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Delaware Basin Health and Air Quality
Spatiotemporal Analysis of Air Pollutants Collected from Ground and Space
Instruments Around the Guadalupe Mountains and
Carlsbad Caverns National Parks

DEVELOP Technical Report

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1. Abstract

Nitrogen dioxide (NO₂) is a precursor for secondary air pollutants, which are associated with decreased visibility, and decreased ecosystem and respiratory health. NO₂ is a growing threat to national parks within the Delaware Basin where nearby oil and gas activity contributes to deteriorating park conditions, implying adverse effects on the local tourism economy and public health. To demonstrate spatial and temporal patterns of air pollution in the parks, we examined average monthly, seasonal, and annual tropospheric column concentrations of NO₂ in Carlsbad Caverns (CAVE) and Guadalupe Mountain (GUMO) National Parks. We used both the NASA Ozone Monitoring Instrument (OMI) and the European Space Agency (ESA) Tropospheric Monitoring Instrument (TROPOMI) to map NO₂ tropospheric column densities. Using ground-based emissions values from the National Oceanic and Atmospheric Administration (NOAA) and the New Mexico Oil Conservation Division (OCD) for two nearby natural gas processing plants (Indian Basin Gas Plant and South Carlsbad Plant), we extrapolated monthly trends from these point sources and compared seasonal emissions levels with the measurements recorded by OMI and TROPOMI. The NEI data show an 8% increase in flaring from 2013–2021. OMI measured a 38.3% NO₂ increase over the Delaware Basin, 15.29% increase over CAVE, and 4.26% decrease over GUMO from 2011–2018. TROPOMI measured a -1% NO₂ change over the Delaware Basin, 3% over CAVE, and 7% over GUMO from 2018–2020. The analysis indicates a positive correlation between emissions from fossil fuel exploration and NO₂ concentrations above CAVE and GUMO. This information will inform National Park Service air quality monitoring and policy efforts to ensure compliance with the Clean Air Act.

2. Introduction

2.1 Background Information

Located near the western Texas and southern New Mexico border, the Delaware Basin is home to both Guadalupe Mountains National Park (GUMO) and Carlsbad Caverns National Park (CAVE) (Figure 1). The Delaware Basin is a part of a larger Permian Basin that is known for its oil and gas deposits (Wright et al., 2011). The Permian Basin continues to be the most productive oil basin, and one of the most productive natural gas basins, in the United States. It produces over five million barrels of oil and over twenty trillion cubic feet of natural gas per day, according to the U.S. Energy Information Administration. Aside from the exceptional case that took place in 2020 during the global COVID-19 pandemic, rig counts have risen in the Permian basin since January 2017, suggesting the attractiveness of this region to oil and gas drillers (“Drilling Productivity Report,” n.d.). The oil and gas extraction process releases air pollutants in many ways. Primarily, the machinery required to run these oil and gas wells emit pollutants. In addition, natural gas leaks combined with the deliberate burning of gases (also known as flaring) are common, emitting additional pollutants (Veloski et al. 2014).

Over the past decade, GUMO and CAVE reported deteriorating visibility and air quality. During this same time, increased oil and gas activity has occurred near the park boundaries. Oil and gas activity emissions often include pollutants such as nitrogen dioxide (NO₂). This pollutant can have a myriad of effects on ecosystems and public health, such as decreased visibility, increased water acidity, and altered soil chemistry (Follett et al., 2001). In the short term, people with acute cardiovascular and pulmonary conditions who are exposed to NO₂ can experience increased severity of their symptoms. Meanwhile, long-term exposure is linked to the development of respiratory conditions, such as recurring infections and asthma (Latza et al., 2009).

GUMO and CAVE are classified by the Clean Air Act as Class I areas. The Class I indication is the greatest level of air quality protection administered by the National Park Service (NPS) and is assigned to national parks that are deemed “sensitive ecosystems” (“National Parks and the Clean Air Act,” n.d.; “NPS Class I Areas,” n.d.). Therefore, the region is the subject of many scientific studies to determine potential causes of reduced visibility and air quality, as well as to map monthly and seasonal trends around both parks.

Previous studies investigating these concerns in the region have included a 2017 study conducted at CAVE, which utilized ground measurements and HYSPLIT trajectories to determine the severity of volatile organic

compounds (VOCs) in the park (Benedict et al., 2020). Another study investigated the TROPOMI retrieval accuracy of nitrogen oxides (NO_x) in rural areas by comparing satellite reports to nearby emissions reports (Goldberg et al., 2019). Results of that study suggest that TROPOMI is well-suited for estimating NO_x emissions for both seasonal and intra-seasonal timeframes. Meteorological variables and their impacts on pollution and visibility in the Permian Basin are well-researched. A two-year study (2018–2020) focused on TROPOMI NO₂ and surface wind direction to determine ways in which meteorology in the area affects NO₂ transportation. Results of this study showed that due to the short lifetime of NO₂, the highest concentrations occur near anthropogenic sources. Winds carried NO₂ as far as the western Delaware Basin, with the highest concentrations settling near Carlsbad, New Mexico (NM) and Pecos, Texas (TX) (Crosmán, 2021). The methods and findings demonstrated through these studies guided our project and contributed to further understanding of the unique meteorological and geologic issues experienced in GUMO and CAVE during our study period from May 2010 to May 2021.

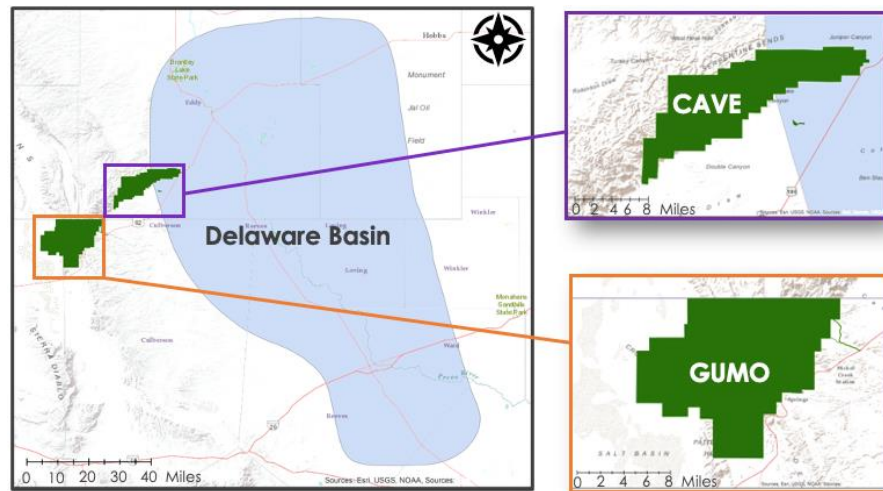


Figure 1. The boundaries of various areas within our study region are shown. The Delaware Basin is in blue. Boundaries for GUMO and CAVE are shown in the orange and purple insets respectively.

2.2 Project Partners & Objectives

The project partners for this term were the National Park Service (NPS) Intermountain Region, Carlsbad Caverns National Park, and Guadalupe Mountains National Park. The NPS observed a reduction in air quality and visibility over GUMO and CAVE over the last decade. Partners are alarmed about the adverse impacts the deteriorating air quality will have on the pristine environments of the national parks and the local tourism economy. There is concern that oil and gas exploration has exacerbated these issues and the NPS is interested in using satellite data to identify temporal and spatial changes in air pollutants over the Delaware Basin region to aid in their decision-making process. This study set out to evaluate the relationships between pollution sources within CAVE and GUMO by using *in situ* and satellite-based data, as well as to create maps of NO₂ around the Delaware Basin to assist with CAVE and GUMO’s park management policies surrounding air quality and visibility.

3. Methodology

3.1 Data Acquisition

The European Space Agency (ESA) released version 2.2.0 of TROPOMI’s Level 2 NO₂ product to address artificially low tropospheric NO₂ columns over heavily polluted regions. Then, the need to eliminate discontinuity in NO₂ data introduced by processor changes in December 2020 led to further reprocessing and the release of Version 2.3.1 (S5P-PAL Data Portal, n.d.). We acquired the TROPOMI Level 2 NO₂ product through the creation of a Python script that used the PySTAC package (“PySTAC Documentation – Pystac 1.3.0 Documentation”, n.d.) to automate data download from the S5P-PAL data portal (S5P-PAL Data

Portal, n.d.). We set a $6.0^\circ \times 6.0^\circ$ extent centered at 32.0°N , -104.0°W . Our team then ran the script which download all files between May 2018–May 2021 that captured the specified spatial extent.

OMI data from NASA’s Aura satellite was downloaded from NASA Earthdata Search. To configure spatial boundaries for data acquisition, we set a point at 32.20°N , -102.70°W to ensure the swath would cover the study area. We then collected records of each satellite flyover time during the study period from 2010–2021 and compiled these into a text file. With the satellite flyover times in this text file, we ran a Unix module to review each point and download the corresponding OMI HE5 file.

We also utilized three non-satellite datasets:

1. Annual global flaring dataset from the National Oceanic and Atmospheric Administration (NOAA), Colorado School of Mines, and the World Bank (“NOAA dataset”)
2. A dataset from the New Mexico State Government’s Oil Conservation Division (OCD, “OCD dataset”)
3. Ground monitor NO_2 data from the Environmental Protection Agency’s AirData site.

The NOAA dataset contains flaring values at the individual well level but only provides annual estimates of flaring. The OCD dataset contains sum-aggregated flaring values at the broader district level but provides monthly estimates of flaring. Ground measures of NO_2 were only available from one Environmental Protection Agency (EPA) air monitor in the Delaware Basin region. These data were available for site #350151005 (at 32.38012°N and -104.263°W) daily from 2010-2021, which we aggregated into 120 monthly averages using Excel. The below table (Table 1) contains a data dictionary of acquired datasets, their uses, and their spatial resolution prior to oversampling.

Table 1
Data dictionary for datasets used.

Dataset Name	Source	Product Version / Level	Spatial Resolution	Temporal Resolution	Temporal Extent	Justification
NO_2	TROPOMI	2.03.01/L2 (S5P-PAL)	3.5×7 km	Daily	May 2018–May 2021	Evaluation of hyperlocal trends across the Delaware Basin, CAVE, and GUMO
NO_2	OMI	3/L3	$0.25^\circ \times 0.25^\circ$ (~25 km)	Daily	May 2010–May 2021	Evaluation of regional trends around the Delaware Basin
Global flaring dataset	NOAA, Colorado School of Mines, World Bank	n/a	Well level	Yearly estimates	2017–2020	Estimation of emissions from oil and gas wells
Monthly production of natural gas and flaring	Oil Conservation Division of New Mexico	n/a	District level	Monthly estimates	2017–2020	Ground comparison of column NO_2 TROPOMI observations with temporally

						collocated gas well emissions
AirData	Environmental Protection Agency	n/a	One point; Carlsbad, New Mexico	Monthly averages	2010–2021	Ground-based measurement of NO ₂ to supplement satellite column measures

3.2 Data Processing

We utilized four Interactive Data Language (IDL) scripts to clip TROPOMI and OMI data to the specified extent to reduce computation time and increase the efficiency of our workflow. Two of the scripts re-gridded the data to a $0.01^\circ \times 0.01^\circ$ for TROPOMI and a $0.25^\circ \times 0.25^\circ$ resolution for OMI, using an oversampling procedure from Goldberg et al., (2021). To complete this procedure, we read the existing NCTROPOMI NetCDF files and OMI HE5 files, defined new variables, and changed NO₂ units from moles/m² to molecules/cm² by multiplying by Avogadro's Number (6.02214×10^{19}), over 10^4 . We then applied a quality assurance value of 0.75 as recommended by our science advisors, which filters cloud radiance fractions greater than 50%. With these changes, we created a new NetCDF file.

Once the TROPOMI data were oversampled and re-gridded, another IDL script was used to make monthly aggregates. We created a total of thirty-five monthly aggregates of TROPOMI data, spanning from May 2018–April 2021. To load these NC files into ArcGIS Pro as raster files, we ran a Python script to rescale, reposition, project, and export the files as TIFs. We then added these TIFs to a mosaic dataset in ArcGIS and added the time dimension of “Month” to each one using the Make Multidimensional Raster tool.

The OMI data, once re-gridded, was used to create yearly and seasonal aggregates. To do this, we repeated the process used for creating the multidimensional mosaic raster dataset with TROPOMI, with the oversampled and re-gridded OMI dataset. We did not convert NO₂ units in the OMI datasets because the HE5 files already defined NO₂ as molecules/cm². The yearly aggregates spanned May 2010–May 2021, with 2010 only encapsulating May–December and the 2021 aggregate covering January–May. We ended with twelve yearly aggregate files of OMI data.

For the OMI seasonal aggregates, we defined the seasons as:

- Spring: March–May
- Summer: June–August
- Fall: September–November
- Winter: December–February

Specifically, the winter season represents December of the defined year, going into January and February of the next calendar year. For example, winter 2010 is defined as December 2010–February 2011. We excluded the May 2010 data from the seasonal aggregates as it only encompassed one month of spring. For the spring 2021 file, we noted that the months included were March–May 1st. This period did not include the entire month of May, but we still included it to view the potential impacts of the COVID-19 pandemic on NO₂ production. The total number of OMI seasonal files created was 44.

We then created two Python scripts: one to plot the data, and the other to create a GIF file of each monthly, yearly, or seasonal aggregate. The Python script for plotting defined the color bar limits, which were decided by looking at the TROPOMI monthly files to determine the best fit scale for our area. We decided on a color bar that spanned $0 - 3.5 \times 10^{15}$ with units of molecules/cm² (Appendix A). For the monthly TROPOMI files, each month from May 2018–April 2021 was plotted and read into the second Python script, creating a GIF file with each image. The OMI yearly files encapsulated 2011–2020 fully, with 2010 and 2021 showing eight

months and five months of data, respectively. We exported each of these generated images into the Python GIF script, creating one GIF showing the yearly progression of NO₂ in the region. The OMI seasonal data was plotted starting in summer 2010 and ending in spring 2021. The plots were broken into their respective seasons, and four GIF files were created, representative of spring, summer, fall, and winter. Our team used an Excel file containing the approximate latitude and longitude of Carlsbad, NM and El Paso, TX in the Python plotting script to create geographic points in each image. We did this to create greater spatial awareness within each plotted image.

For flaring data, we downloaded the 2017–2020 annual global flaring estimate data from NOAA, World Bank, and Colorado School of Mines, with which we performed ArcGIS mapping of these flaring points to identify global flaring hotspots near the two parks in New Mexico and Texas. We benchmarked the NOAA annual global flaring data to oil production and flaring data (in units of billion cubic meters) reported by New Mexico’s Energy, Minerals, and Natural Resources department. These data provided by New Mexico (OCD data) were in a monthly format and were not oil- and gas-well specific; instead, the flaring data (in units million cubic feet) were aggregated by district. The monthly flaring data by district were summed on an annual basis and converted to units of billion cubic meters to allow for benchmarking against the NOAA annual global flaring data. Prior to benchmarking, we used GIS to attribute NOAA annual flaring data to New Mexico districts.

Given the strong correlation, we used the OCD monthly dataset to create an estimated monthly view of the NOAA flaring dataset. Our team calculated the percentage share of annual volume for the OCD dataset every month. For example, in January 2017, the state of New Mexico reported 0.0361 billion cubic meters (bcm) of flaring emissions statewide, which is approximately 8% of annual flaring. This value defines the adjustment factor for the annual NOAA flaring dataset for the corresponding month. Multiplying the annual volume by the adjustment factor creates an estimated monthly temporal pattern from the NOAA dataset. Therefore, we multiplied the 2017 NOAA annual NM flaring data (across all flare sites) by 8% to create the January 2017 flaring volume estimate. We repeated this methodology for the years 2017–2020 to create a monthly profile of volumetric flaring in New Mexico and Texas near the study area. To create the estimates for NO₂ from the monthly flaring volumetric data produced above, we applied a correlation factor used in a prior study focused on emissions from flaring (Umukoro & Ismail, 2017).

Flaring fires are composed of multiple gases, thus emissions resulting from the burning of flares are never precisely known. According to the Umukoro & Ismail study, the anticipated global gaseous emissions from an annual flaring rate of 126 bcm per year (2000–2011) results in 560 mmt (millions of metric tons) of carbon dioxide (CO₂), 48 mmt of carbon monoxide (CO), 91 mmt of nitrogen monoxide (NO), 93 mmt of NO₂, and 50 mmt of sulfur dioxide (SO₂). Thus, for every billion cubic meters of gases flared during natural gas production, we estimated NO₂ emissions to be 0.73 mmt. We applied these ratios to individual wells in the modified NOAA dataset, showing monthly NO₂ emissions for individual wells around GUMO and CAVE. We used the resulting dataset for ground validation of TROPOMI and OMI column measurements. Several assumptions were made here:

1. New Mexico gas production and flaring between 2017–2020 was representative of nearby Texas gas production and flaring during the same period.
2. The monthly flaring at each well site is constant and the volumes of flaring do not deviate strongly from the statewide trends.

3.3 Data Analysis

We verified the spatial projection of our TROPOMI maps generated from Python by collecting the latitude and longitude coordinates of Carlsbad, New Mexico and El Paso, Texas. We corresponded these cities with NO₂ values by overlaying the geographic coordinates with the TROPOMI map using a scatter plot in Python. To define locations on the map, we specified points of the scatter plot with labels mentioning each city’s name.

To statistically evaluate TROPOMI and OCD data, we uploaded shapefile boundaries of GUMO and CAVE National Parks and the Delaware Basin extents to ArcGIS. Because natural gas flaring is most active within the boundaries of the Delaware Basin, we created a shapefile boundary using the Intersect tool to extract the area that is within ten miles of CAVE and inside the Delaware Basin. Our team uploaded the TROPOMI raster files representing monthly NO₂ average column densities to ArcGIS. Using the Zonal Statistics to Table tool, we then calculated the average NO₂ column densities for each month within each extent of interest (i.e., GUMO, CAVE, Delaware Basin, and the intersection region). The spatial averages for each extent of interest and month were recorded in a separate Excel workbook. TROPOMI seasonal column densities of NO₂ at the National Parks were then graphically compared against TROPOMI seasonal column densities of NO₂ in the Delaware Basin. Finally, we graphically compared the TROPOMI seasonal column densities of NO₂ at the intersection of the CAVE ten-mile buffer zone and the Delaware basin against the TROPOMI seasonal column densities of NO₂ in the Delaware Basin.

4. Results & Discussion

4.1 Analysis of Results

Oil and gas flaring observations have increased steadily since 2010. There were seventeen active oil and gas wells within ten miles of CAVE in 2021. OMI saw a 6.6% increase in NO₂ from 2010–2018 (Figure 2), and TROPOMI saw annual average levels of NO₂ molecules/cm² increase by 2.5% from 2018–2021 (Figure 6).

4.1.1 NO₂ Emission Estimates from Flaring Data

Using the method described in section 3.2, the NO₂ emission estimates from flaring data were tabulated. The results show an annual percentage increase of 8% from 2013–2021. We found that the annual reported flaring estimates in the NOAA data were 35% higher than the data reported by the New Mexico government. The annual New Mexico OCD flaring data correlated well with the NOAA annual flaring data, both on a spatial and temporal basis. Spatially, the highest volumes of annual flaring were in districts 1 and 2 in both datasets. Temporally, annual flaring was found to be lowest in 2017 and highest in the years 2018 and 2019.

4.1.2 OMI

Mean yearly OMI NO₂ column densities were graphed in a 6° bounding box surrounding the Delaware Basin, CAVE, and GUMO from May 2010–April 2021, although only 2010–2018 were analyzed with OMI, reserving 2018–2021 for the higher-resolution TROPOMI. The Delaware Basin showed a +38.3% change in NO₂ column densities from 2011–2018, with a -1% change from 2018–2020. This decrease is bracketed off in Figure 4 with two blue dashed lines to emphasize the trend. The partial years of 2010 and 2021 were not included in the annual statistics because the seasonality present in NO₂ column densities would inflate the annual mean calculations of these years. See Figure 2 for a visualization of this seasonality.

From the years of 2011–2018, CAVE and GUMO exhibit opposite trends. The percent change in NO₂ concentration over CAVE is +15.29%, while over GUMO, the percent change is -4.26%. CAVE had a much smaller concentration of NO₂ in 2010. The rate of change over CAVE was negative on average until 2015, when a local spike in NO₂ column density over the Delaware Basin contributed to a spike in NO₂ column density over CAVE. As NO₂ column density continued to rise on average over the Delaware Basin after 2015, column densities over CAVE remained relatively constant during the same time interval. NO₂ column density measurements over GUMO increased on average through 2015, matching what is found over the Delaware Basin over the same time interval. After 2015, column density decreased, showing an opposite trend to the Delaware Basin over the same time interval.

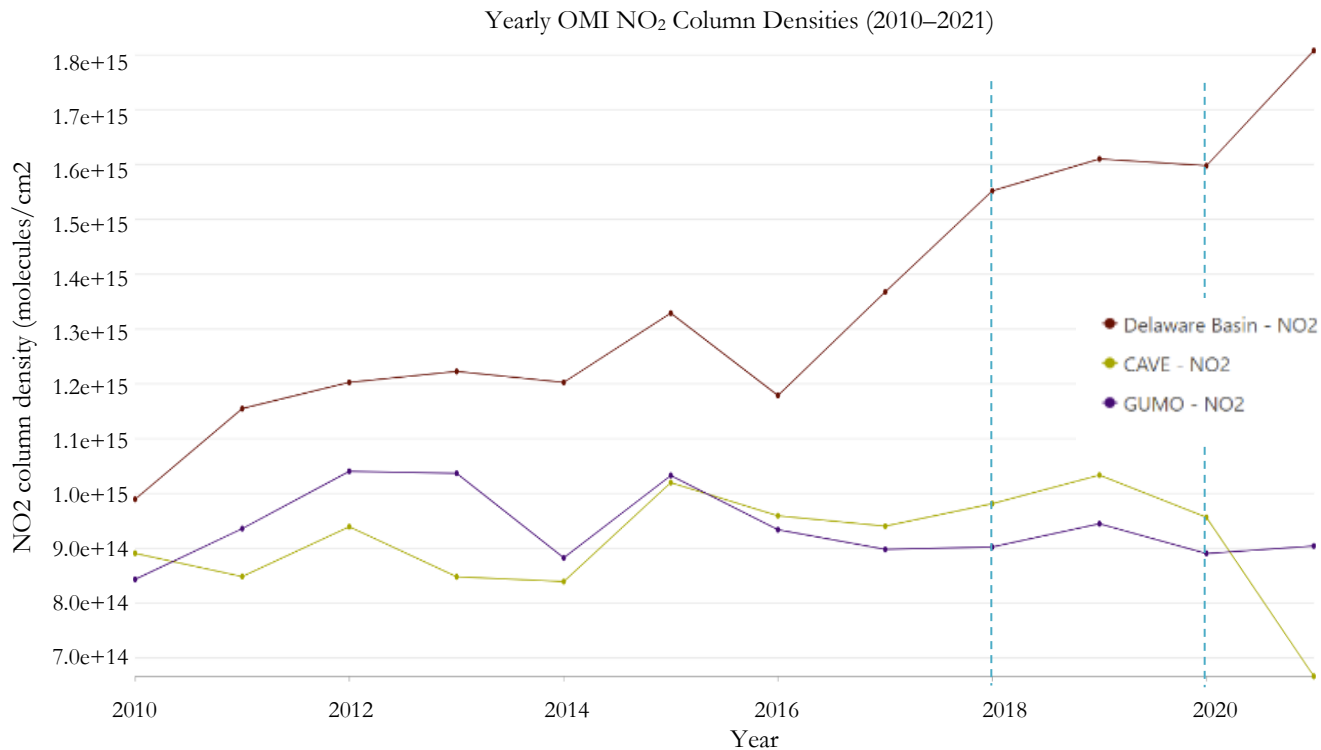


Figure 2. Yearly column densities from the study region from May 2010–May 2021 derived from OMI observations. The 1% decrease between 2018–2022 is emphasized by two blue dashed lines.

4.1.3 TROPOMI

TROPOMI seasonal column densities of NO₂ at the National Parks were graphically compared against TROPOMI seasonal column densities of NO₂ in the Delaware Basin (Figure 3). We also graphically compared the TROPOMI seasonal column densities of NO₂ at the intersection of the CAVE ten-mile buffer zone and the Delaware basin against the TROPOMI seasonal column densities of NO₂ in the Delaware Basin (Figure 4). Additionally, the finest temporal resolution we investigated was at a monthly scale. It is likely that NO₂ can creep into parks for hours, days, or even weeks when the wind blows air pollution in that direction. Therefore, the presence of NO₂ is still palpable within Carlsbad Caverns and Guadalupe Mountains National Parks.

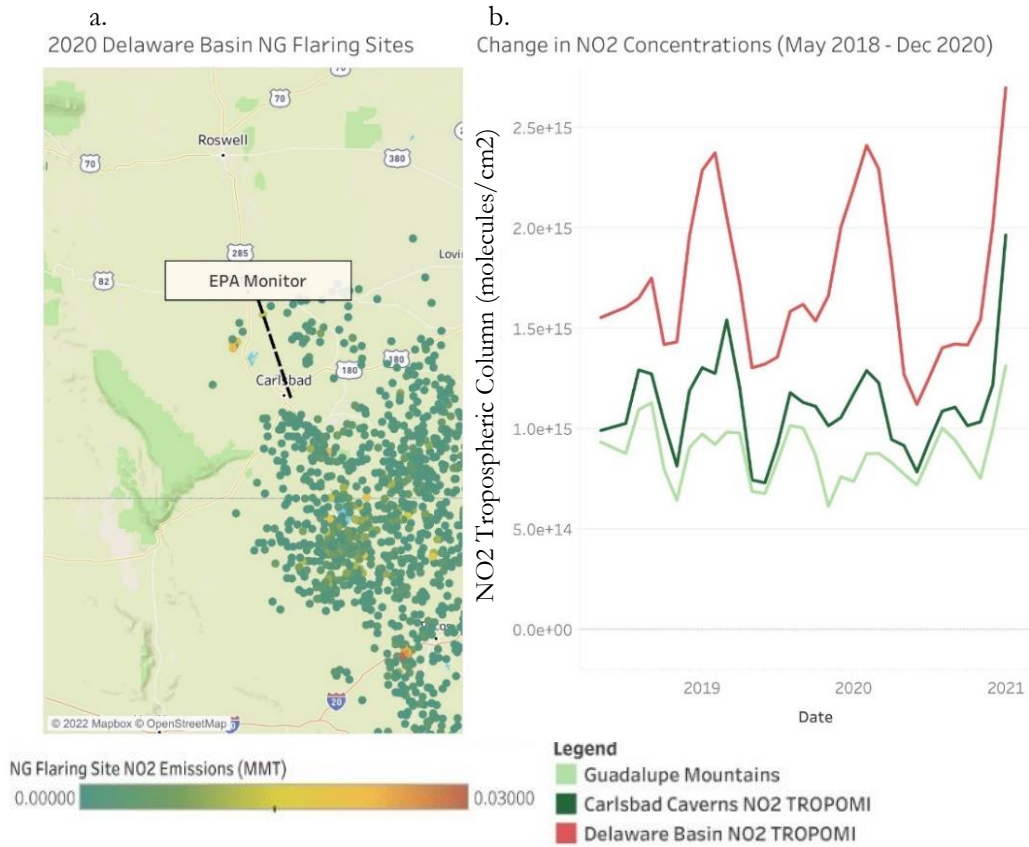


Figure 3. Study area oil and gas flaring sites, and their estimated 2020 NO₂ emissions (a). Monthly average column densities over key points in our study area derived from TROPOMI from May 2018–May 2021 (b).

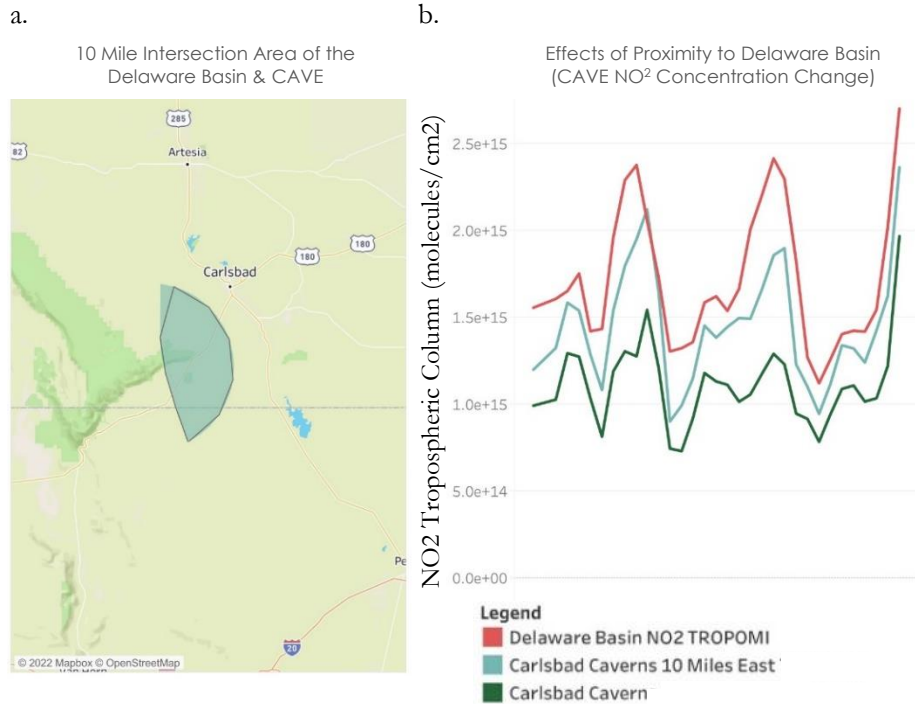


Figure 4. Zoomed in view of the ten-mile intersection area of the Delaware Basin and CAVE within our study area (a). Monthly average column densities over areas closest to oil and gas exploration in our study area derived from TROPOMI from May 2018–May 2021(b).

Statistically driven data were graphed alongside monthly TROPOMI NO₂ column densities from the Delaware Basin region, showcasing a seasonal alignment amongst different data sources (Figure 5). This alignment provides confidence that the TROPOMI measurements in the Delaware Basin region are accurate to local monitoring estimates (EPA monitor) and that the seasonal shape of the NO₂ column densities is driven in part by the natural gas flaring occurring in the region. We found less alignment between the seasonal NO₂ column density patterns in the Delaware Basin and the NO₂ concentrations within the boundaries of the national parks, although both CAVE and GUMO still show a seasonal trend (Figure 6). TROPOMI measured a -1 % change over the Delaware Basin, a +3% change over CAVE, and a +7% change over GUMO from 2018–2020. On average, the NO₂ column densities within the two national park boundaries were also found to be much lower than in the Delaware Basin. This indicates that on a monthly average basis, the flaring effects from the Delaware Basin are not as apparent within the boundaries of the parks. However, daily NO₂ concentrations from natural gas flaring activities can still vary dramatically despite lower average monthly NO₂ column densities.



Figure 5. Seasonal averages between flaring observations and TROPOMI retrievals (top); seasonal average comparison between EPA ground monitor data and TROPOMI retrievals (bottom).

We found stronger alignment between monthly NO₂ column density patterns within ten miles east of the CAVE national park and inside CAVE than anywhere else in the Delaware Basin. Figure 3 compares mean monthly NO₂ measurements inside CAVE to within ten miles of CAVE. The plot in Figure B1a shows a strong correlation between their measurements, denoted by an R² value of 0.87. Figure B1b shows an R² value of 0.65 between NO₂ column densities inside CAVE and measurements beyond the ten-mile region closest to CAVE. On average, NO₂ column densities within ten miles of CAVE intersecting the Delaware Basin were higher than NO₂ column densities within the boundaries of CAVE. This indicates that the NO₂ column density effects of natural gas flaring are more apparent directly outside of CAVE. Additionally, this distance relationship between CAVE and the ten-mile zone outside CAVE within the Delaware Basin indicates that NO₂ trends within CAVE will likely respond more directly to changes in NO₂ activity that occur closer to the park. The column densities found in GUMO do not correlate with the areas within ten miles of CAVE or beyond ten miles of CAVE, showing R² values of 0.46 and 0.27, respectively (Figures B1c and B1d).

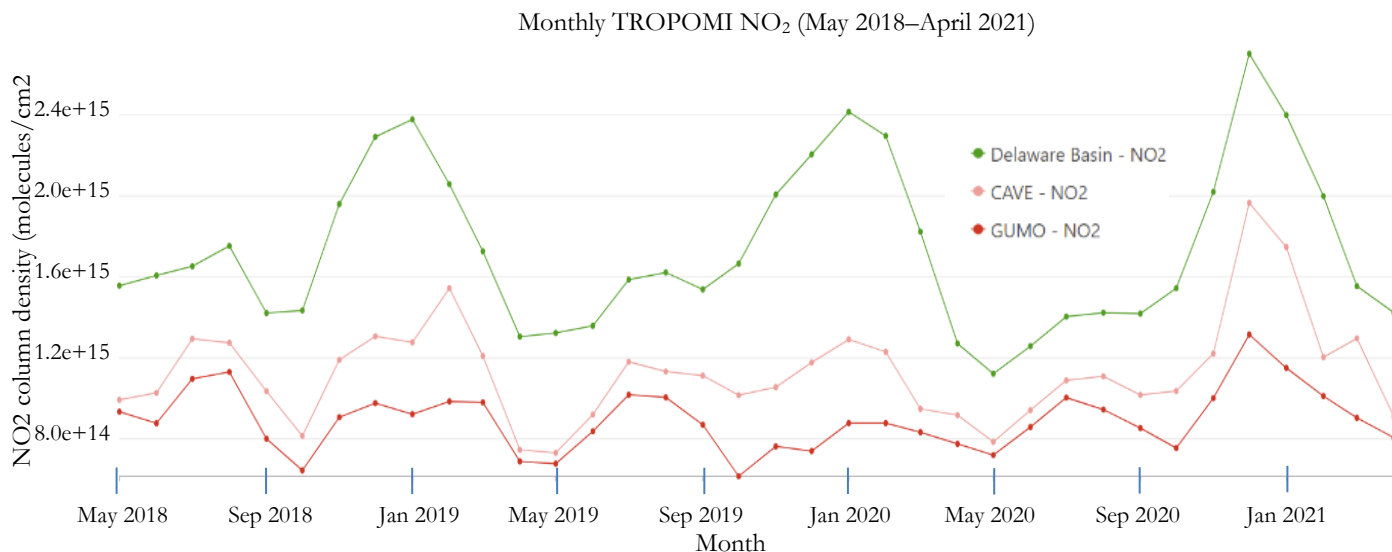


Figure 6. Monthly TROPOMI column density observations from May 2018–April 2021 for CAVE, GUMO, and Delaware Basin.

4.2 Future Work

If this project was given an additional term, an environmental degradation study would be insightful for managing park health and safety. This term measured a rise in NO_2 near the study area, but the environmental effects of this change on vegetation, water quality, health, and wildlife still remain unknown. Additionally, this work can be expanded by investigating a larger set of atmospheric pollutants. Data from the Global Gas Flaring Reduction Partnership (GGFR) shows flaring near the park; however, the exact combination of pollutants that are emitted from oil and gas flaring is never precisely known. Identifying the existing combinations can further elucidate specific interventions that need to be taken. Future projects can also build upon our work and supplement our results by incorporating measures from a wider array of ground-based monitors. If the parks or other stakeholders in the region install other NO_2 monitors than the ones currently used, ground validation could be improved. Alternatively, the parks recently stationed a network of low-cost PurpleAir monitors, which measure particulate matter. These monitors would be a valuable tool to implement in a future study. Lastly, future work should focus on visibility. Haze during the day obstructs the scenery of the park, while light pollution prevents stargazing at night (“Air Pollution & Visibility,” n.d.), and may also disrupt the migratory and sleeping patterns of local wildlife. The National Parks aim to protect natural resources not only for the protection and preservation of wildlife but also for the promotion of visitor education and experience. Exploring these miscellaneous pollutants and measures can offer critical information to help protect park natural resources and improve the park experience for visitors.

5. Conclusions

America’s National Parks were originally designed to preserve areas of natural and historic significance. Today, they are also areas where members of the public can experience and appreciate pristine sites. Since the formation of the NPS, numerous efforts have been enacted to protect park natural resources, including air quality, efforts such as the Clean Air Act and the NPS Night Skies program. This analysis capitalized on OMI and TROPOMI satellite sensing, ground-based monitor measurements, gas and oil flare data, and emissions data. Through this analysis, we were able to demonstrate an increase in NO_2 column densities around the Guadalupe Mountains and Carlsbad Caverns National Parks in the past decade. This historical overview offers insight into the spatial and temporal pattern of NO_2 precursor pollutants. Spatially, the greatest increases in NO_2 column densities around the parks occurred within 10 miles east of Carlsbad Caverns National Park, near the overlap area between the Delaware Basin and the park, closest to oil and gas flaring activity. Temporally, the greatest increases occurred in 2017–2018, and more specifically during the winter

seasons. We illustrated these variations using ArcGIS maps, Python plots, and statistical analyses in Excel. These outputs will inform the placement of new air monitoring stations to better inform visitors of air quality and will provide NPS staff with critical data imperative for supporting improved park experience, health, and stewardship. Ecosystem health and visibility in GUMO and CAVE National Parks are vital to maintaining the natural resources and unique biodiversity of these national emblems, and this data will equip partners with insight to assist with park management policy.

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Any opinions, findings, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

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7. Glossary

bcm – billions of cubic meters

CAVE – Carlsbad Caverns National Park

ECMWF – European Centre for Medium-range Weather Forecasts

EPA – Environmental Protection Agency

ESA – European Space Agency

GGFR – Global Gas Flaring Reduction Partnership

GIS – Geographic Information System

GUMO – Guadalupe Mountain National Park

IMPROVE - Interagency Monitoring Protection of Visual Environments

mmt – millions of metric tons

NO₂ – Nitrogen dioxide

NO_x – Nitrogen Oxides are a family of poisonous, highly reactive gases.

NOAA – National Oceanographic and Atmospheric Administration

NPS – National Park Service

OCD – Oil Conservation Division

OMI – Ozone Monitoring Instrument

PySTAC – Python SpatioTemporal Access Catalog

S5P-PAL – Sentinel-5 Precursor Product Algorithm Library

TROPOMI – Tropospheric Monitoring Instrument

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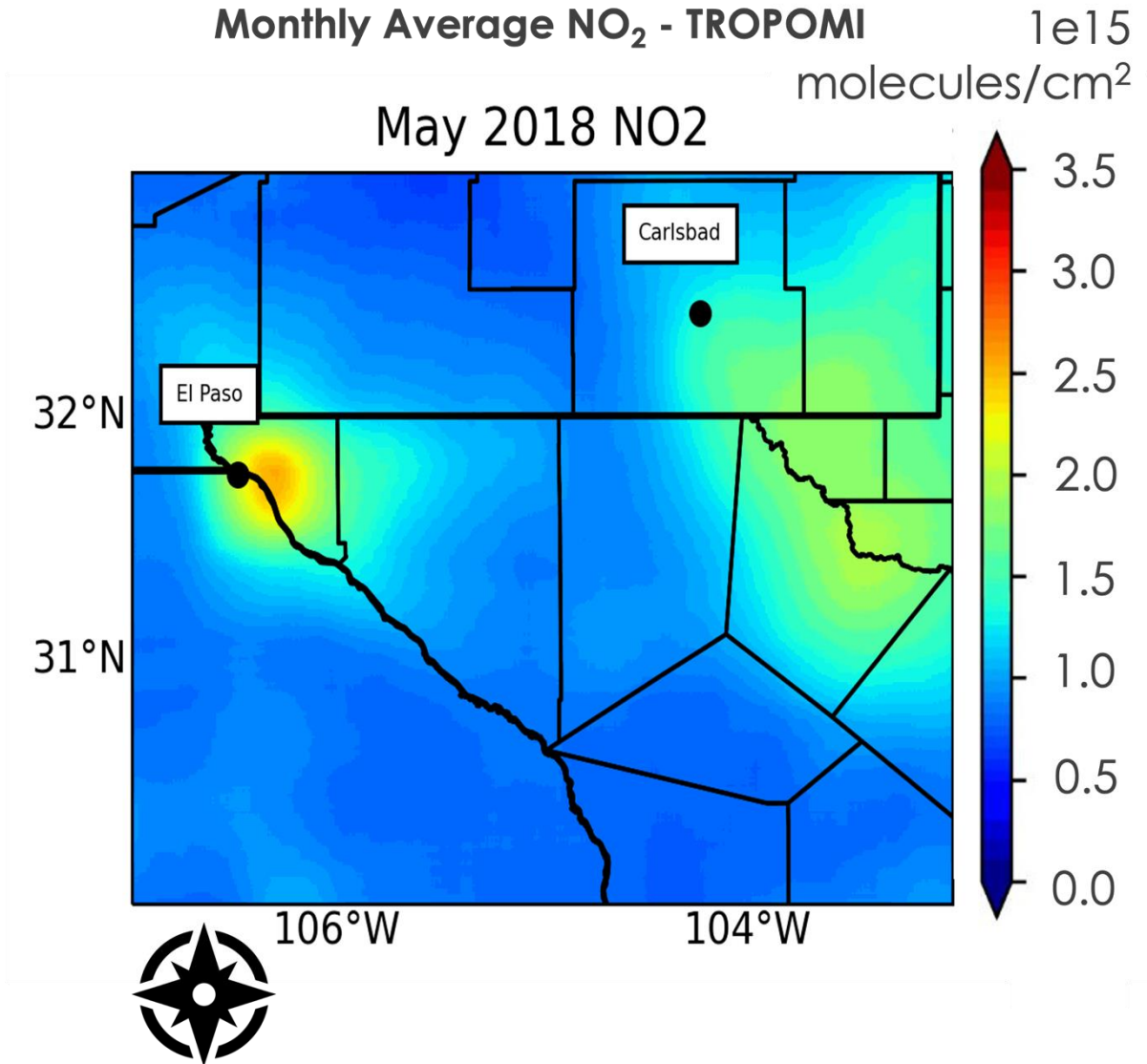
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9. Appendices

Appendix A: Color Map Bar Example

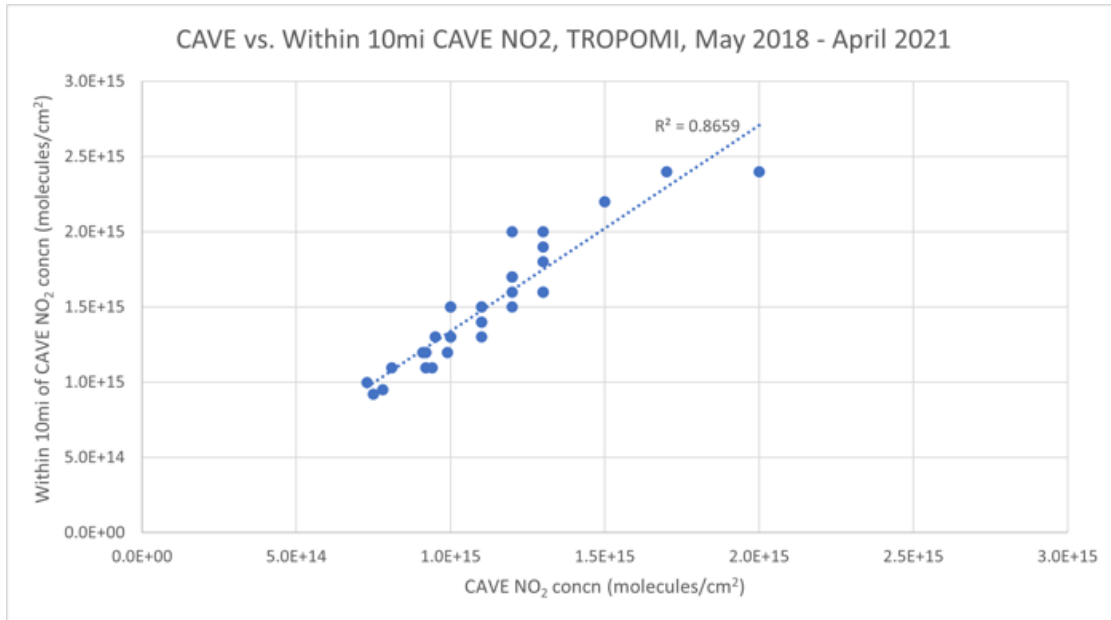
Appendix A: Example of images used in GIF file of each monthly, yearly, or seasonal aggregate with a color bar that spanned $0 - 3.5 \times 10^{15}$ with units of molecules/cm². This specific image is for the TROPOMI monthly average NO₂ for May 2018.



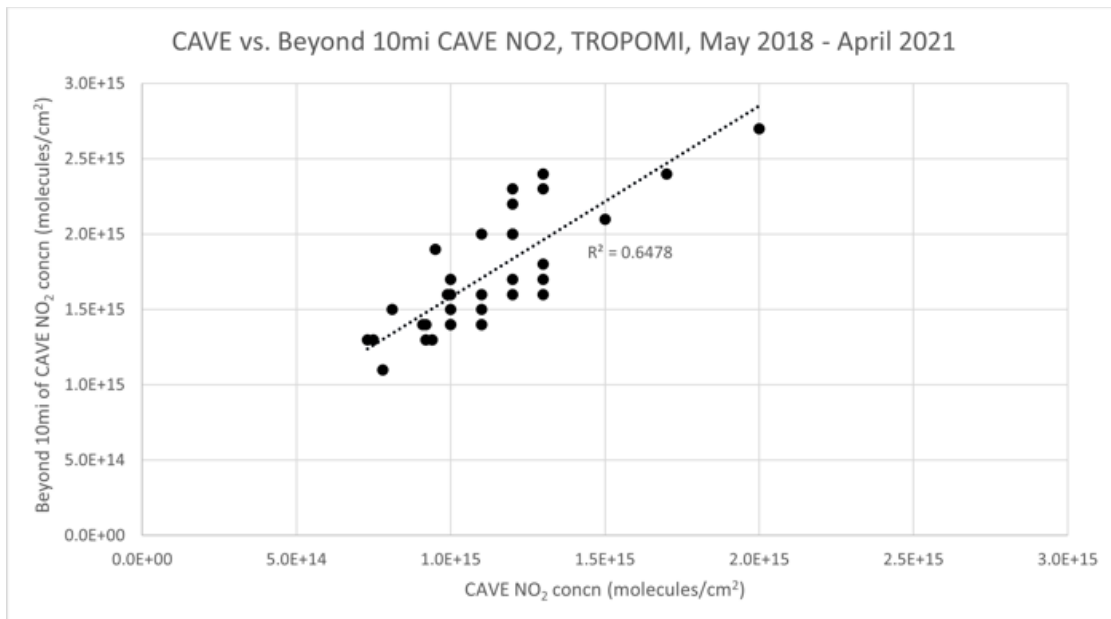
Appendix B: Scatter Plots of Monthly NO₂ column densities

Figure B1. Scatter plots of average monthly NO₂ column densities: (a) within 10 miles of CAVE compared to inside CAVE boundaries, (b) beyond 10 miles of CAVE compared to inside CAVE boundaries, (c) within 10 miles of GUMO compared to inside GUMO boundaries, (d) beyond 10 miles of GUMO compared to inside GUMO boundaries.

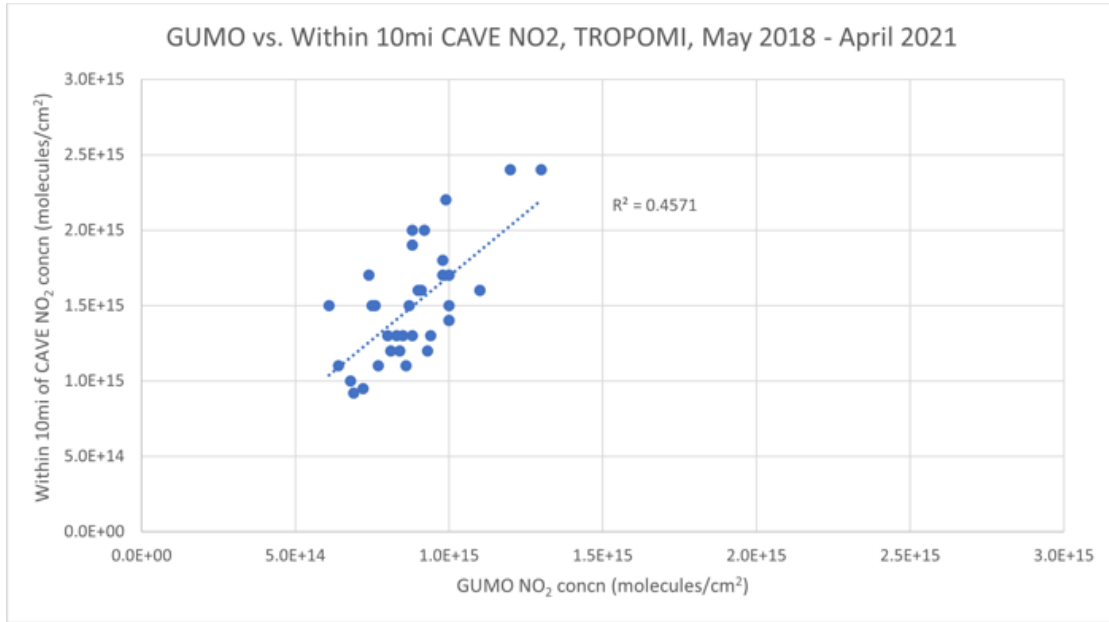
a.



b.



c.



d.

