing time. Pandora and OMI data are matched at the same GMT and then converted to local solar time, GMT + Longitude/15. The OMI overpass HCHO and NO_2 data are found at https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L2OVP/OMHCHO/.

https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L2OVP/OMNO2/

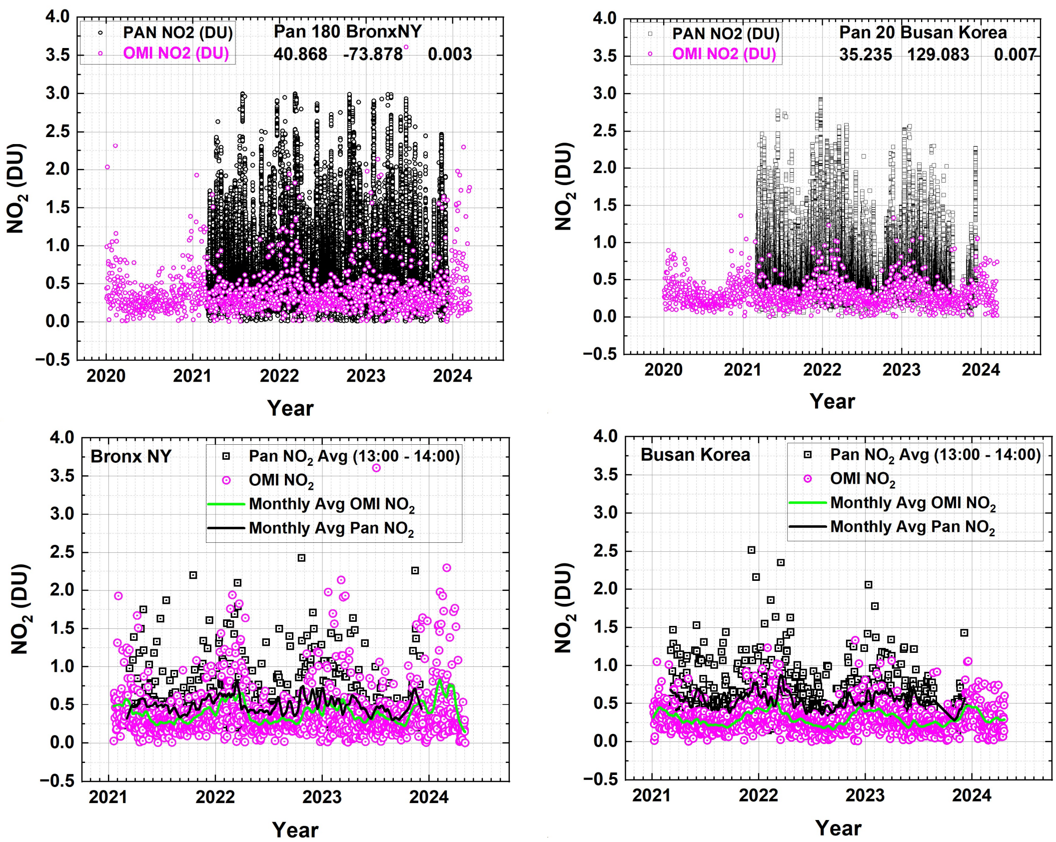

Fig. 07 Upper Panels: Comparison of OMI (approximately 13:30) and Pandora (09:00 – 16:00) total column NO_2 time series in Bronx NY (40.868^{O}N, -73.878^{O}W) and Busan Korea (35.235^{O}N, 129.083^{O}E). Lower Panels: Pandora averaged between 13:00 – 14:00 hours. Local principal investigator for Pan20 is Jae Hwan Kim and for Pan 180 is Dr. Luke Valin

Figure 7 illustrates that OMI only captures a fraction of the daily values of total column NO_2 and fails to detect the extent of the daily pollution at both the Bronx New York City and Busan Korea sites. This is

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because OMI and other polar orbiting satellites only collect data once per day (occasionally twice per day) at any given location at mid-afternoon, frequently when TCNO2 is below its daily maximum (Herman et al., 2019). The lower panels of Fig. 7 show a comparison with OMI when Pandora data are averaged between 13:00 and 14:00, which contains the OMI overpass time. This shows that OMI and Pandora TCNO2 agree more closely at the overpass time. The monthly average Pandora (13:00 to 14:00) values are larger than those from OMI especially at Busan suggesting that the OMI field of view 13 x 24 km^2 may include areas of lower NO_2 values over the nearby ocean. In the case of the Bronx, the differences are not statistically significant.

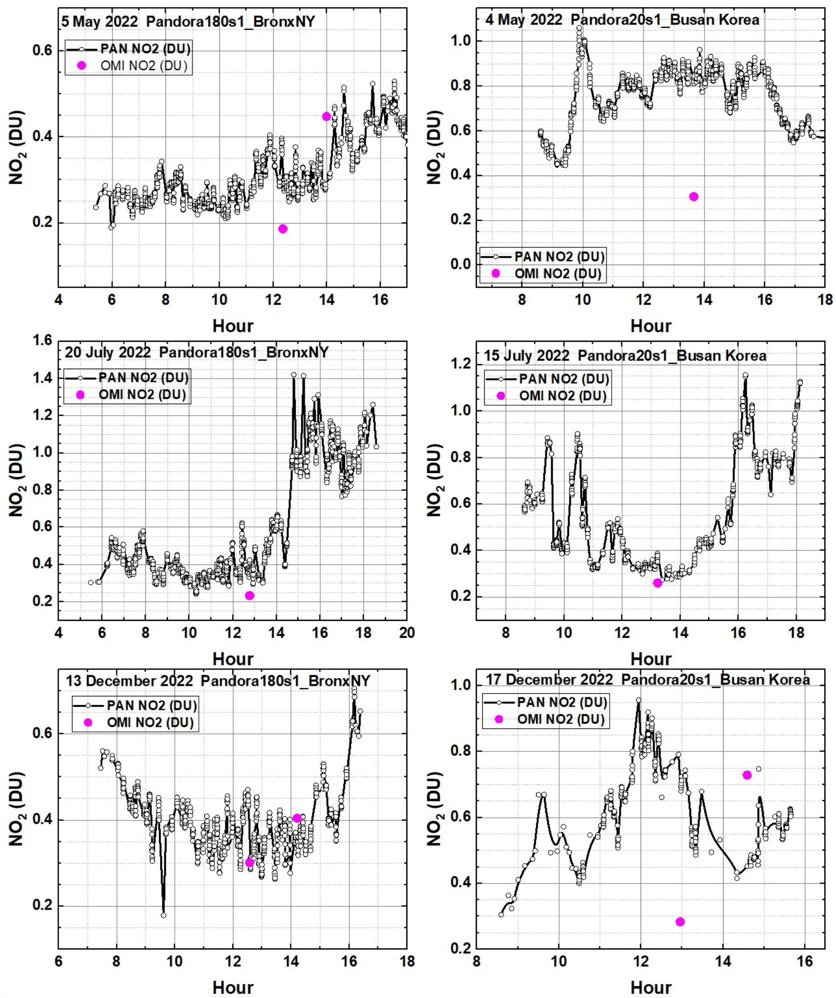

Fig. 08 A comparison between Pandora and OMI (purple circle) total column NO_2. The Local principal investigator for Pan 180 is Dr. Luke Valin and for Pan 20 is Dr. Jae Hwan Kim.

Figures 8 and 9 show the diurnal daytime variation for 3 selected days for Pandora retrieved total column NO_2 and HCHO compared with OMI at the overpass time for both Bronx New York City and

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Busan Korea. These are typical examples of the highly variable hourly variation of TCHCHO and TCNO2 as observed by Pandora at most sites. The hourly variation of TCHCHO and TCNO2 on any given day can take on unique shapes depending on the presence of surface winds, changes in temperature, and sunlight. The variability of TCNO2 is also driven by the strength of the sources (automobile exhaust, power generation, industry, etc.) as well as the meteorological conditions. Occasionally, there is good agreement but in general the OMI overpass values do not agree with Pandora retrieved values for both TCHCHO and TCNO2. In the sample shown in Figures 8 and 9, the cases of agreement are less than 50 %.

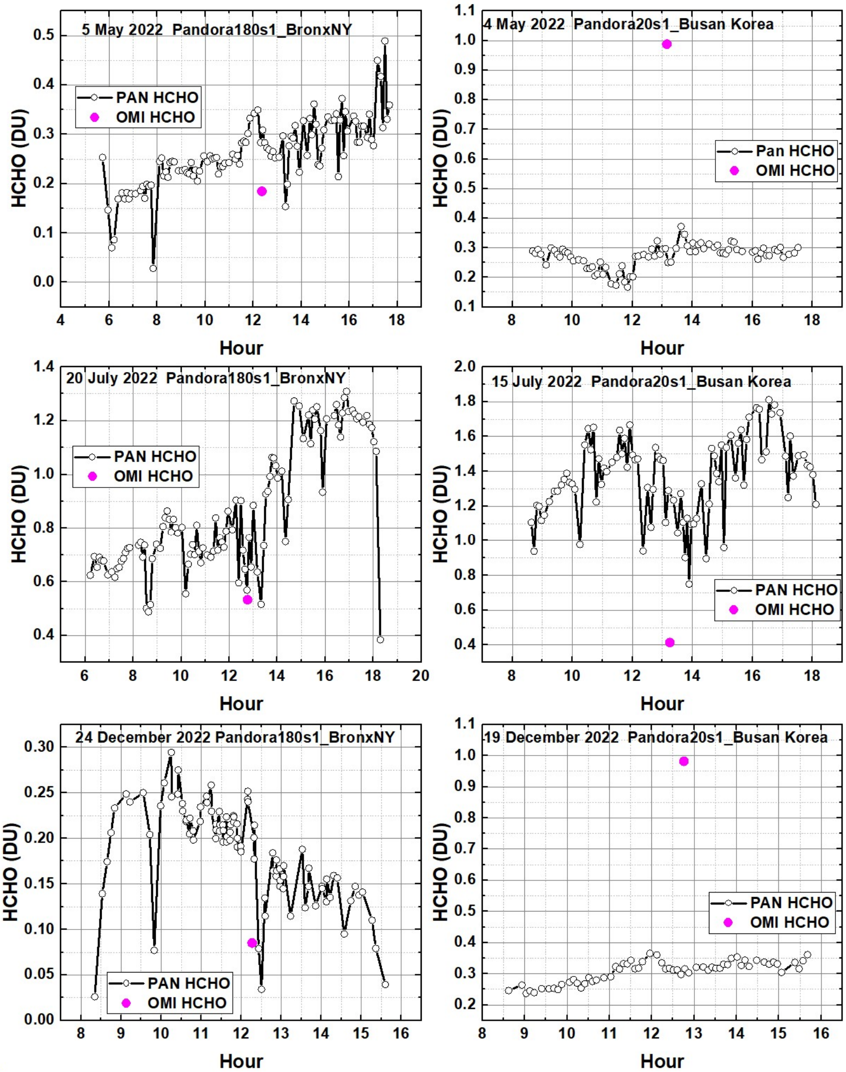

Fig. 09 A comparison between Pandora and OMI (purple circle) total column HCHO. The Local principal investigator for Pan 180 is Dr. Luke Valin and for Pan 20 is Dr. Jae Hwan Kim.

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Figure 9 illustrates the comparison of TCHCHO retrievals from Pandora and OMI. The spectral fitting algorithm for detecting HCHO absorption is in the same short wavelength UV spectral region as used for ozone retrieval, 300 – 360 nm (Gratien et al. 2007). This means that the retrieval sensitivity for "seeing" all the way to the surface is reduced. Also, small errors in ozone retrieval can affect the detection of HCHO. This problem is not present for the spectral fitting of NO_2, since that usually occurs in the visible range 410 – 450 nm where there is only interference from a weak and narrow water vapor line.

Pandora TCHCHO daily average data (Fig. 10) for University of Toronto in Toronto-Scarborough (Lat = 43.784^{O}N, Lon = -79.187^{O}W) shows clear peaks in the summer from the vegetation in a surrounding park area whereas TCNO2 shows only small seasonal variation with small peaks also occurring in the summer for values less than 0.4 DU. Higher values do not show any seasonal variation. The University of Toronto is located near a major highway, which is a strong source of NO_2 from automobiles and trucks. Unlike many sites, OMI TCHCHO data over Toronto East (centered on 43.74^{0}N, -79.27^{0}E about 8 km from the Pandora site) also shows sporadic summer peak values that are higher than the Pandora daily averages and all of the Pandora data (Fig. 10b).

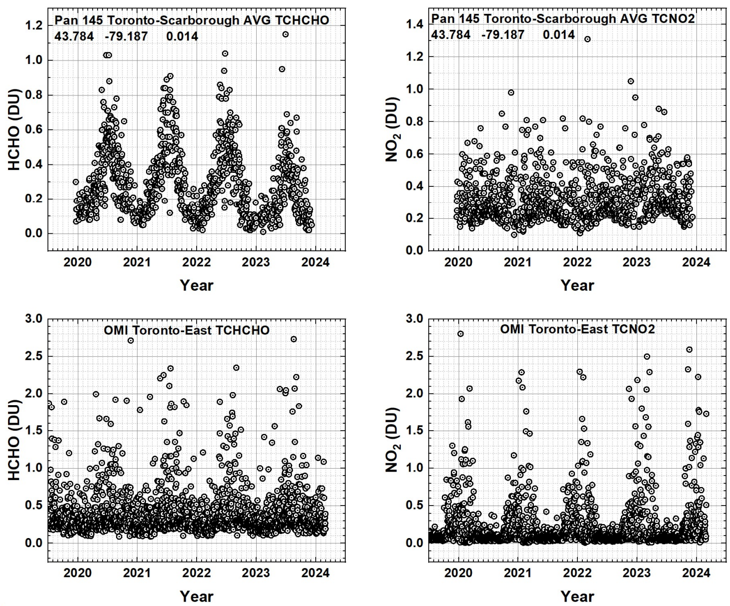

Fig. 10a A comparison of Pandora TCHCHO and TCNO2 daily average total column amounts for Toronto-Scarborough University of Toronto and OMI data for Toronto East (43.740^{O}N, -79.270^{O}W at approximately 14:20 Local Standard Time). The local principal investigator for Pan 145 is Dr. Vitali Fioletov.

The Pandora site is in a park setting outside of Toronto while the nominal OMI Toronto East location and OMI's field of view includes the city. The OMI NO_2 amounts at 14:20 show a clear peak in December – January corresponding to the peak winter heating for the city, while the remote Pandora site only shows NO_2 from the highway traffic. HCHO peaks in June – July for both OMI and Pandora, but the Pandora seasonal cycle is much stronger. Using all the Pandora data for Toronto-Scarborough (Fig.11), there is no hint of an TCNO2 annual cycle whereas the TCHCHO cycle is obvious with maximum values close to that seen by OMI.

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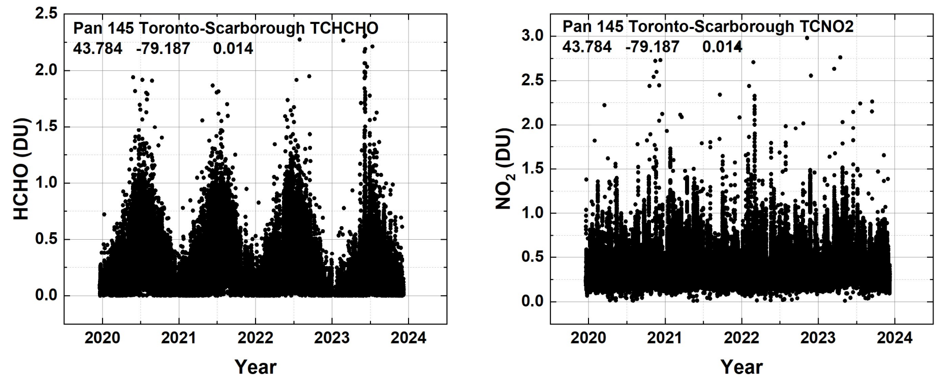

Fig. 10b The same as Fig. 10a but for all the Pandora 145 data.

2.2 Total Ozone Column

The retrieval of total column ozone amounts TCO serves as a check on the calibration of both OMI and Pandora that is also needed for spectrally overlapping TCHCHO retrievals. Comparisons of Pandora TCO with TCO measured by OMI show good agreement suggesting both instruments are well calibrated in the UV range also needed for retrieving TCHCHO. The good TCO agreement is partly because most of the O_3 is in the stratosphere near 25 km and the fact that ozone is slowly changing spatially over the OMI field of regard for the overpass data. Figure 11 shows an example obtained over Washington DC from the roof of the NASA Headquarters building and Fig. 12 is from the roof of a building at Pusan University, Korea.

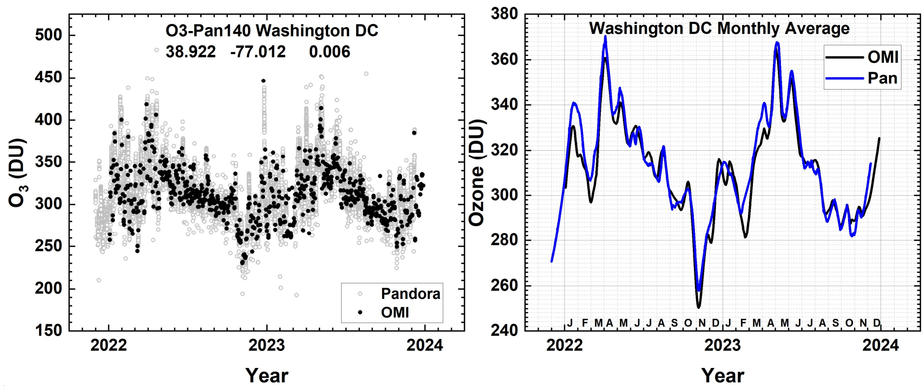

Fig. 11 A comparison of OMI Total Column Ozone values with those obtained from Pandora 140 over the Washington DC site at 38.922°N and -77.012°W. The local principal investigator for Pan 140 is Dr. Jim Szykman.

A test of Pandora UV data is a comparison between EPIC, OMI and Pandora TCO at the specific OMI and EPIC overpass times (Fig. 13a and 13b). that shows good agreement within 1 to 3 %. OMI TCO overpass data for all Pandora sites and more are available from https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L2OVP/OMTO3/

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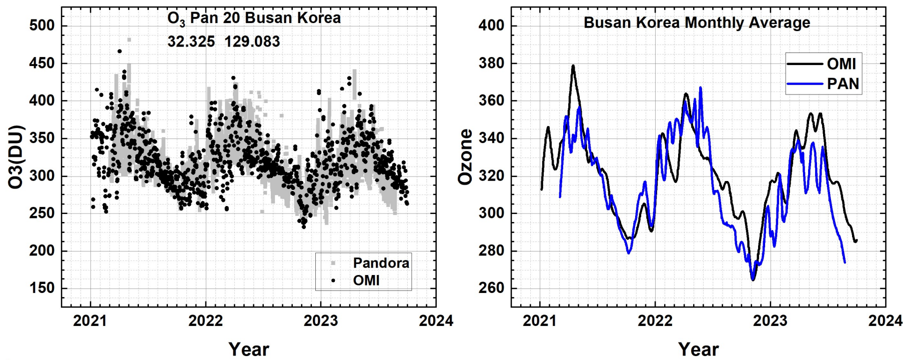

Fig. 12 A comparison of OMI Total Column Ozone values with those obtained from Pandora 20 over the Busan, Korea site at 32.325^{O}N and 129.083^{O}E. The local principal investigator for Pan20 is Jae Hwan Kim.

There is also good agreement between daily OMI TCO with that obtained from Pandora (Fig. 13a) at most sites. The values obtained at Granada differ by about 8 DU or 2.8 %.

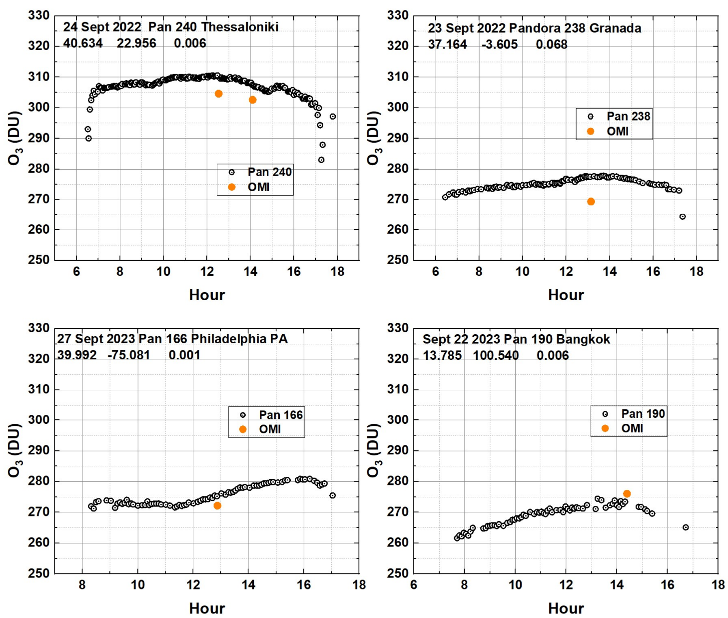

Fig. 13a A comparison of Pandora and OMI retrievals of total column O_3 at the time of the OMI satellite overpass. Local Principal Investigators: Pan 240 Alexander Cede, Pan 238 Inmaculada Foyo Moreno, Pan 166 Lukas Valin, and Pan 190 Surassawadee Phoompan.

The diurnal variation of TCO seen by Pandora can be compared (Fig. 13b) with that observed by the Earth Polychromatic Imaging Camera (EPIC) on the DSCOVR (Deep Space Climate Observatory) satellite orbiting about the Earth-Sun gravitational balance Lagrange-1 point (Herman et al., 2018). EPIC obtains simultaneous data from sunrise to sunset once per hour (once per 90 minutes during Northern

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Hemisphere winter) as the Earth rotates in EPIC's FOV (field of view). Examples of EPIC's view of the whole illuminated Earth are available from https://epic.gsfc.nasa.gov/. The spatial resolution for TCO is 18 x 18 km^2 at the center of the image (the color images have 10 x 10 km^2 resolution).

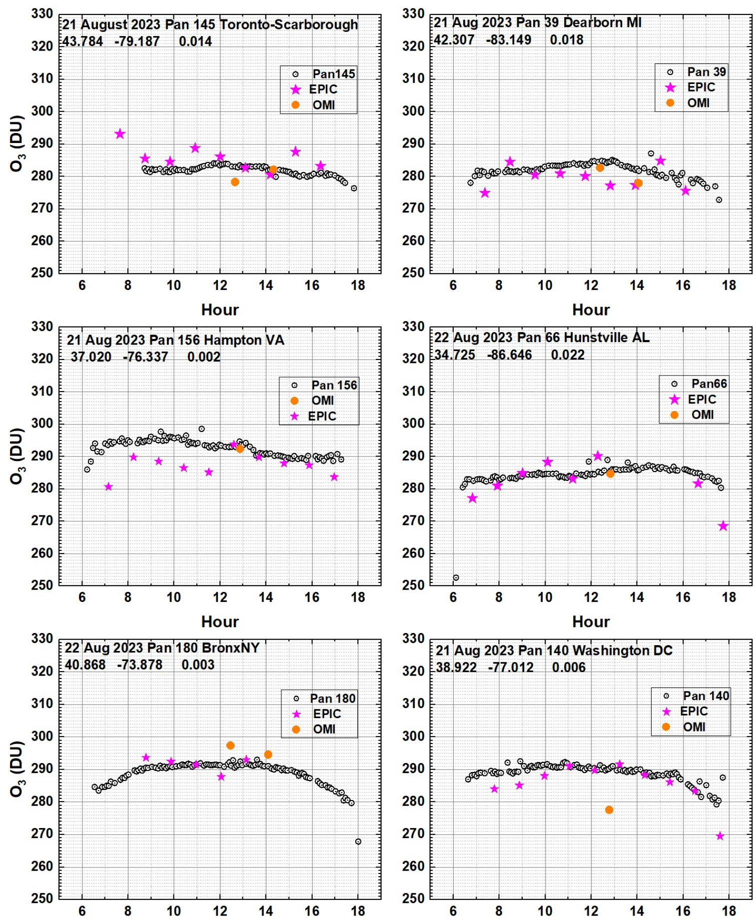

Fig. 13b A comparison of Pandora (Open Circles), EPIC (magenta stars), and OMI (orange circles) retrievals of total column O_3 at the times of the satellite overpasses. Local Principal Investigators: Pan 145 Vitali Fioletov, Pan 66 Lukas Valin, Pan 39 Lukas Valin, Pan 156 Alexander Cede, Pan 66 Nader Abuhassan, Pan180 Lukas Valin, and Pan 140 Jim Szykman

The TCO values in the early morning and late afternoon are not correctly retrieved for both Pandora and EPIC because of the high solar zenith angle exceeding 75^{O}. For the cases shown, the TCO data are properly retrieved between 07:00 and 17:00 local solar time. The 10:20 and 11:30 EPIC value for Hampton, VA of 286.5 and 285DU differs from Pandora by -3 %. Other differences are smaller. Occasionally, OMI differs from Pandora values as is the case, -4.6 %, for 21 August 2023 over Washington, DC.

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3.0 Summary

Typical examples of the seasonal variability of HCHO, NO_2, and O_3 in terms of their measured total column TCHCHO, TCNO2, and TCO have been presented from both Pandora Spectrometer instruments and the OMI spectrometer instrument overpass retrievals of selected Pandora sites. For TCO, an additional hourly comparison is made with the EPIC instrument located in an orbit about the Earth-Sun Lagrange-1 point. For most sites, OMI does not observe the strong seasonal variation of TCHCHO that is clearly seen in the Pandora data. The lack of OMI seasonal variation in TCHCHO at most sites suggests that OMI is not seeing the lowest layers of the HCHO variation.

OMI TCNO2 at one shown site, Toronto-Scarborough, appears to show seasonal variability that the Pandora 145 does not see. This could be because OMI is detecting the NO_2 source from winter heating in the city, while the Pandora site (University of Toronto campus) is fairly remote from Toronto city buildings and is mostly affected road traffic as the source of NO_2.

A comparison between the multi-year time series of Pandora and OMI TCNO2 in urban areas shows that OMI is underestimating the degree of atmospheric pollution. The results for TCNO2 and TCO agree with data, 2012 – 2017, from a previous study before the Pandora upgrade (Herman et al., 2019). When Pandora is limited to an average of data obtained between 13:00 and 14:00 hours, the agreement between Pandora and OMI TCNO2 is much better. Comparisons of daily time series TCHCHO and TCNO2 with OMI overpass values show agreement about 50 % of the time.

Total column ozone agrees well in both seasonal variation and in the comparison with Pandora at the OMI overpass time. Given the nature of the ozone retrieval algorithm, the good agreement with TCO suggests that the UV calibrations for both Pandora and OMI are correct. There is good agreement between Pandora TCO with the hourly TCO obtained from the DSCOVR-EPIC instrument observing the Earth from an orbit about the Earth-Sun gravitational balance Lagrange-1 point.

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Author contribution:

Jay Herman is responsible for writing the paper and creating the figures. Jianping Mao obtained the EPIC overpass data for the Pandora sites and discussed aspects of the paper.

Data Availability

Worldwide Pandora data for 63 sites can be freely downloaded from the Austrian Pandonia website https://data.pandonia-global-network.org/ or from a NASA backup site updated every week. https://avdc.gsfc.nasa.gov/pub/DSCOVR/Pandora/DATA_02/

The OMI overpass TCHCHO and TCNO2 data are found at https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L2OVP/OMHCHO/.

https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L2OVP/OMNO2/

OMI TCO overpass data are available from https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L2OVP/OMTO3/

Competing interests:

The authors declares that they have no conflicts of interest.

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Figure Captions

Fig. 1 Seasonal and daily behavior of HCHO and NO_2 from Pan 180 located in the Bronx, NYC at 40.868^{O}N, -73.878^{O}W. The red line is a Lowess(0.03) fit to the data, which is approximately a 1-month local least-squares average. The Local principal investigator for Pan 180 is Dr. Luke Valin.

Fig. 2 The daily average seasonal variation of HCHO and NO_2 over Fordham University in Bronx, New York City from Pandora 180 at 40.868^{O} latitude and -73.878^{O} longitude. Each point is a daily average of the data in Fig.1. Local principal investigator: Dr. Luke Valin

Fig. 3 The seasonal variation of TCHCHO and TCNO2 over New Haven Connecticut from Pandora 64 at 41.301^{O}N latitude and -72.903^{O}W longitude. Each point is a daily average. Local principal investigator: Dr. Nader Abuhassan.

Fig. 4 The seasonal variation of TCHCHO and TCNO2 over equatorial Bangkok Indonesia at 13.785^{O}N and 100.540^{O}E. The local principal investigator is Surassawadee Phoompanit.

Fig. 5 Seasonal variation in daily average TCHCHO and TCNO2 in Tel Aviv Israel from Pandora 182 located at 32.113^{O}N 34.085^{O}E at a height of 8 meters. The local principal investigator for Pan 182 is Dr. Michal Rozenhaimer.

Fig. 6 Seasonal variation in daily average HCHO and NO_2 in Wakkerstroom South Africa from Pandora 159 located at -27.359^{O}S and 30.144^{O}E. Local principal investigator: B. Scholes

Fig. 7 Comparison of OMI (approximately 13:30) and Pandora (09:00 – 16:00) total column NO_2 time series in Bronx NY (40.868^{O}N, -73.878^{O}W) and Busan Korea (35.235^{O}N, 129.083^{O}E). Local principal investigator for Pan20 is Jae Hwan Kim and for Pan 180 is Dr. Luke Valin

Fig. 8 A comparison between Pandora and OMI (purple circle) total column NO_2. The Local principal investigator for Pan 180 is Dr. Luke Valin and for Pan 20 is Dr. Jae Hwan Kim.

Fig. 9 A comparison between Pandora and OMI (purple circle) total column HCHO. The Local principal investigator for Pan 180 is Dr. Luke Valin and for Pan 20 is Dr. Jae Hwan Kim.

Fig. 10a A comparison of Pandora TCHCHO and TCNO2 daily average total column amounts for Toronto-Scarborough University of Toronto and OMI data for Toronto East (43.740^{O}N, -79.270^{O}W at approximately 14:20 Local Standard Time). The local principal investigator for Pan 145 is Dr. Vitali Fioletov.

Fig. 10b The same as Fig. 10a but for all the Pandora data.

Fig. 11 A comparison of OMI Total Column Ozone values with those obtained from Pandora 140 over the Washington DC site at 38.922^{O}N and -77.012^{O}W. The local principal investigator for Pan 140 is Dr. Jim Szykman.

Fig. 12 A comparison of OMI Total Column Ozone values with those obtained from Pandora 20 over the Busan, Korea site at 32.325^{O}N and 129.083^{O}E. The local principal investigator for Pan20 is Jae Hwan Kim.

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Fig. 13a A comparison of Pandora and OMI retrievals of total column O_3 at the time of the OMI satellite overpass. Local Principal Investigators: Pan 240 Alexander Cede, Pan 238 Inmaculada Foyo Moreno, Pan 166 Lukas Valin, and Pan 190 Surassawadee Phoompan.

Fig. 13b A comparison of Pandora (Open Circles), EPIC (magenta stars), and OMI (orange circles) retrievals of total column O_3 at the times of the satellite overpasses. Local Principal Investigators: Pan 145 Vitali Fioletov, Pan 66 Lukas Valin, Pan 39 Lukas Valin, Pan 156 Alexander Cede, Pan 66 Nader Abuhassan, Pan180 Lukas Valin, and Pan 140 Jim Szykman.