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**Modeling Inventories for Mexico and Caribbean Countries to  
Support Quantitative Analysis of International Transport  
Impacts on Ozone Design Values and Regional Haze  
Final Report**

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Prepared for:

Jim Smith

Texas Commission on Environmental Quality

121 Park 35 Circle MC 164

Austin, TX 78753

Prepared by:

Tejas Shah, Lynsey Parker, John Grant, and Greg Yarwood

Ramboll

773 San Marin Drive, Suite 2115

Novato, California, 94998

[www.ramboll.com](http://www.ramboll.com)

P-415-899-0700

F-415-899-0707

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**RAMBOLL**

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## EXECUTIVE SUMMARY

International transport of pollution has increased in importance as the US National Ambient Air Quality Standards for ozone and particulate matter (PM) have become more stringent in recent years. PM leads to regional haze and visibility degradation in protected areas such as National Parks located in Texas. The TCEQ uses the Comprehensive Air Quality Model with extensions (CAMx) to evaluate ozone and regional haze. Accurately quantifying emissions in foreign countries that can be upwind of Texas is important for several reasons, including improving the accuracy of regional air quality models, improving attribution of ozone and visibility degradation to the correct sources, and accounting for effects of foreign emissions in air quality management plans. Mexican anthropogenic emissions contribute to ozone and PM transport into Texas. The purpose of this project is to improve anthropogenic emissions from lands south of Texas and the continental United States within the TCEQ's CAMx modeling.

This project draws upon several data sources to improve the anthropogenic emission inventory for Mexico. Ramboll reviewed existing emissions inventory data for Mexico included in EPA's modeling platform and the Community Emissions Data System (CEDS). We compared the emission inventories to satellite-derived emission estimates for large Sulfur Dioxide (SO<sub>2</sub>) sources, nitrogen oxide (NO<sub>x</sub>) emissions, and flaring associated with oil and gas production.

The anthropogenic inventory data for Mexico from the global CEDS inventory generally shows good agreement in terms of country-wide total emissions with EPA's inventory for Mexico. Satellite data for SO<sub>2</sub> reveal that some large SO<sub>2</sub> sources are not captured in the EPA inventory and should be added. We also used tropospheric NO<sub>2</sub> column retrievals from National Aeronautics and Space Administration (NASA) to evaluate EPA's bottom-up NO<sub>x</sub> inventory. The NO<sub>2</sub> column data indicate that there is good spatial agreement between the EPA NO<sub>x</sub> emissions inventory for stationary industrial sources and satellite NO<sub>2</sub> column data because the large NO<sub>x</sub> point sources are observed in the NO<sub>2</sub> columns. Satellite-derived global flare data indicate that upstream oil and gas sources are not well represented in the EPA inventory, and a bottom-up emission inventory should be developed for this sector.

## 1.0 INTRODUCTION

International transport of pollution has increased in importance as the US National Ambient Air Quality Standards for ozone and particulate matter (PM) have become more stringent in recent years. PM leads to regional haze and visibility degradation in protected areas such as National Parks located in Texas. Accurately quantifying emissions in foreign countries that can be upwind of Texas is important for several reasons, including improving the accuracy of air quality model inputs (and hence model accuracy), improving attribution of ozone and visibility degradation to the correct sources, and accounting for effects of foreign emissions in air quality management plans.

Mexican anthropogenic emissions contribute to ozone and PM transport into Texas, and to better characterize these contributions the Texas Commission on Environmental Quality (TCEQ) is expanding southward its regional air quality modeling domain to encompass all of Mexico plus several Caribbean and Central American countries. The expanded CAMx domain is referred to as “New Central American” domain (nca\_12km) and presented in Figure 1-1. Much of Mexico (including Mexico City) is outside the EPA’s CONUS 12 km and TCEQ’s existing 36 km domains but included in the TCEQ’s New Central American CAMx modeling domain. The purpose of this project is to improve anthropogenic emissions from lands south of Texas and the continental United States within the TCEQ’s expanded modeling domain for the Comprehensive Air Quality Model with extensions (CAMx). Several information sources are used, including emissions inventory data for Mexico included in EPA’s modeling platform, a new global data set of anthropogenic emission inventories (Hoesly et al., 2018), and satellite-derived emission estimates for large Sulfur Dioxide (SO<sub>2</sub>) sources (Fioletov et al., 2016), tropospheric NO<sub>2</sub> column data, and flaring associated with oil and gas production (Elvidge et al., 2009 and 2015).

An overview of the existing Mexico inventory available from EPA and emission summaries are provided in Section 2. Section 2 also compares global emissions inventory data to the existing EPA inventory. Section 3 provides an overview of a global catalogue of large SO<sub>2</sub> sources detected by satellite and compares data to the existing inventory. Section 4 describes tropospheric NO<sub>2</sub> column data from satellite measurement and compares it with the EPA NO<sub>x</sub> emissions inventory for Mexico. Section 5 describes flaring data detected by satellite and compares them to the existing inventory. Finally, Section 6 provides overall summary and recommendations to improve the existing emissions inventory.



**Figure 1-1. TCEQ’s New Central American CAMx Modeling Domain**

## 2.0 THE MEXICO EMISSIONS INVENTORY AVAILABLE FROM EPA

Ramboll reviewed emissions inventory data for Mexico included in EPA’s “2011v6/v3” modeling platform that are available at EPA’s Air Emissions Modeling site<sup>1</sup> for the years of 2008, 2011, 2014, 2017, 2023 and 2028 and for the primary source categories of area, non-road, on-road, and point. These data are provided by EPA in the input format of the SMOKE emissions modeling system (USEPA, 2016). Ramboll used the data provided by EPA as of mid-January 2018 and reviewed them to determine whether data gaps exist for any of the years and/or primary source categories. Modeling years of interest to TCEQ are 2012, 2016, 2023, 2028 and 2064 for their air quality management plans.

Table 2-1 provides a summary of available Mexico inventory data from EPA’s modeling platform and describes how they are derived, including on-road sources. EPA’s modeling platforms include inventory data for Mexico compiled from the Inventario Nacional de Emisiones de Mexico, 2008 (2008 INEM) and future year projections (2018, 2025, and 2030) developed by ERG (ERG, 2014). EPA linearly interpolated between 2008 emissions and projected 2014 emissions to represent the year 2011 in their recent 2011-based platforms. For the 2014-based modeling platform, EPA developed projected 2014 emissions from the 2008 INEM (ERG, 2016). EPA used projected 2018 emissions directly for 2017, linearly interpolated projected 2018 and 2025 to get 2023 emissions, and interpolated projected 2025 and 2030 to develop 2028 emissions. The on-road mobile sources in Mexico were updated to year-specific level based on MOVES-Mexico runs for 2011, 2014, 2023 and 2028.

Table 2-2 summarize criteria air pollutant emissions by source category for Mexico from the EPA inventory. Area source category in the 2008 and 2017 inventories includes wildfires and agricultural fires emissions. For all other years, EPA has a separate “ptfire\_mxca” source category based on FINN emissions in their modeling platform. On-road emissions for 2008 and 2017 are older estimates based on the MOBILE6-Mexico model, while other years are based on the MOVES-Mexico model. There are some large VOC differences between MOBILE6 and MOVES estimates for Mexico on-road sources.

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<sup>1</sup> <ftp://ftp.epa.gov/EmisInventory/2011v6/v3platform/>

**Table 2-1. Summary of Available Mexico Inventory from EPA**

Year	TCEQ Modeling Year	Available Year from EPA Platform	ERG Mexican Emissions Development	Notes	On-road
2008		2011ek	2008	2008 INEM (ERG, 2014)	MOBILE6-Mexico
2011		2011en		2011en (linear interpolation between 2008 and 2014), with updated MOVES	MOVES-Mexico
2012	X				
2014		2014fa*	2014	ERG projected 2008 to 2014 for area, point, and nonroad; used MOVES-Mexico for on-road (ERG, 2016)	MOVES-Mexico
2016	X				
2017		2017ek		MOBILE6-Mexico	MOBILE6-Mexico
2018			2018	ERG projected from 2008	MOBILE6-Mexico
2023	X	2023en		EPA interpolated projected 2018 and 2025, except MOVES-Mexico for onroad	MOVES-Mexico
2025			2025	ERG Projected from 2008	
2028	X	2028el		EPA interpolated projected 2025 and 2030, except MOVES-Mexico for onroad	MOVES-Mexico
2030			2030	ERG Projected from 2008	
2064	X			Emissions summary only; not intended for modeling	

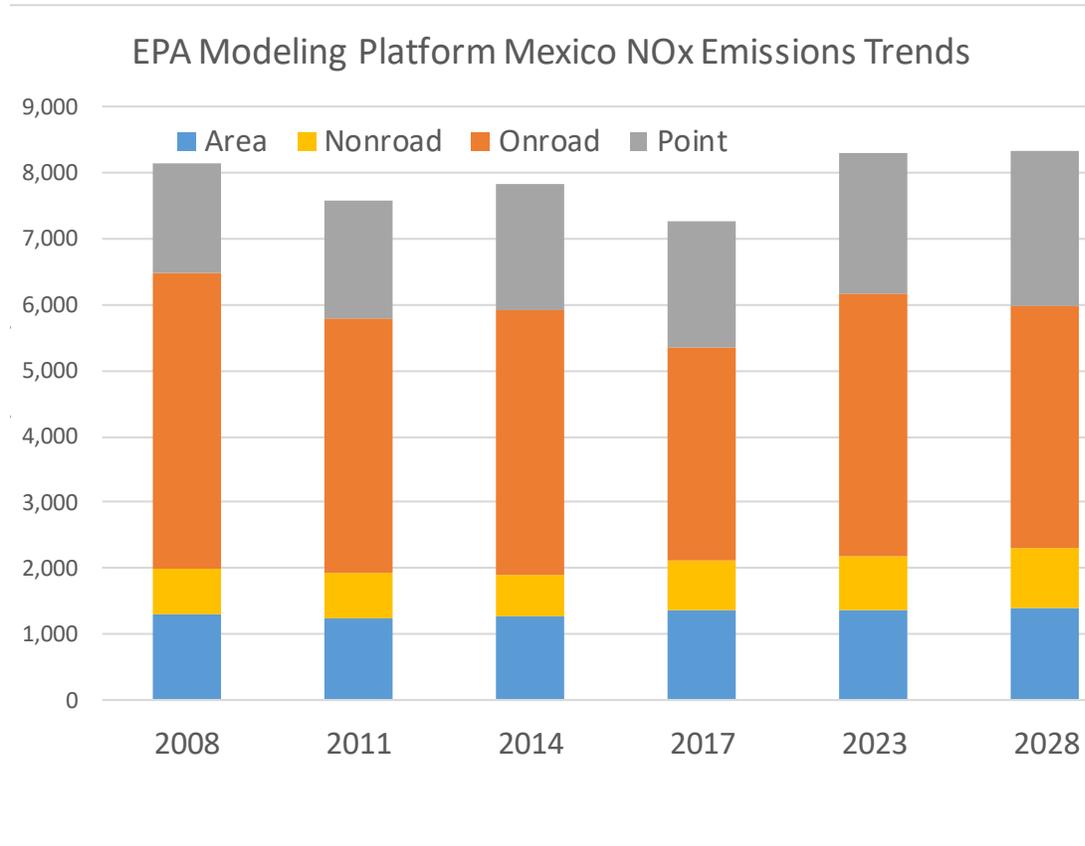
\* Not part of 2011v6.3 platform

**Table 2-2. Emissions Summary for Mexico by Source Category from EPA**

Source Category	2008	2011	2014	2017	2023	2028
<b>CO</b>						
Area	8,041	6,664	6,908	8,775	7,549	7,861
Non-road	401	404	401	433	461	490
On-road*	63,618	16,131	17,262	42,781	16,682	15,145
Point	1,902	1,873	1,843	2,220	2,544	2,754
<b>CO Total</b>	<b>73,962</b>	<b>25,072</b>	<b>26,414</b>	<b>54,209</b>	<b>27,236</b>	<b>26,250</b>
<b>NH<sub>3</sub></b>						
Area	2,334	2,399	2,485	2,383	2,384	2,403
Non-road	0	0	0	0	0	0
On-road*	146	25	27	198	33	38
Point	86	90	93	107	124	142
<b>NH<sub>3</sub> Total</b>	<b>2,566</b>	<b>2,514</b>	<b>2,605</b>	<b>2,688</b>	<b>2,541</b>	<b>2,583</b>
<b>NO<sub>x</sub></b>						
Area	1,291	1,244	1,253	1,371	1,359	1,390
Non-road	686	692	638	758	830	901
On-road*	4,522	3,868	4,037	3,230	3,986	3,680
Point	1,661	1,785	1,909	1,907	2,125	2,379
<b>NO<sub>x</sub> Total</b>	<b>8,160</b>	<b>7,589</b>	<b>7,837</b>	<b>7,266</b>	<b>8,300</b>	<b>8,350</b>
<b>PM<sub>2.5</sub></b>						
Area	1,162	1,024	1,059	1,258	1,137	1,179
Non-road	83	84	79	86	90	93
On-road*	33	119	144	35	200	230
Point	441	461	480	506	578	659
<b>PM<sub>2.5</sub> Total</b>	<b>1,719</b>	<b>1,688</b>	<b>1,762</b>	<b>1,885</b>	<b>2,005</b>	<b>2,161</b>
<b>SO<sub>2</sub></b>						
Area	71	59	59	71	60	60
Non-road	59	62	11	71	83	95
On-road*	70	62	68	29	88	100
Point	6,558	6,238	5,917	5,613	5,769	5,978
<b>SO<sub>2</sub> Total</b>	<b>6,758</b>	<b>6,421</b>	<b>6,055</b>	<b>5,784</b>	<b>6,000</b>	<b>6,233</b>
<b>VOC</b>						
Area	9,469	9,679	10,023	10,667	11,139	11,723
Non-road	88	88	88	93	98	103
On-road*	5,916	1,483	1,520	4,439	1,542	1,582
Point	796	833	869	997	1,172	1,359
<b>VOC Total</b>	<b>16,269</b>	<b>12,083</b>	<b>12,500</b>	<b>16,196</b>	<b>13,951</b>	<b>14,767</b>

\*on-road numbers for 2008 & 2017 are older estimates based on MOBILE6-Mexico, while all other years are based on MOVES-Mexico

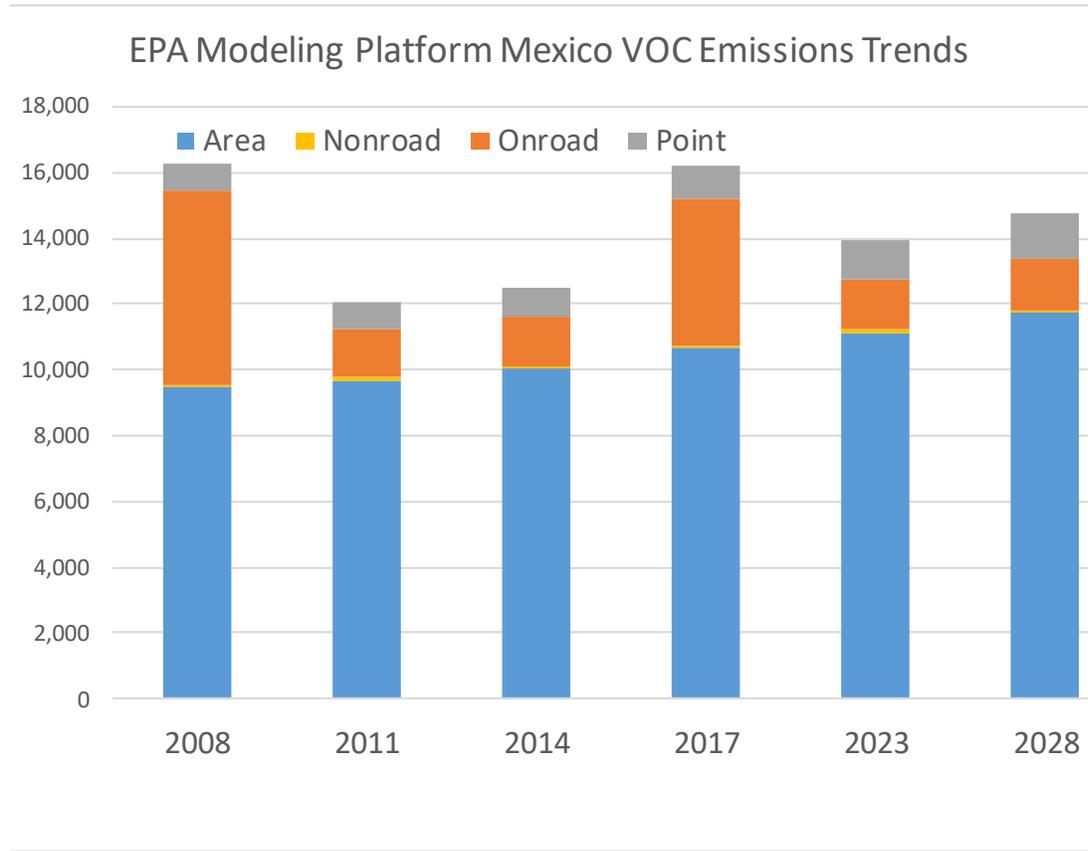
Figure 2-1 illustrates NOx emissions trends (in TPD) for each source category based on Mexico emissions data presented in Table 2-2. On-road sources dominate overall NOx inventory followed by point and area sources. On-road source emissions increase by approximately 4% from 2011 to 2014, ~3% from 2011 to 2023 but drop by ~5% from 2011 to 2028. Mexico vehicular emission standards for light- and heavy-duty vehicles are not aligned with the United States. As such, we are seeing less aggressive emission reductions in future years compared to the United States. Growth in area and non-road sources from 2011 to 2017 is consistent with Mexico population growth (~9%) provided in the World Bank’s World Development Indicators<sup>2</sup>.



**Figure 2-1. Mexico NOx Emissions Trend (in TPD) by Source Category in the EPA Inventory.**

<sup>2</sup> <https://data.worldbank.org/country/mexico>

Similarly, Figure 2-2 presents Mexico VOC emissions trends for each source category. Area sources dominate overall VOC inventory followed by on-road sources. Like the NOx trends, growth in area sources from 2011 to 2017 is consistent with Mexico population growth (~9%). On-road source VOC trend is like NOx except we are not seeing dip in emissions for 2028 indicating less aggressive control assumption for VOC. Industrial point sources increase in future years but trend shows much higher annual percent growth for farther future years.



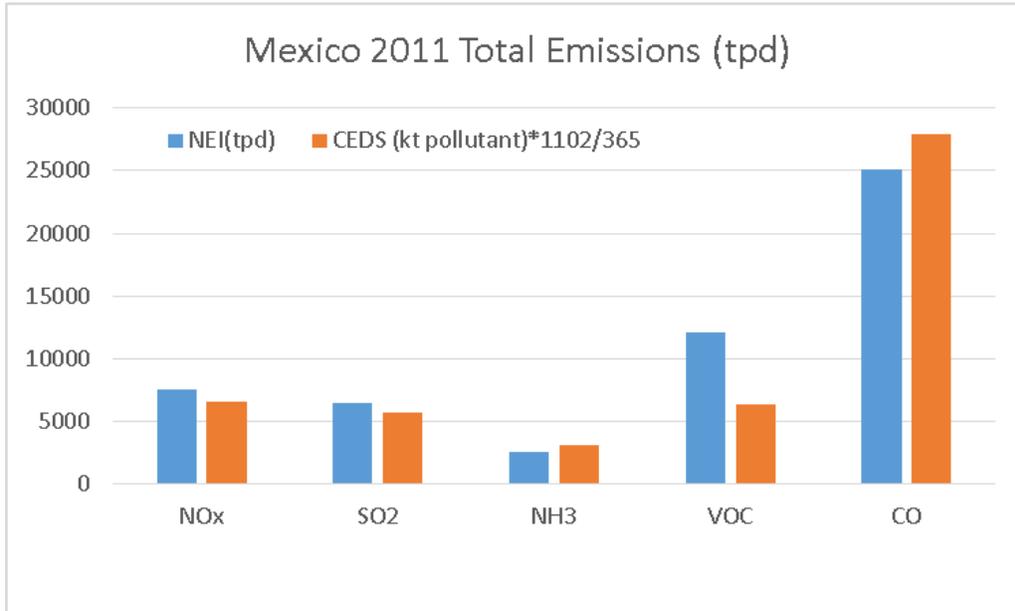
**Figure 2-2. Mexico VOC Emissions Trend (in TPD) by Source Category in the EPA Inventory.**

## 2.1 Global Emissions Inventory

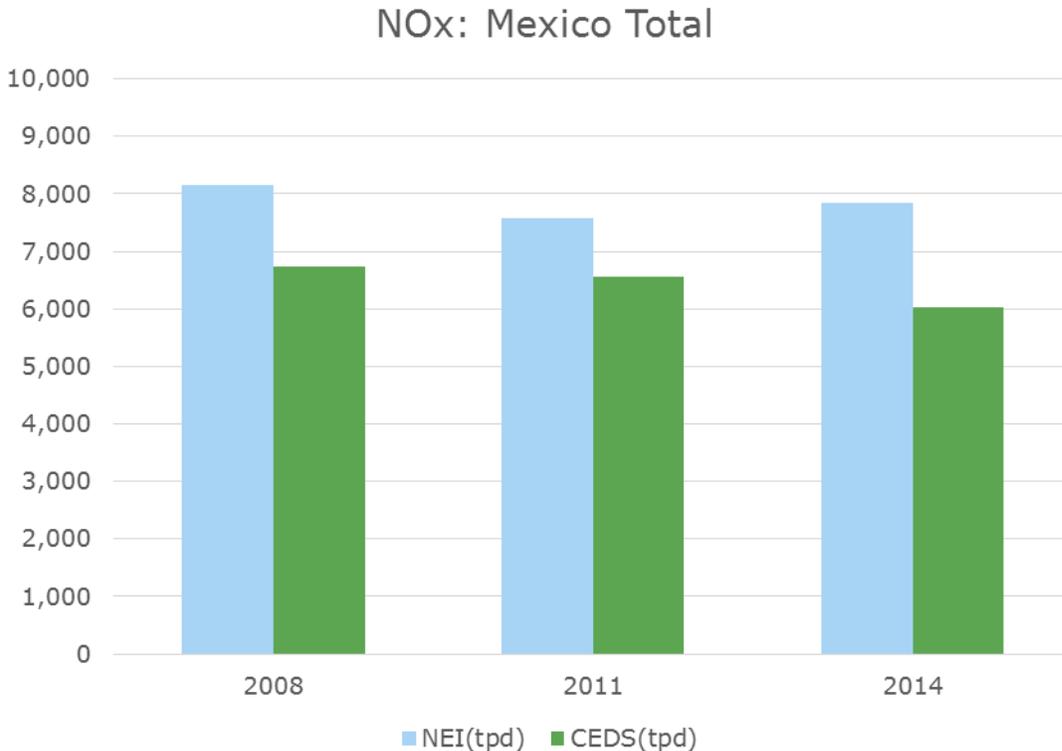
We compared the existing EPA inventory to a new data set of annual anthropogenic emissions developed with the Community Emissions Data System (CEDS) (Hoesly et al., 2018). The core outputs of the CEDS system are country-level annual historical (1750 - 2014) emissions aggregated to the CEDS sector level. The CEDS system relies on existing energy consumption data sets, and regional and country-specific inventories to produce trends over recent decades. The emissions developed with the CEDS are also available as gridded emission data with monthly seasonality in CF-compliant NetCDF format<sup>3</sup>.

<sup>3</sup> <http://cfconventions.org/>

Figure 2-3 shows a comparison of 2011 emissions for Mexico between the CEDS and EPA inventory. Generally, there is a good agreement between the two inventories except VOC. VOC emissions are higher by a factor of 2 in the EPA inventory compared to the CEDS. Figure 2-4 illustrates historical NOx trend (in TPD) between the CEDS and EPA inventory for the available years. In general, EPA NOx estimates are higher than CEDS. The trends were comparable between the two inventories and we didn't identify any red flags.



**Figure 2-3. 2011 Emissions Comparison for Mexico between the CEDS and EPA Inventory.**



**Figure 2-4. Mexico Historical NOx Trend between CEDS and EPA Inventory.**

## 2.2 Future Year 2064 Projections

For the year of 2064, Ramboll developed adjustment factors for the area, non-road, on-road, and point source categories that could be applied to the existing 2028 data sets to create 2064 future year emissions projections. We recognize that estimating emissions for 2064 is uncertain and understand that the 2064 emissions projections will be used by TCEQ for summary emissions analyses rather than for air quality modeling purposes. The projection factors were developed for area, non-road, on-road and point categories and applied to the 2028 EPA data sets. The projection factors were based on the Representative Concentration Pathway (RCP) 4.5 (Thomson et al., 2011) and RCP6.0 (Masui et al., 2011) databases<sup>4</sup> which is likely to provide a moderate estimate of 2064 emissions.

Table 2-3 presents emissions summary (in TPD) for the projected 2064 inventory by source category. The summary shows approximately 47% NOx reduction from 2028 for the on-road source category. The 2064 projections based on RCP4.5 scenario show a large VOC increase for point sources.

<sup>4</sup> <https://tntcat.iiasa.ac.at/RcpDb>

**Table 2-3. Mexico 2064 Projections (in TPD) Based on RCP4.5 and RCP6.0.**

Source Category	2028	2064 RCP4.5	2064 RCP6.0
<b>CO</b>			
Point	2,754	2,283	2,209
Area	7,861	5,289	3,473
Non-road	490	330	216
On-road	15,145	8,671	9,133
<b>CO Total</b>	<b>26,250</b>	<b>16,572</b>	<b>15,032</b>
<b>NH<sub>3</sub></b>			
Point	142	182	121
Area	2,403	2,499	3,978
Non-road	0	0	0
On-road	38	41	32
<b>NH<sub>3</sub> Total</b>	<b>2,583</b>	<b>2,723</b>	<b>4,132</b>
<b>NO<sub>x</sub></b>			
Point	2,379	1,634	1,914
Area	1,390	1,485	1,034
Non-road	901	962	670
On-road	3,680	2,250	1,956
<b>NO<sub>x</sub> Total</b>	<b>8,350</b>	<b>6,331</b>	<b>5,574</b>
<b>PM<sub>2.5</sub></b>			
Point	659	447	313
Area	1,179	816	562
Non-road	93	65	44
On-road	230	135	106
<b>PM<sub>2.5</sub> Total</b>	<b>2,161</b>	<b>1,462</b>	<b>1,025</b>
<b>SO<sub>2</sub></b>			
Point	5,978	2,904	4,300
Area	60	43	27
Non-road	95	68	43
On-road	100	70	51
<b>SO<sub>2</sub> Total</b>	<b>6,232</b>	<b>3,085</b>	<b>4,421</b>
<b>VOC</b>			
Point	1,359	4,763	1,278
Area	11,723	11,407	11,790
Non-road	103	100	104
On-road	1,582	1,130	1,213
<b>VOC Total</b>	<b>14,767</b>	<b>17,400</b>	<b>14,384</b>

## 2.3 Summary and Recommendations for Using Existing Mexico Emissions Inventory

Below, we provide a summary of findings of this task and recommendations for using existing Mexico emissions inventory from EPA.

1. Even though 12US2 emissions cover the northern part of Mexico only, EPA inventory data cover all 32 states of Mexico
2. EPA inventory data trend for Mexico looks reasonable when comparing with growth indicators like population and in the light of future vehicle/fuel standards
3. TCEQ can linearly interpolate available inventory data sets from EPA to develop emissions for their modeling years
4. There are some large VOC differences between MOBILE6 and MOVES estimates for Mexico on-road sources. Avoid mix and match of EPA on-road inventory based on different model (i.e MOBILE6-Mexico vs. MOVES-Mexico) for interpolation.
5. Mexico inventory data from EPA are generally in good agreement with the new global inventory data developed with the CEDS.
6. TCEQ can use either RCP4.5 or RCP6.0 for 2064 projections. If RCP4.5 is used, consider over-riding the increase in point source VOC that looks inconsistent with other species.

### 3.0 SATELLITE DATA FOR LARGE SO<sub>2</sub> SOURCES

The National Aeronautics and Space Administration (NASA) provides a global catalogue of large SO<sub>2</sub> point sources or clusters of sources that are observable from space by satellite instruments<sup>5</sup> (Fioletov et al., 2016). Globally, 491 sources have been identified and classified by country and source type including volcanoes; power plants; smelters and oil and gas industry sources. There are 20 large SO<sub>2</sub> sources identified by satellite in Mexico.

#### 3.1 SO<sub>2</sub> Sources in Mexico Identified by Satellite

The list of large SO<sub>2</sub> sources in Mexico identified by satellite is provided in Table 3-1 and shown in Figure 3-1. The catalogue provides annual emission estimates for the period 2005 – 2014 (available at the time of access). The annual emission estimates of these large SO<sub>2</sub> sources for Mexico are plotted in Figure 3-2 by source type. The two largest sources are the Popocatepetl volcano and Cantarell offshore Oil and Gas (O&G) source in the Bay of Campeche. Both sources exceed 1,000 kilotonnes (kt) of SO<sub>2</sub> per year and have emissions that vary by a factor of 5 over the period 2005 – 2014. The SO<sub>2</sub> emissions from Popocatepetl peaked in 2012 which was a year of escalated activity that peaked in April 2012<sup>6</sup>. All other SO<sub>2</sub> sources in Mexico had emissions less than 300 kt per year for most years. Satellite-derived SO<sub>2</sub> emission estimates for the Carbon Power Plant, located close to the Texas border, are shown in Figure 3-2. The Carbon power plant emissions vary between 150 kt and 200 kt per year over the period. A comparison of emissions with the EPA 2011v6.3 inventory for Mexico is provided in the next section. The stated uncertainty budget (Fioletov et.al., 2016) for the satellite-derived SO<sub>2</sub> emissions is ±55 % for sources above 100 kt/year and > ±67 % for sources below 50 kt/year.

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<sup>5</sup> <https://SO2.gsfc.nasa.gov/measures.html#aq>

<sup>6</sup> [https://volcano.si.edu/volcano.cfm?vn=341090#bgvn\\_201205](https://volcano.si.edu/volcano.cfm?vn=341090#bgvn_201205)

**Table 3-1. List of large SO<sub>2</sub> sources in Mexico identified by satellite**

Source Type	Name	Elevation (m)	Latitude	Longitude	Comment
Smelter	Sonora	1456	30.49	-109.63	Nacozari de Garcia, Sonora (La Caridad) Copper smelter
Power Plant	Puerto Libertad	10	29.91	-112.69	
Power Plant	Carbon	307	28.46	-100.68	Carbon I and II Coal power plants
Power Plant	Guaymas	4	27.94	-110.86	Carlos Rodriguez Rivero (Guaymas II) Thermal power plant
Power Plant	Topolobampo	50	25.61	-109.05	
Oil and Gas	Cadereyta	322	25.59	-99.94	Refineria Pemex Cadereyta
Power Plant	Ciudad Juarez	1160	25.49	-103.57	Power plant near Ciudad Juarez
Power Plant	Mazatlan	12	23.19	-106.36	Jose Aceves Pozos (Mazatlan II) Thermal power plant
Oil and Gas	Tampico	8	22.27	-97.81	Pemex Ciudad Madero Refinery, Altamira Oil power plant 25 km north-west
Power Plant	Villa De Reyes	1820	21.83	-100.94	
Power Plant	Tuxpan	2	21.02	-97.33	Power plant and oil refinery neat Tuxpan
Power Plant	Salamanca	1720	20.57	-101.17	Oil refinery and power plant near Salamanca
Oil and Gas	Tula	2125	20.05	-99.28	Refinery, other sources
Oil and Gas	Cantarell	1	19.40	-92.24	Oil fields in Gulf of Mexico
Power Plant	Manzanillo	42	19.08	-104.28	Manzanillo power plant and oil refinery
Volcano	Popocatepetl	5100	19.02	-98.62	
Power Plant	Petalcalco	13	17.98	-102.12	
Oil and Gas	Minatitlan	16	17.98	-94.53	Refinería General Lázaro Cárdenas del Río, other oil refineries in the area
Oil and Gas	Reforma	22	17.89	-93.19	Oil and gas factories near Reforma
Oil and Gas	Salina Cruz	9	16.21	-95.18	Salina Cruz Oil refinery

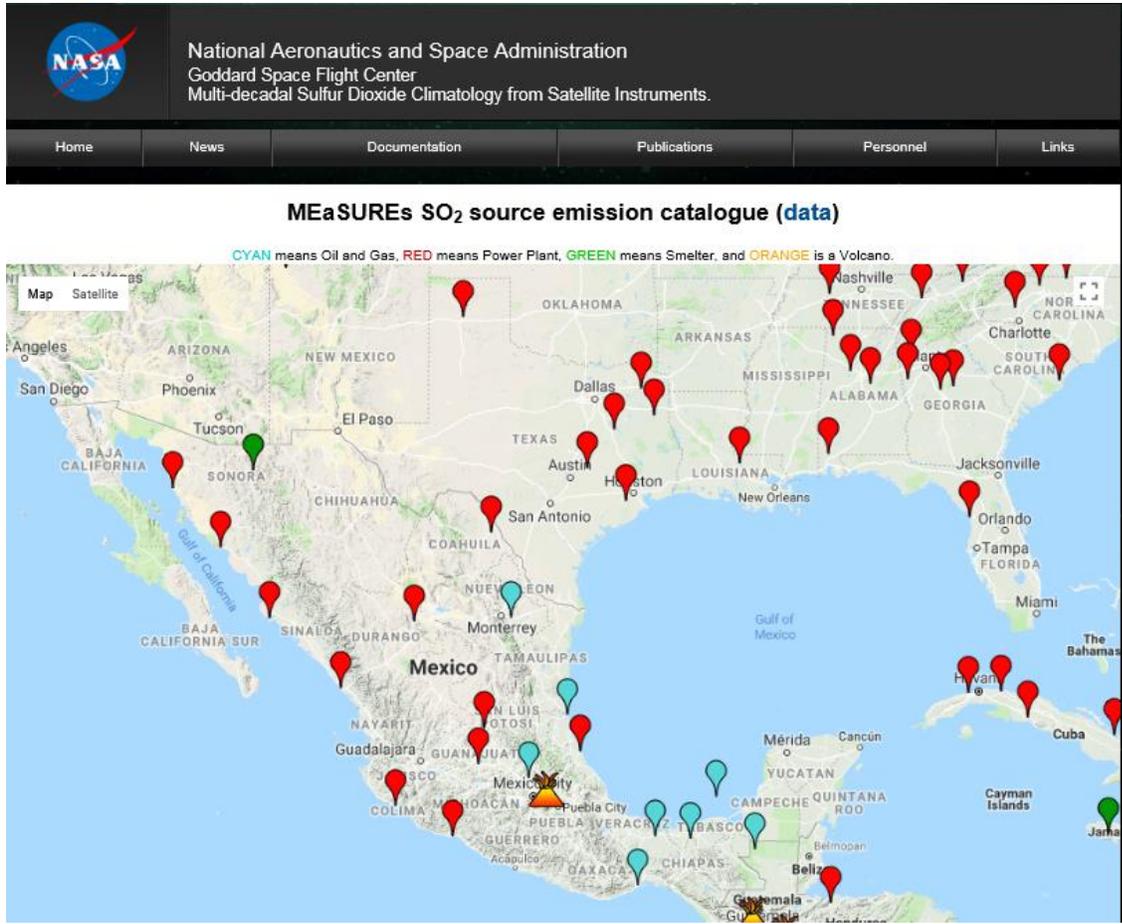
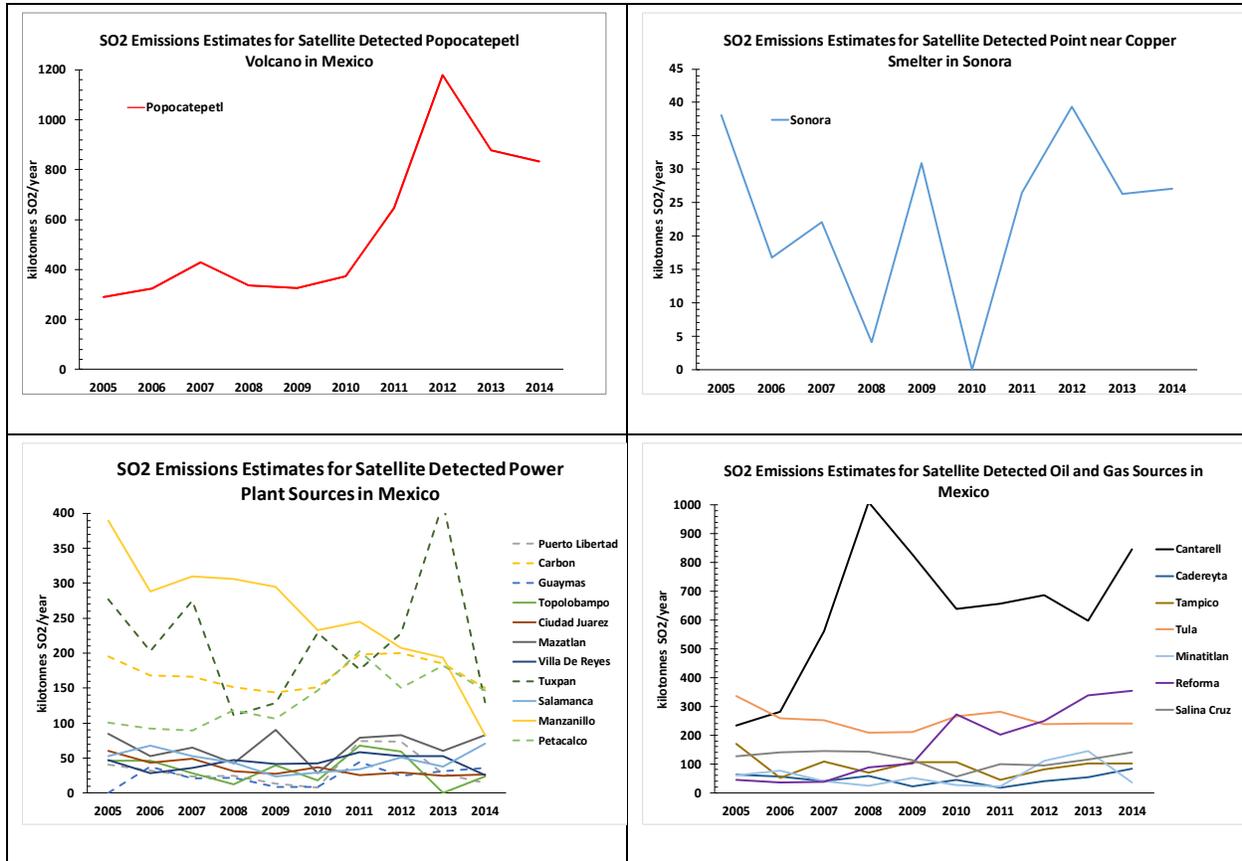


Figure 3-1. Map of large SO<sub>2</sub> sources in Mexico identified by satellite.

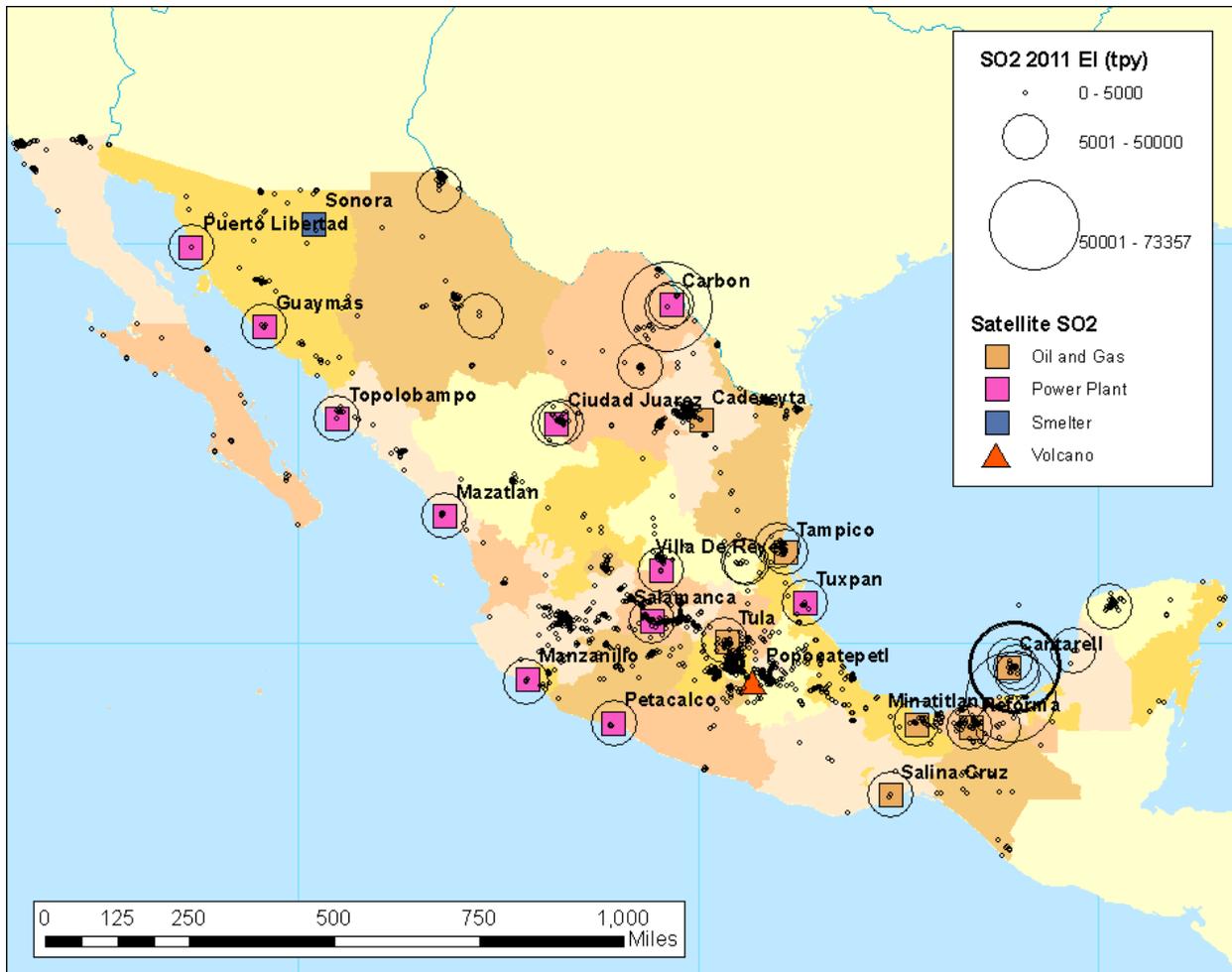


**Figure 3-2. Annual emission estimates for large SO<sub>2</sub> sources in Mexico determined by satellite.**

### 3.2 Comparing Location and Magnitude of Inventory and Satellite SO<sub>2</sub> Sources

The catalogue of large SO<sub>2</sub> sources can be used to evaluate major SO<sub>2</sub> sources in the currently available modeling inventories for Mexico. We compared large SO<sub>2</sub> sources identified by satellite to point source inventory data for Mexico included in EPA’s “2011 v6.3” modeling platform (“2011en”). TCEQ is currently using Mexico inventory data from this EPA platform for developing emissions for input to CAMx. To determine whether all the satellite SO<sub>2</sub> sources are present in the EPA inventory, we created an overlay of the satellite SO<sub>2</sub> sources and EPA inventory sources with ArcGIS software as shown in Figure 3-3. The figure shows the EPA inventory sources as unfilled circles with size of the circles proportional to the SO<sub>2</sub> emissions rate. In this plot, large SO<sub>2</sub> sources in EPA inventory clearly stand out from the multitude of smaller sources. As noted above, the satellite-identified sources are differentiated by the four source types: Oil and Gas, Power Plant, Smelter and Volcano. Each satellite SO<sub>2</sub> source is encircled by a large point source in the EPA inventory emitting more than 5,000 tons per year (tpy) indicating a good agreement between the two datasets, except for Cadereyta, Sonora, and Popocatépetl. Upon further investigation of Cadereyta source, which is an O&G source, we found cluster of several co-located point sources in the EPA inventory. Sum of SO<sub>2</sub> emissions

from these cluster of sources would fall in the range of 5000-50,000 tpy but individually they are small and do not show up as a large source. However, we could not find any large SO<sub>2</sub> sources nor cluster of smaller sources that would sum up to a large SO<sub>2</sub> source near Sonora. We don't expect to find the Popocatepetl volcano in the EPA inventory because the EPA point inventory typically includes anthropogenic sources only but excludes natural sources such as volcano. There are some sources in the EPA inventory in the 5000-50,000 tpy range that were not included in the NASA satellite catalogue. We confirmed that they are all actual emissions sources but may not have met the size threshold to have been included in the NASA catalogue.



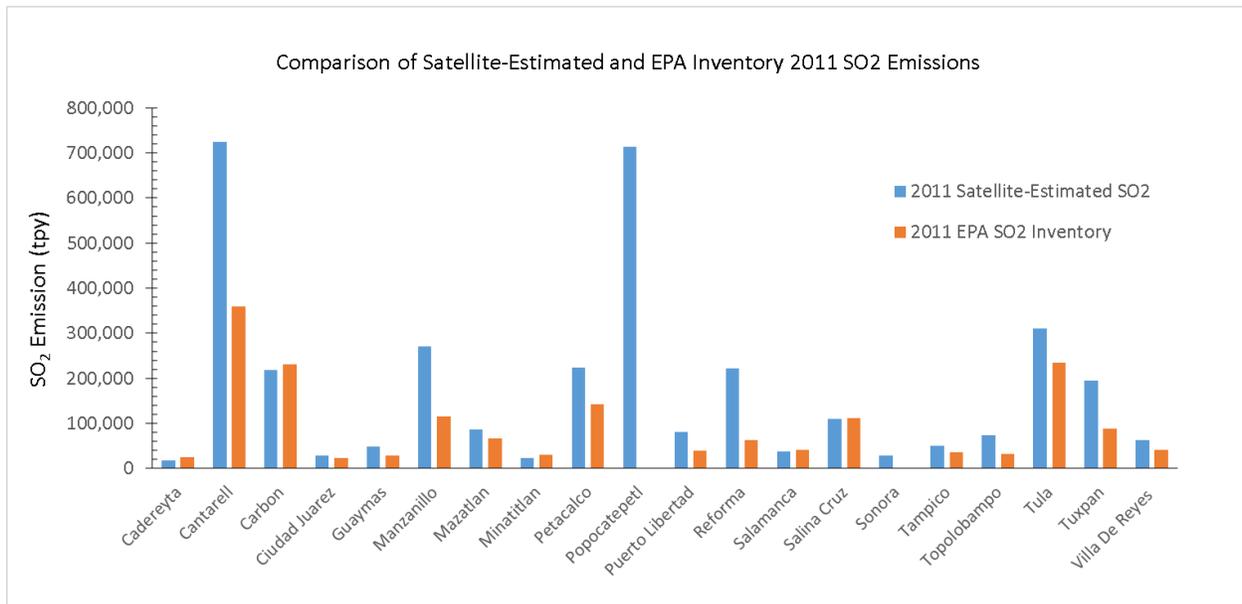
**Figure 3-3. Overlay of the satellite SO<sub>2</sub> sources and EPA inventory sources.**

The NASA SO<sub>2</sub> catalogue provided actual facility or volcano name for many identified sites (example, Carbon Power Plant, Cadereyta Refinery); otherwise, the sites were labelled by the name of the nearest town names. In cases of multiple sources, the site coordinates were assigned to the largest source. To compare satellite-derived SO<sub>2</sub> estimates with the EPA inventory magnitude, we extracted point sources in the EPA inventory within 20-km buffer around each of the SO<sub>2</sub> source identified by satellite. In many cases, the extracted inventory sources were from one or two facilities with a couple of stacks with large emissions. However,

in some cases, there were several stacks that belonged to many different facilities, for example Ciudad Juarez.

EPA point source SO<sub>2</sub> emissions within the 20-km buffer of each site were summed together and plotted alongside satellite estimates in Figure 3-4. As you can see, some sources show good agreement with satellite estimates while others do not. Table 3-2 shows emissions magnitude comparison for each site between the satellite-derived emission estimates and EPA inventory SO<sub>2</sub> emissions for 2011.

The NASA catalogue data identified the SO<sub>2</sub> source in Sonora as a copper smelter. We confirmed the existence of this Sonora source using Google Earth as shown in Figure 3-7. However, there are no sources found in the EPA inventory at that location. The EPA inventory included a source just beyond the 20-km buffer around the Sonora source which is located at a copper mine (known as “MEXICANA DE COBRE S.A. DE C.V. UNIDAD LA CARIDAD”). Emissions from this source are reported in Table 3-2 which are negligible in comparison with satellite data. Two small point source were found in the EPA inventory that were within the 20-km buffer of the Popocatepetl volcano. These small sources are not reported in Table 3-2 for the Popocatepetl volcano because they are not related to volcano.



**Figure 3-4. Comparison of satellite-derived SO<sub>2</sub> emission estimates and EPA inventory sources.**

**Table 3-2. Emissions comparison for SO<sub>2</sub> sources identified by satellite.**

Name	Type	2011 Satellite SO <sub>2</sub> (tpy)	2011 EPA SO <sub>2</sub> Inventory (tpy)	Ratio of Satellite to EPA
Cadereyta	Oil and Gas	18,302	24,516	0.75
Cantarell	Oil and Gas	724,873	359,909	2.01
Carbon	Power Plant	218,398	230,667	0.95
Ciudad Juarez	Power Plant	28,435	23,540	1.21
Guaymas	Power Plant	48,980	29,363	1.67
Manzanillo	Power Plant	270,075	115,898	2.33
Mazatlan	Power Plant	87,412	67,524	1.29
Minatitlan	Oil and Gas	23,956	67,524	0.35
Petalcalco	Power Plant	224,097	142,381	1.57
Popocatepetl	Volcano	713,424	0	∞
Puerto Libertad	Power Plant	81,582	39,843	2.05
Reforma	Oil and Gas	221,809	63,497	3.49
Salamanca	Power Plant	37,767	41,777	0.90
Salina Cruz	Oil and Gas	109,504	111,646	0.98
Sonora	Smelter	29,238	132	222.10
Tampico	Oil and Gas	50,039	35,104	1.43
Topolobampo	Power Plant	74,555	33,018	2.26
Tula	Oil and Gas	310,334	234,881	1.32
Tuxpan	Power Plant	194,979	89,266	2.18
Villa De Reyes	Power Plant	63,947	40,993	1.56

Figure 3-5 shows a scatter plot of 2011 SO<sub>2</sub> emission estimates for the satellite sources versus EPA inventory data. The satellite-derived SO<sub>2</sub> estimates are generally higher than the EPA inventory data, and larger SO<sub>2</sub> sources generally have a larger absolute positive bias. There is no clear tendency for the Oil and Gas sources nor the Power Plant sources to have a particular bias in terms of direction or magnitude of the bias.

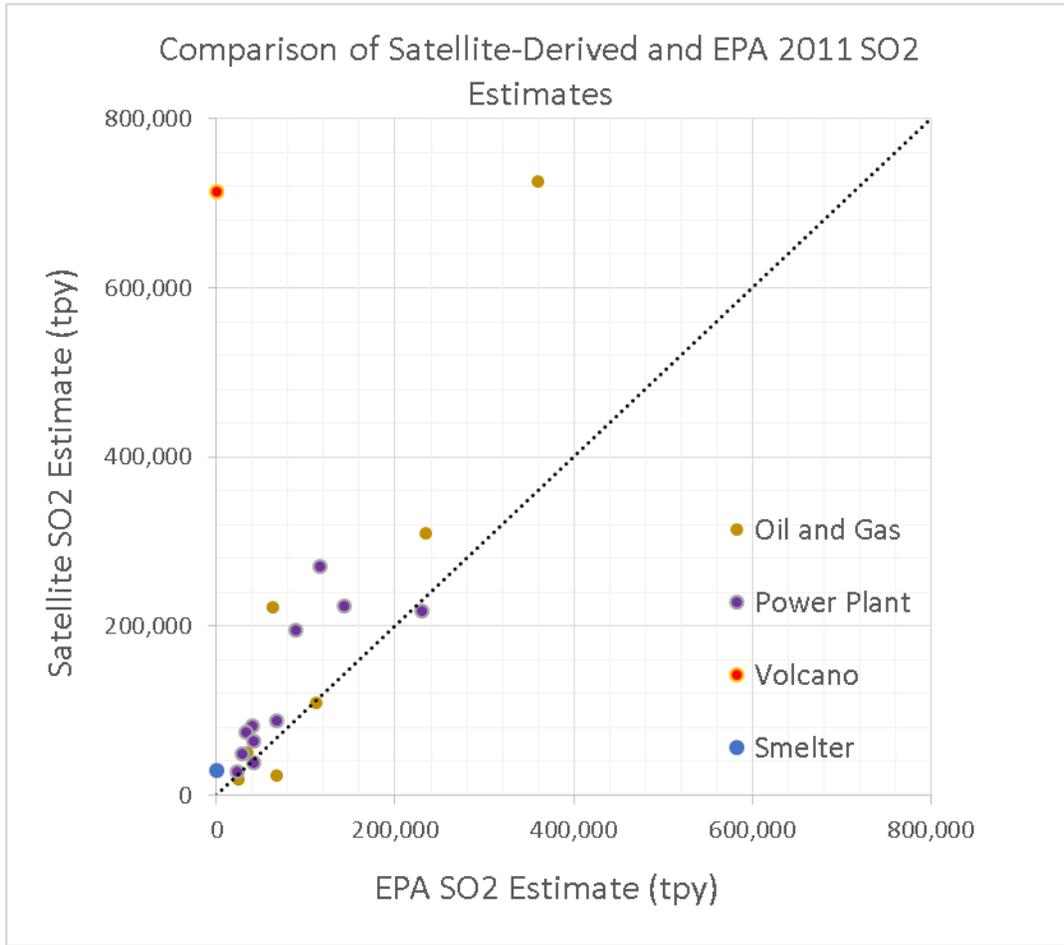


Figure 3-5. Comparison of satellite-derived SO<sub>2</sub> emission estimates and EPA inventory data.

### 3.3 Recommended Updates to the EPA Inventory Data

#### 3.3.1 Popocatépetl volcano

Popocatépetl is an active volcano near Mexico City with large SO<sub>2</sub> emissions. Figure 3-6 shows a satellite photo of the volcano. The SO<sub>2</sub> emissions from this volcano peaked in 2012 which is a year of escalated activity. It is by far the largest SO<sub>2</sub> emissions source in 2012 among all the satellite SO<sub>2</sub> sources in Mexico. The symmetrical cone of Popocatépetl rises to an elevation of 17,930 feet (5,450 metres) and emits high in the atmosphere, well above the planetary boundary layer (Grutter et al., 2008), and can be an important source for long range transport.

##### 3.3.1.1 Emissions Inventory Recommendation:

We recommend that SO<sub>2</sub> emissions from the Popocatépetl volcano be added to the emissions inventory.

Popocatépetl is a high emission rate and passively degassing active volcano that smokes all the time, but may have periods of high and low activity. The annual SO<sub>2</sub> estimates from satellite measurements are available for 2005-2014. However, we do not have reliable data to distribute emissions within a given year for temporal variation. We assumed a flat temporal profile for EPS3 processing. The grid cell containing Popocatépetl volcano has a base elevation of 2394 m in WRF/CAMx. In the CAMx input file, we assigned plume top (PTOP) = 3500 m and plume bottom (PBOT) = 3000 m to approximate plume rise. We developed and provided a full EPS3 run stream for the volcano emissions that include inputs, cross-reference files, userin files, message files, and EPS3 outputs ready for input to CAMx.



**Figure 3-6. Satellite image of the smoking crater of the Popocatepetl volcano, near Mexico City.**

### 3.3.2 Copper Smelter in Sonora

The satellite-identified SO<sub>2</sub> source in Sonora was determined by NASA to be a copper smelter. As previously mentioned, we confirmed that the smelter source exists with Google Earth as shown in Figure 3-1 and Figure 3-7 and noted that the 2011 EPA inventory does not include any point sources within 20 km of that site. There is a source just beyond 20 km (that is located at the La Caridad copper mine) and is identified as “MEXICANA DE COBRE S.A. DE C.V. UNIDAD LA CARIDAD”. SO<sub>2</sub> emissions from this EPA source are 132 tpy, which is approximately 200 times less than satellite-derived SO<sub>2</sub> emission estimates for 2011. As presented in Figure 3-2, satellite-derived SO<sub>2</sub> emission estimates for this source vary widely from year to year and had low numbers for 2008 and 2010. We investigated the smelter in Sonora and determined that the owner of the smelter is the Southern Copper Company, a subsidiary of Grupo Mexico<sup>7</sup>. The Southern Copper Company website<sup>8</sup> states:

*“Our Mexican operations are conducted through our subsidiary, Minera Mexico S.A. de C.V. (“Minera Mexico”), which we acquired on April 1, 2005. Minera Mexico engages principally in the mining and processing of copper, molybdenum, zinc, silver, gold and lead. Minera Mexico operates through subsidiaries that are grouped into three separate*

<sup>7</sup> <http://www.gmexico.com/site/en/us/mining.html>

<sup>8</sup> <http://www.southerncoppercorp.com/ENG/about/Pages/HomeMore.aspx#sitemap>

*units...Mexicana de Cobre S.A. de C.V. operates La Caridad, an open-pit copper mine, a copper ore concentrator, a SX/EW plant, a smelter, refinery and a rod plant.”*

Note that the only rod plant owned by Southern Copper Company is at the “La Caridad” location. Production statistics from Southern Copper Company annual reports<sup>9</sup> indicate relatively continuous copper concentration production at the La Caridad location from 2006 – 2014 as shown in Figure 3-8. The increase in Southern Copper Company rod production in 2011 is likely due to increased copper mining operations at the nearby Buenavista mine<sup>10</sup> at Cananea when multi-year strikes ended and operations resumed and copper mined at the Buenavista site was processed at the La Caridad smelter, and potentially other reasons such as the 2010 shutdown of the Potosi copper smelter discussed below. It is unclear whether the high variability in satellite-estimated SO<sub>2</sub> emissions for the Copper Smelter is due primarily due to limitations of the satellite measurements or is reflective of operations at the Smelter. Nevertheless, since 2011, Southern Copper Company production statistics for La Caridad and satellite-derived SO<sub>2</sub> emission estimates do not indicate wide variations.

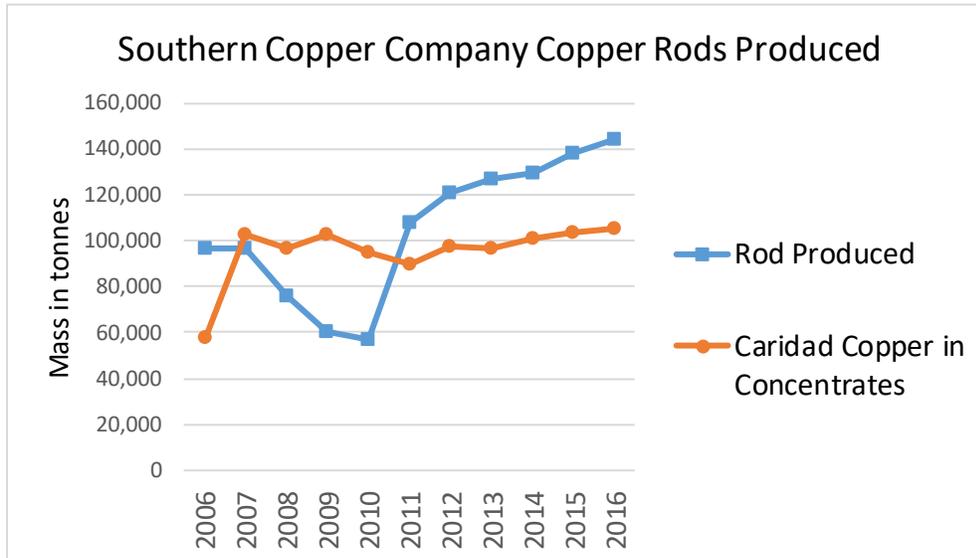
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<sup>9</sup> <http://www.southerncoppercorp.com/ENG/invrel/2014/default.aspx>

<sup>10</sup> <http://www.southerncoppercorp.com/ENG/intope/Pages/PGIntOperation.aspx#cuadros>



Figure 3-7. Google Earth and web images of copper smelter at Sonora.



**Figure 3-8. Southern Copper Company copper rods produced.**

### 3.3.2.1 Emissions Inventory Recommendation:

We recommend that emissions from the La Caridad copper smelter be added to the emissions inventory.

The satellite SO<sub>2</sub> estimate for 2011 is 29,238 tpy, and we propose using that values as the basis for emissions estimates for the La Caridad copper smelter. Other estimates based on the satellite SO<sub>2</sub> data were considered, including using the period-wide mean value, the median value, or the average of more recent years, and all those methods result in similar estimates. Therefore we selected the most simple estimate for SO<sub>2</sub> emissions. To get source profile and other pollutant emissions for the Sonora smelter, we used inventory data for other copper smelters in Mexico. We searched the 2011 EPA inventory and identified a smelter at Potosi, Mexico as a similar source that can be used to develop an inventory for the Sonora smelter. SO<sub>2</sub> emissions from the Potosi smelter facility were 1,183 tpy for 2008 in the EPA inventory. We researched details regarding the Potosi copper smelter online and found that while it was operational in 2008, the plant closed in 2010 and should therefore be removed from the inventory for years 2011 and later. We also found that the Southern Copper Company (owner of the La Caridad, Sonora Copper Smelter) was also the owner of the Potosi copper smelter and consulted company annual reports to compare characteristics of each facility. The Southern Copper Company 2008 annual report<sup>11</sup> states that:

*“The San Luis Potosi Copper Smelter has a production capacity of 66 tons of blister copper per day”*

<sup>11</sup> <http://www.southerncoppercorp.com/ENG/invrel/2008/AnnualReport/m2008i.pdf>

*“La Caridad Metallurgic Complex La Caridad Smelter started operating in July, 1986, with a production capacity of 493 tons of anode per day and was expanded to 932 tons in March, 1997.”*

In addition, there are two other major copper processing facilities at the La Caridad site:

*““La Caridad Refinery” started operating in July, 1997, with a production capacity of 493 tons of copper cathode per day and was expanded to 822 tons in January, 1998.”*

*“La Caridad Wire Rod Plant” started operating in April, 1998, with a production capacity of 300 tons of wire rod per day and was expanded to 411 tons in March, 1999.”*

Thus, in 2008, the La Caridad facility had a smelter production capacity 14 times higher than the Potosi smelter, as well as additional copper processing facilities. In addition, Southern Copper Company reports that copper smelting that would have been taken place at Potosi prior to 2010 was instead to take place at the La Caridad smelter instead, and hence copper smelting has increased in more recent years at the La Caridad smelter. Given the production capacity differences between the two smelters, as well as increased production in recent years at the La Caridad smelter, the satellite SO<sub>2</sub> emissions estimate of 29,238 tons in 2011 at the La Caridad, Sonora copper smelter compared to the Potosi 2008 EPA EI emissions estimate of 1,183 tons in 2011 (a factor of 24.7 times higher) does not seem unreasonable.

In addition, the USGS online spatial data<sup>12</sup> of copper smelters include locations and characteristics of copper smelters throughout the world in 2002. It reports the capacity of the La Caridad smelter to be ten times higher than the Potosi smelter.

Thus, we propose using the Potosi copper smelter facility from the EPA inventory as the basis for developing the La Caridad copper smelter inventory for modeling. The individual emission sources in the inventory should be scaled such that total matches with the 2011 satellite SO<sub>2</sub> emissions. Emissions of other pollutants should also be scaled using the same factor, and stack parameters and SCC codes of the Potosi copper smelter should be used for the La Caridad copper smelter in Sonora.

### **3.3.3 EI Recommendation Summary**

1. Add the Popocatepetl volcano near Mexico City to the inventory. Use SO<sub>2</sub> emissions from satellite measurement for this source not captured in the EPA inventory.
2. Add the La Caridad copper smelter to the inventory. Scale Potosi copper smelter emissions to match satellite SO<sub>2</sub> estimate for 2011, use same scaling factor for other pollutants.

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<sup>12</sup> <https://mrdata.usgs.gov/copper/>

- a. Note, we developed and provided a full EPS3 run stream for this facility that include inputs, cross-reference files, userin files, message files, and EPS3 outputs ready for input to CAMx.
3. Remove Potosi copper smelter facility emissions from inventory for 2011 and onwards.

## 4.0 SATELLITE DATA FOR NO<sub>2</sub> COLUMNS

In this section, we compare the EPA NO<sub>x</sub> emissions inventory for Mexico with tropospheric NO<sub>2</sub> column data available from earth orbiting satellites. First, we describe the satellite data and its strengths and limitations, then we describe how we acquired and processed satellite data for Mexico, and finally we present comparisons with the EPA inventory for Mexico.

### 4.1 Overview of Satellite Tropospheric NO<sub>2</sub> Column Data

Measurements taken from earth orbiting satellites can provide estimates of tropospheric NO<sub>2</sub> columns. Tropospheric NO<sub>2</sub> columns are the sum of all NO<sub>2</sub> molecules from the surface extending upwards through the upper troposphere at about 10 km above sea level<sup>13</sup>. The Ozone Monitoring Instrument (OMI) aboard the National Aeronautics and Space Administration (NASA) Aura satellite measures solar backscattered radiation in the visible and ultraviolet wavelengths (270 – 500 nm with 0.5 nm spectral resolution) and detects NO<sub>2</sub> from its unique spectral signature.

The OMI is gathering data as part of NASA's Aura mission to: "Understand and protect the air we breathe". The OMI is a contribution of the Netherlands's Agency for Aerospace Programs in collaboration with the Finnish Meteorological Institute and has been observing NO<sub>2</sub> as well as other chemicals and trace gases since 2004 and is currently operating.

NASA's Aura satellite orbits the earth sixteen times a day in a sun-synchronous near-polar orbit at an altitude of 438 miles. Measurements from the OMI span the entire world each day. The satellite crosses the equator at approximately 1:45 pm local time at each passing and approximately 2:20 for Mexico City (RIVERA et al., 2013). OMI is a nadir-viewing (downward-looking) instrument with a highest resolution "pixel" size of 13 x 24 km and a wide viewing angle resulting in daily global NO<sub>2</sub> data

#### 4.1.1 NASA Retrieval Algorithm

Backscattered radiation data measured by the OMI instrument needs substantial processing to be converted into tropospheric NO<sub>2</sub> columns. To perform this conversion a multi-step process known as a "retrieval" is performed. The primary steps in the retrieval algorithm are:

1. Convert measured backscattered radiation to total NO<sub>2</sub> slant column density. This step is achieved with the Differential Optical Absorption Spectroscopy (DOAS) method
2. Remove the stratospheric component of total NO<sub>2</sub> slant column density (SCD) to obtain the tropospheric component of NO<sub>2</sub> SCD. Note that there are different methods for performing the stratospheric removal which use different assumptions regarding the stratospheric component and lead to different NO<sub>2</sub> VCD products
3. Convert tropospheric NO<sub>2</sub> SCDs to tropospheric NO<sub>2</sub> VCDs. This is accomplished by applying an atmospheric mass factor (AMF).

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<sup>13</sup> <https://scied.ucar.edu/shortcontent/troposphere-overview>

Calculation of the AMF requires information about the satellite’s viewing geometry as well as the surface albedo and atmospheric scattering by clouds, aerosols, and air molecules. Assumptions must also be made regarding the vertical distribution of NO<sub>2</sub>. The vertical distribution of NO<sub>2</sub> is estimated with an atmospheric chemistry model and a radiative transfer model is then used to determine the sensitivity of backscattered light entering the detector to the NO<sub>2</sub> profile within the column. The AMF is the ratio of the slant column ( $\Omega_s$ ) to the vertical column ( $\Omega_v$ ).

$$\text{AMF} = \Omega_s / \Omega_v$$

Variants of the basic retrieval algorithm and the use of different auxiliary inputs in the retrieval algorithm produce different tropospheric NO<sub>2</sub> column results even though they are based on the same OMI radiance observations.

For this analysis we use the NASA Standard Product Version 3.0 which uses an improved DOAS algorithm<sup>14</sup>. The DOAS step derives total NO<sub>2</sub> SCD from the OMI spectra (Boersma et al., 2008; Bucsele et al., 2006). Some of the auxiliary input specifications for the NASA retrievals are listed with in Table 4 1.

**Table 4-1. Algorithm inputs for NASA SP3 tropospheric NO<sub>2</sub> column retrieval.**

	NASA Standard Product v 3.0 <sup>15</sup>
<b>Level 3 Product Resolution</b>	0.25°x0.25°
<b>NO<sub>2</sub> Profile Basis</b>	Global Modeling Initiative (GMI) 1.0°x1.25°, monthly average, yearly varying
<b>Albedo</b>	OMI derived, 0.5°x0.5°, monthly

Note that uncertainties associated with tropospheric NO<sub>2</sub> columns were reported in Parker et. al. (2017) and are estimated to be  $\sim 1 \times 10^{15} \text{ molec.cm}^{-2} \pm 20\text{-}30\%$ . Therefore, for this analysis we focus on regions of Mexico with tropospheric NO<sub>2</sub> columns  $> 1 \times 10^{15} \text{ molec.cm}^{-2}$  since analysis of regions below this threshold value may not represent real effects but be due to satellite data “noise”.

## 4.2 Satellite NO<sub>2</sub> Columns for Mexico

Satellite OMI NO<sub>2</sub> data was acquired and evaluated for Mexico and compared with the EPA inventory. We used the Giovanni tool<sup>16</sup> (snapshot provided in Figure 4-1). The Giovanni tool can perform spatial extraction for a user-defined region and temporal averaging. Using these functionalities, we extracted annual average tropospheric NO<sub>2</sub> columns for Mexico from 2008

<sup>14</sup> [https://aura.gesdisc.eosdis.nasa.gov/data/Aura\\_OMI\\_Level2/OMNO2\\_003/doc/README.OMNO2.pdf](https://aura.gesdisc.eosdis.nasa.gov/data/Aura_OMI_Level2/OMNO2_003/doc/README.OMNO2.pdf)

<sup>15</sup> [https://disc.gsfc.nasa.gov/Aura/data-holdings/OMI/omNO2\\_v003.shtml](https://disc.gsfc.nasa.gov/Aura/data-holdings/OMI/omNO2_v003.shtml)

<sup>16</sup> <https://giovanni.gsfc.nasa.gov/giovanni/>

to 2017. The data were downloaded in netCDF format and imported into ArcGIS for further analysis.

Figure 4-2 compares the 2011 satellite NO<sub>2</sub> columns with the point source NO<sub>x</sub> emissions in the EPA inventory. As mentioned above, tropospheric NO<sub>2</sub> columns of  $<1 \times 10^{15}$  molec.cm<sup>-2</sup> may be within the noise of the satellite data. Therefore, we presented all values  $<1 \times 10^{15}$  molec.cm<sup>-2</sup> as white and focused the discussion on regions with tropospheric columns  $>1 \times 10^{15}$  molec.cm<sup>-2</sup>.

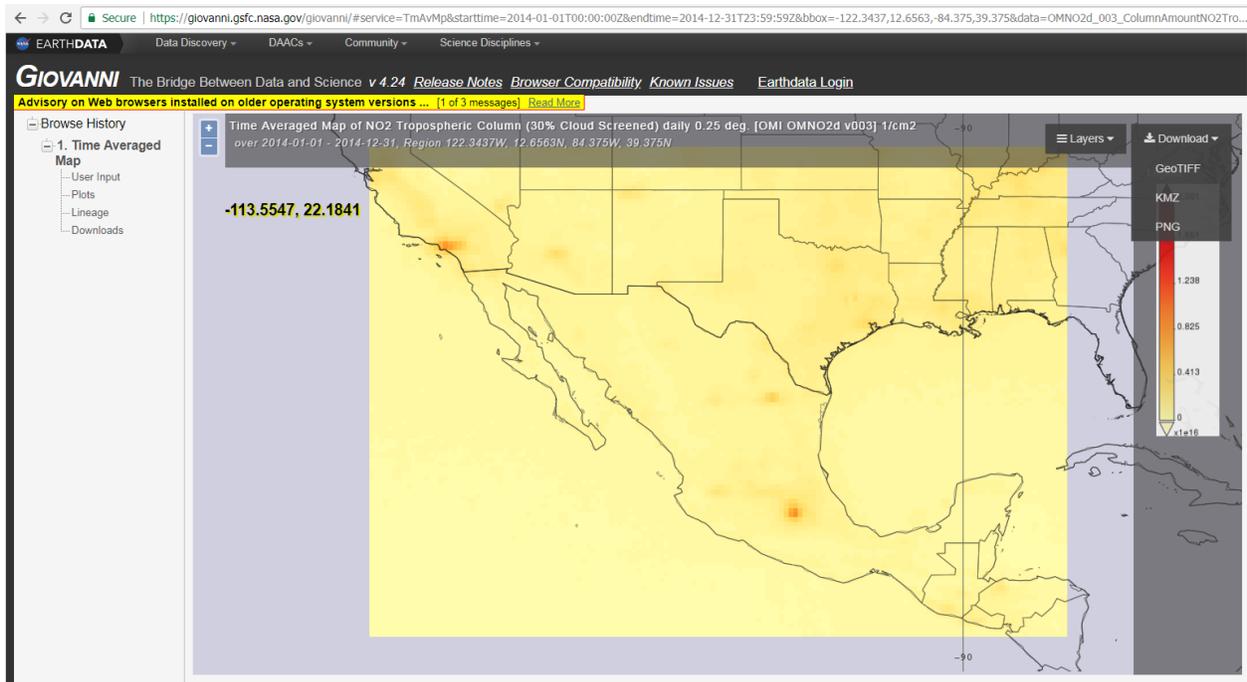


Figure 4-1. A snapshot of the “Giovanni” tool.<sup>17</sup>

<sup>17</sup> Source: <https://giovanni.gsfc.nasa.gov/giovanni/>

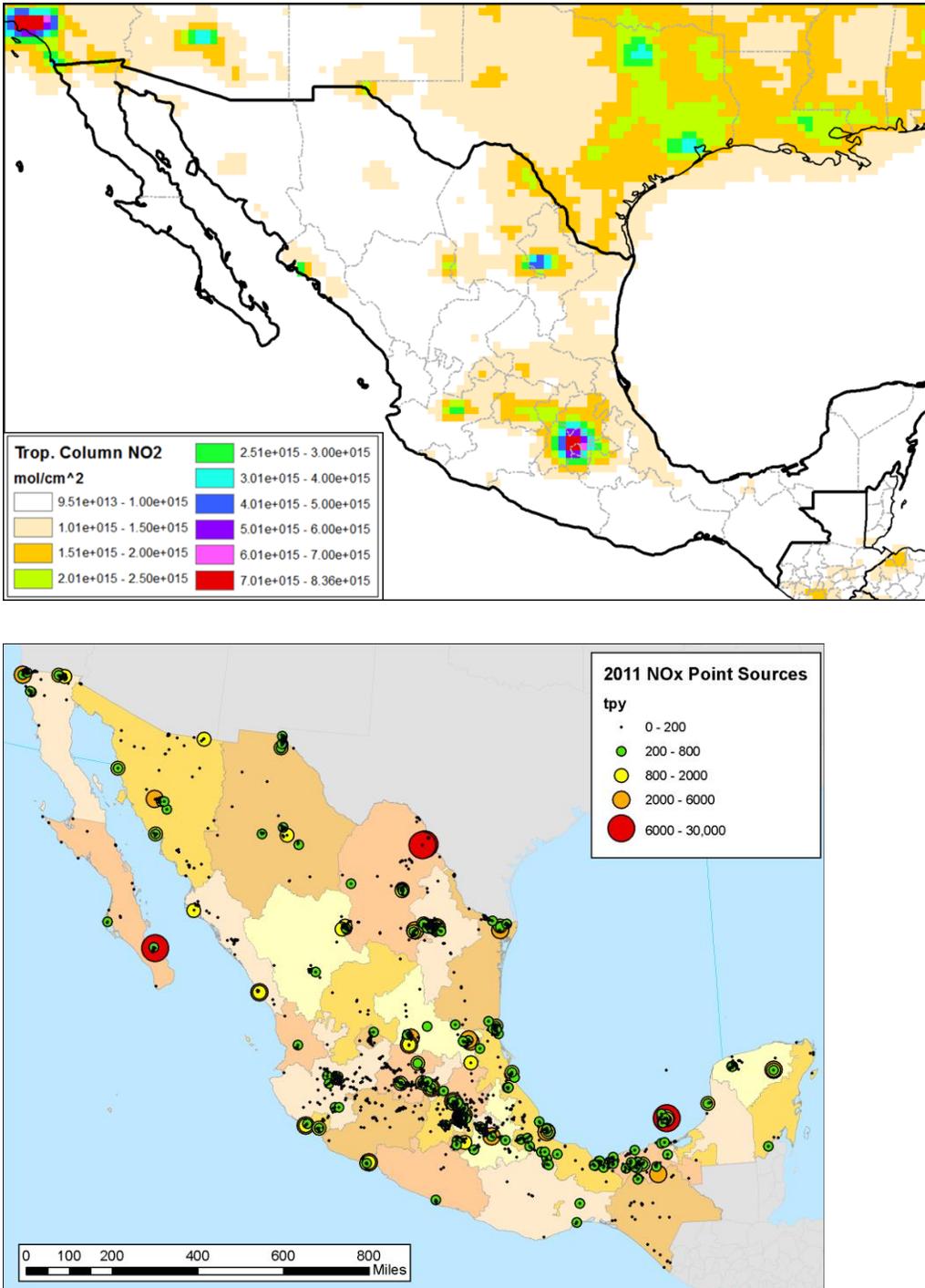
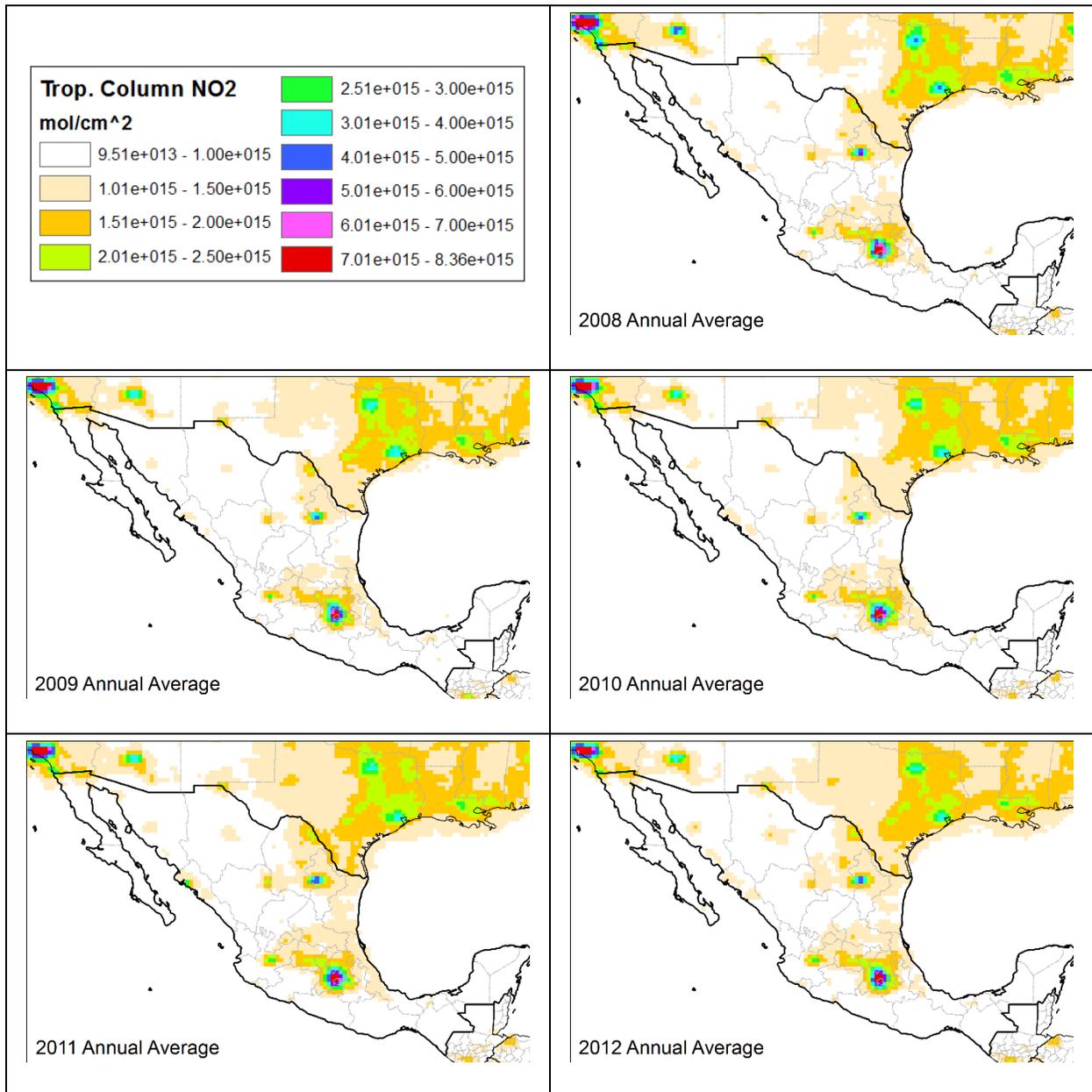
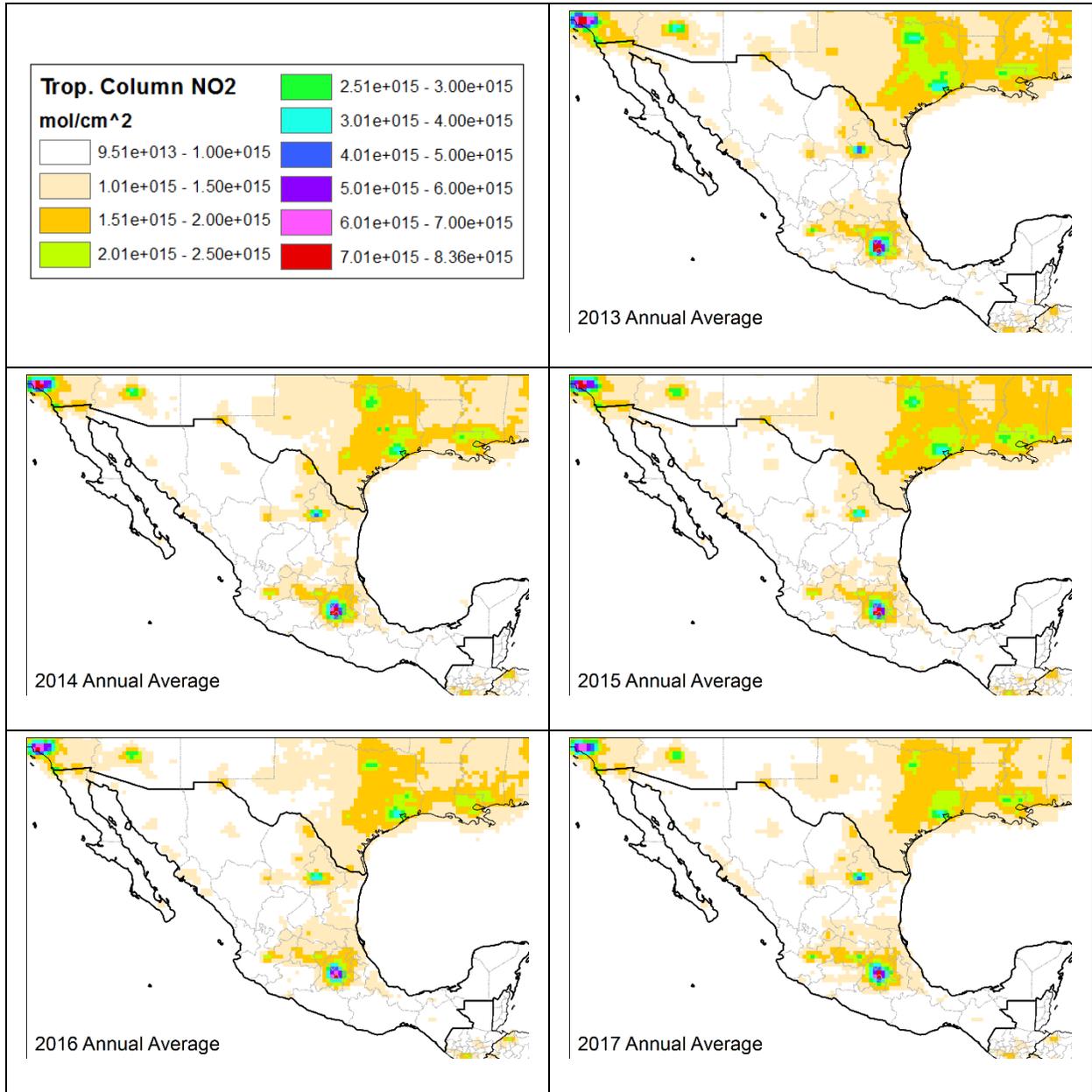


Figure 4-2. Satellite NO<sub>2</sub> Column Data for 2011 (top panel) and Spatial Display of 2011 Point Source NO<sub>x</sub> Emissions in the EPA inventory (bottom panel).

### 4.3 Spatial Analysis of Tropospheric NO<sub>2</sub> Columns: 2008 – 2017

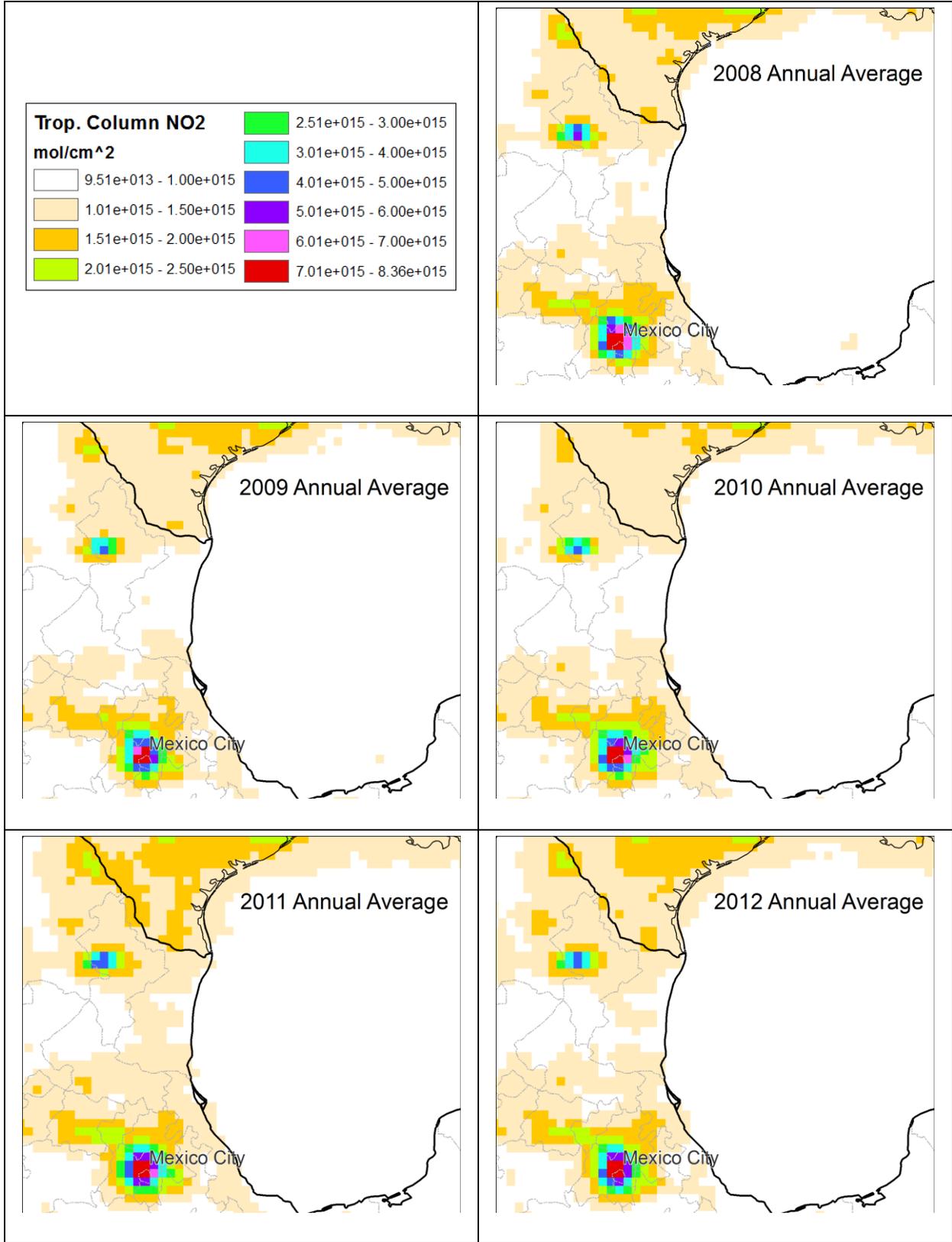
Spatial plots of NO<sub>2</sub> columns from 2008 to 2017 for Mexico and parts of the U.S. are shown in Figure 4-3. In these plots, only the values above uncertainty threshold are shown in color, values below the threshold are not shown. The bin with pale orange color represents regions with NO<sub>2</sub> columns in the range of 1 - 1.5 x 10<sup>15</sup> molec.cm<sup>-2</sup>. It is difficult to discern changes over the years, so in next section we present difference plots.





**Figure 4-3. Spatial plots of NO<sub>2</sub> columns for 2008 – 2017 for Mexico.**

Figure 4-4 presents the same data but with a different extent to observe pixel values for regions of Mexico with high NO<sub>2</sub> columns.



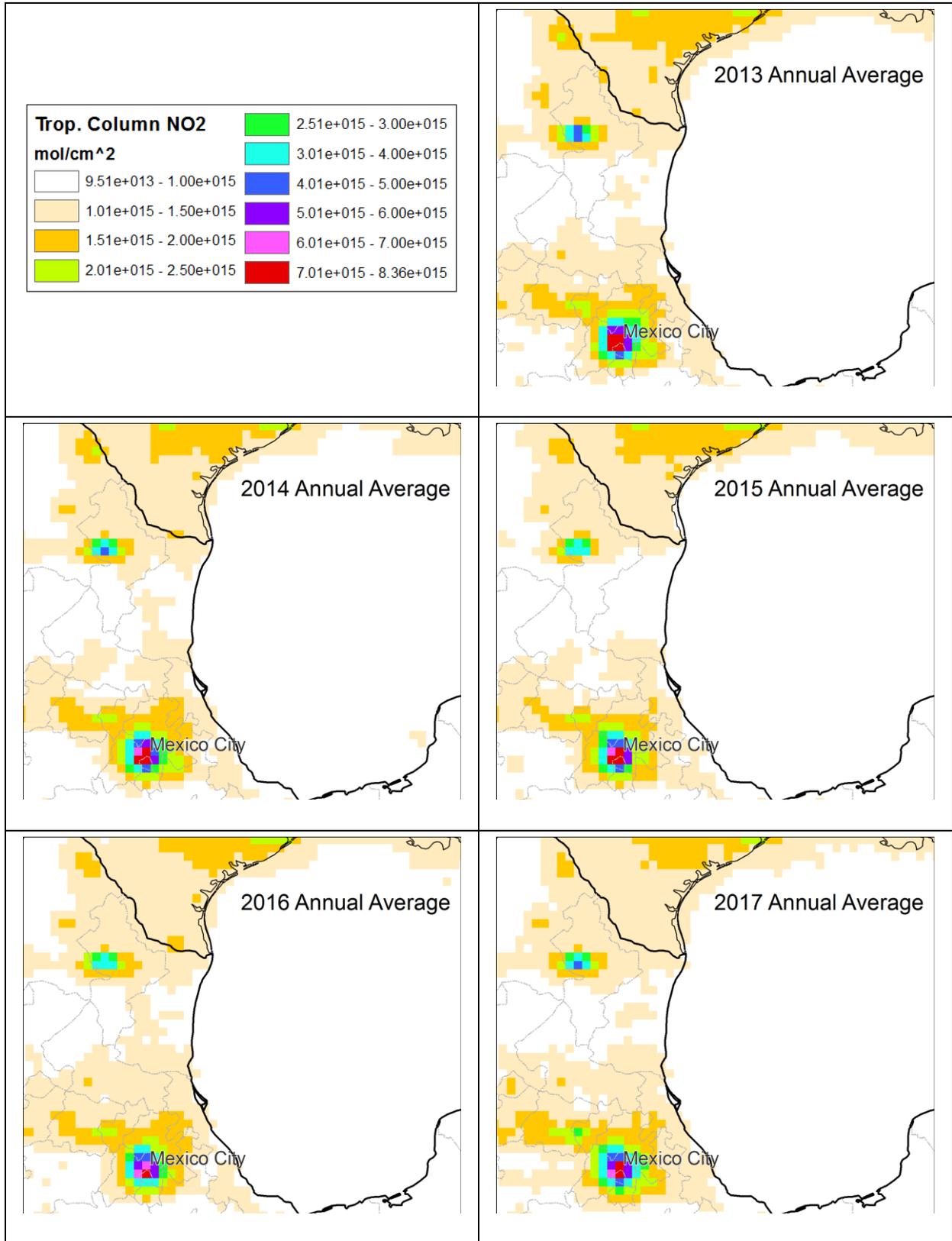


Figure 4-4. Spatial plots of NO<sub>2</sub> columns with focus on a region with high NO<sub>2</sub> columns.

#### 4.3.1 Spatial Difference Plots

In this section, we present difference plots that show how the NO<sub>2</sub> columns have changed over time. Figure 4-5 shows a difference plot (2008 minus 2017) of NO<sub>2</sub> columns for Mexico and part of the U.S. for reference. The NO<sub>2</sub> columns differences between  $-0.5$  to  $0.5 \times 10^{15}$  molec.cm<sup>-2</sup> are shown as white because they are close to the uncertainty limit of the satellite detections and retrieval algorithms. Therefore, we only focus on stronger signals that are greater than uncertainty threshold.

There are no increases in NO<sub>2</sub> columns in Mexico that are greater than  $0.5 \times 10^{15}$  molec.cm<sup>-2</sup>, and there are 4 distinct regions showing decreases, namely close to Mexico City, Monterrey, region near the Carbon Power Plant, and oil field in the Bay of Campeche. Differences in yellow color indicate a value of approximately  $1 \times 10^{15}$  molec.cm<sup>-2</sup>. All decreases are in this range except the Mexico City gridcells, which show larger differences. Most of the areas of reductions in the U.S. are also yellow. Generally, the regions with the highest reductions are Mexico City ( $\sim 3 \times 10^{15}$  molec.cm<sup>-2</sup>) and Los Angeles ( $\sim 5 \times 10^{15}$  molec.cm<sup>-2</sup>), which are also areas with 2008 NO<sub>2</sub> Columns  $> 7 \times 10^{15}$  molec.cm<sup>-2</sup>.

Inter-annual variations in meteorological condition or other factors can affect annual change in NO<sub>2</sub> column data. To minimize these effects and focus on emission trends, we present a similar analysis using the 2008 – 2010 average as the base period and the 2015 -2017 average as the most recent year period. Figure 4-6 shows the reductions are smaller and only Mexico City has reductions  $> 0.5 \times 10^{15}$  molec.cm<sup>-2</sup>. All other regions show differences within uncertainty range.

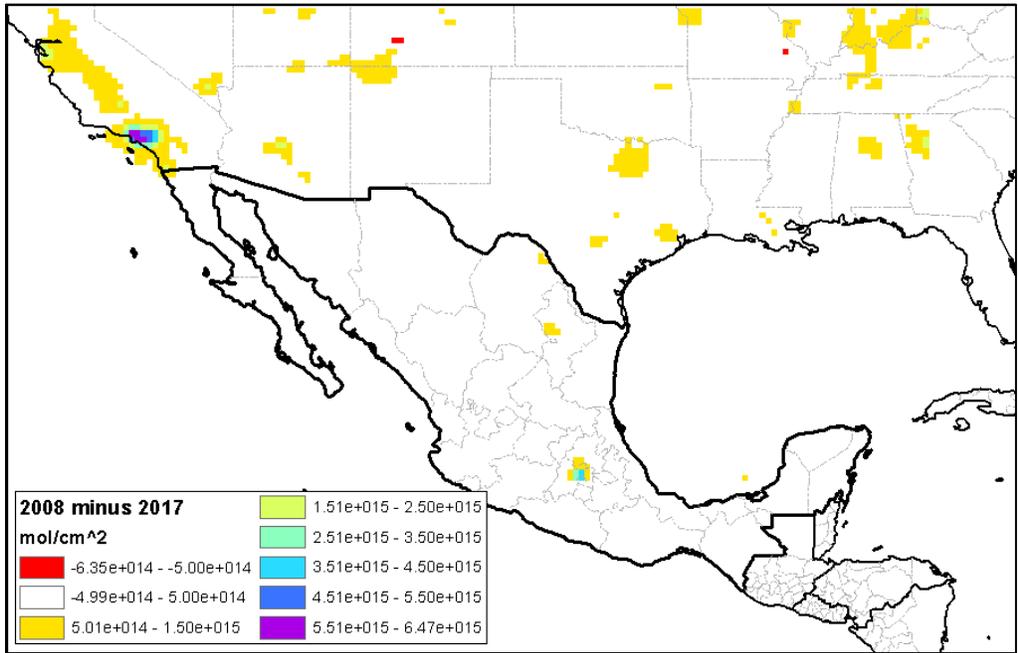


Figure 4-5. Satellite NO<sub>2</sub> Column Difference Plot showing 2008 minus 2017.

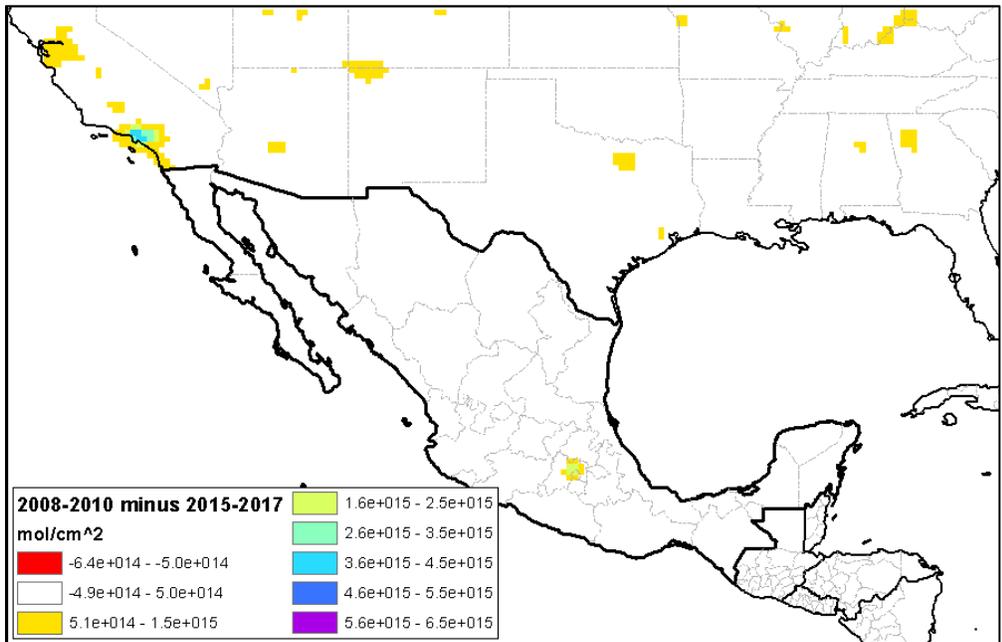


Figure 4-6. Satellite NO<sub>2</sub> Column Difference Plot showing 2008-2010 average minus 2015-2017 average.

#### 4.4 Tropospheric NO<sub>2</sub> Columns Trends

Using ArcGIS, we extracted and averaged tropospheric NO<sub>2</sub> columns of gridcells covering Mexico for each year as shown in Figure 4-7. The average NO<sub>2</sub> column is  $<1 \times 10^{15}$  molec.cm<sup>-2</sup>, and does not show any trend ( $p \gg 0.05$ ) over the period. Figure 4-8 compares the EPA NO<sub>x</sub> inventory data and satellite NO<sub>2</sub> columns for the years when Mexico inventory data are available. The EPA inventory shows slightly downward trends but satellite estimates do not. One of the probable reason for this difference is that the satellite includes large regions with low anthropogenic emissions and trends in anthropogenic NO<sub>2</sub> maybe diluted by averaging over the entire country which includes large areas with low anthropogenic emissions.

A similar analysis was performed for each of the 31 Mexican states plus Distrito Federal. This analysis was done to help alleviate the issue of potential dilution for states with high anthropogenic emissions. Figure 4-9 presents tropospheric NO<sub>2</sub> columns trend for each Mexican state for 2008 – 2017. Distrito Federal has the highest tropospheric NO<sub>2</sub> columns, followed by the neighbouring state of Mexico. Figure 4-10 shows a map of the states of Mexico for reference. Note that the average NO<sub>2</sub> columns for many of the states are  $<1 \times 10^{15}$  molec.cm<sup>-2</sup>. We did not analyse trends for these states because the values are too small (i.e. within uncertainty limits of satellite data) to draw any meaningful conclusions. We noted that many of the states with low tropospheric NO<sub>2</sub> columns may indicate a slight increasing trend that are statistically significant but we can't say whether they represent an actual increase in tropospheric NO<sub>2</sub> columns or are spurious increases due to satellite measurements limitations. We also noted that the states with low values likely have relatively low anthropogenic emissions and increases can be due to biogenic and/or other natural emissions or due to upper tropospheric NO<sub>2</sub> concentration increases. Given these uncertainties we restrict our analysis to the states with higher NO<sub>2</sub> columns: Distrito Federal and Mexico State.

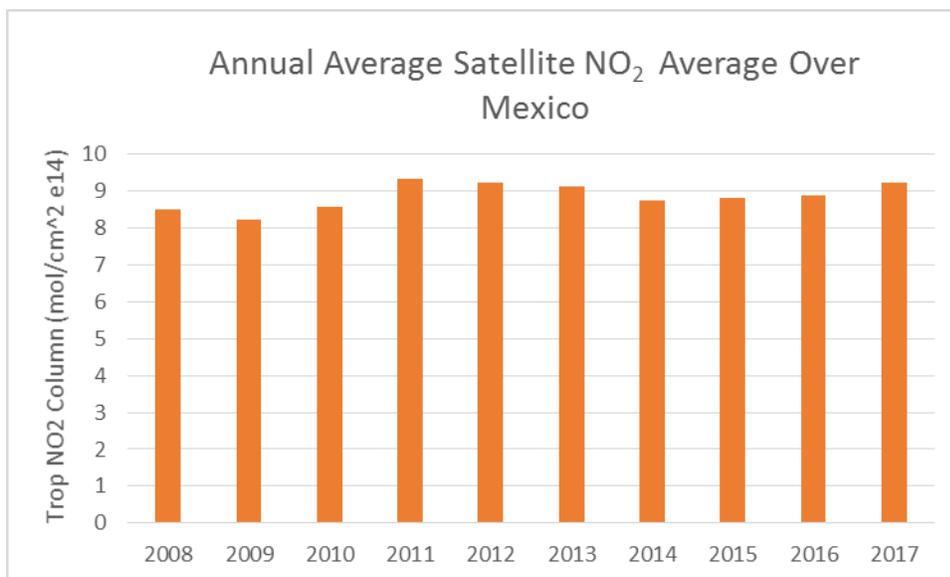
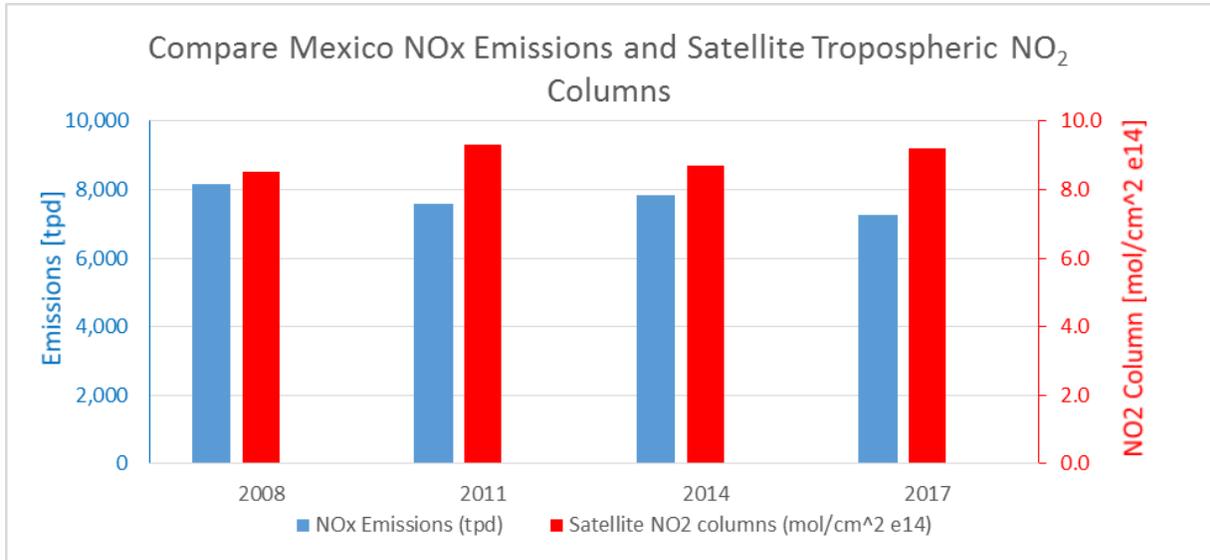
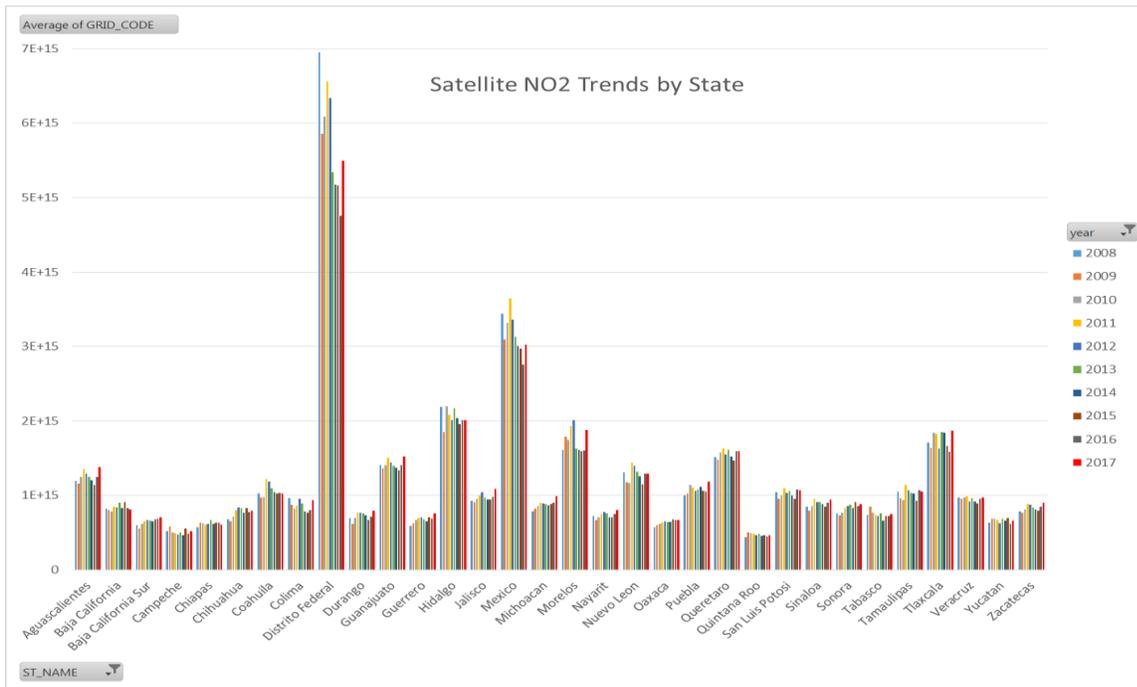


Figure 4-7. Annual Average Satellite NO<sub>2</sub> Columns over Mexico.



**Figure 4-8. Compare NOx emissions in the EPA inventory and Satellite Tropospheric NO<sub>2</sub> columns.**



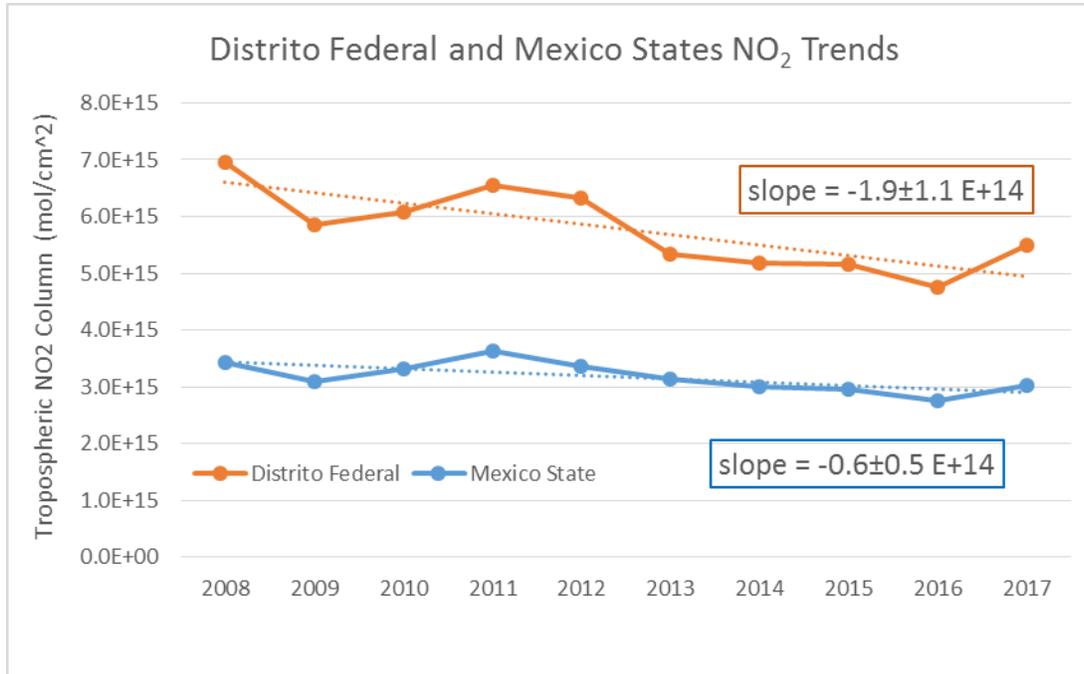
**Figure 4-9. Satellite Tropospheric NO<sub>2</sub> Columns Trends by State in Mexico.**



**Figure 4-10. Map of the States of Mexico.**

#### 4.4.1 Trend Analysis for Mexico State and Distrito Federal

Linear regression analysis reports decreasing trends for Mexico State and Distrito Federal that are statistically significant at the 95 % confidence level with  $p = 0.006$  and  $p = 0.026$ , respectively. The 2008 – 2017 trends are shown in Figure 4-11. The Distrito Federal reduction is  $0.19 \times 10^{15}$  molec.cm<sup>-2</sup> per year, which equates to a period-wide reduction of  $1.7 \times 10^{15}$  molec.cm<sup>-2</sup> (approximately 24%). For Mexico State, the reduction is  $0.06 \times 10^{15}$  molec.cm<sup>-2</sup> per year, or period-wide reduction of  $0.54 \times 10^{15}$  molec.cm<sup>-2</sup> (16%).

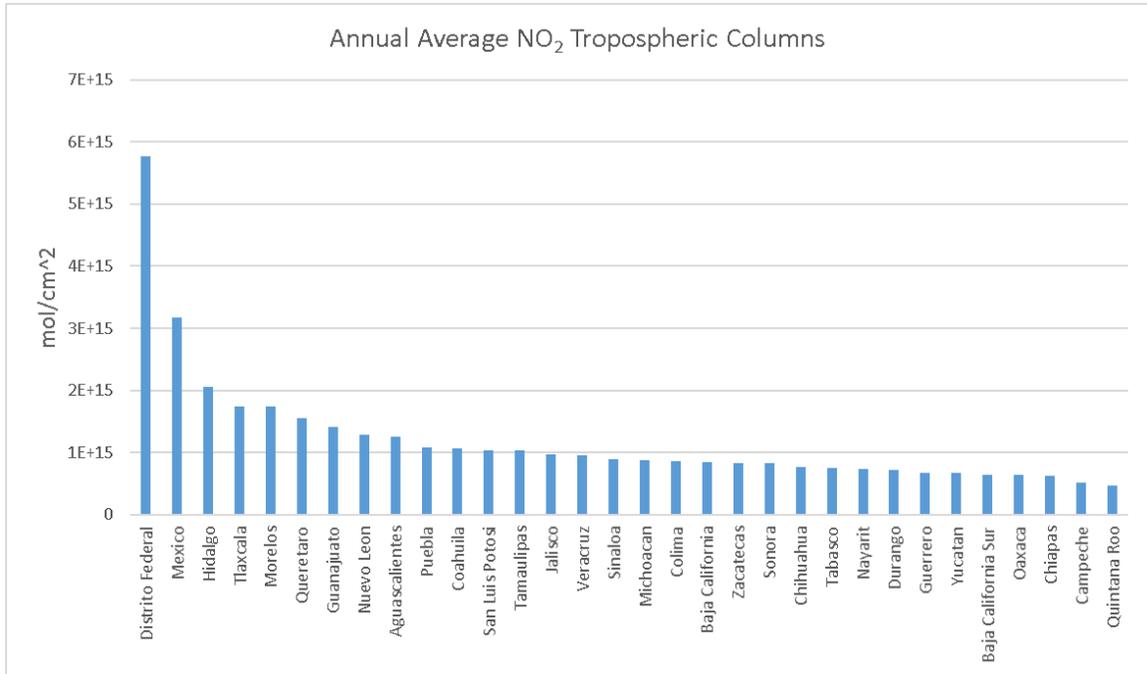


**Figure 4-11. Tropospheric NO<sub>2</sub> Columns Trends for Distrito Federal and Mexico State.**

#### 4.5 State-level Comparison of Tropospheric NO<sub>2</sub> Columns and EPA Inventory

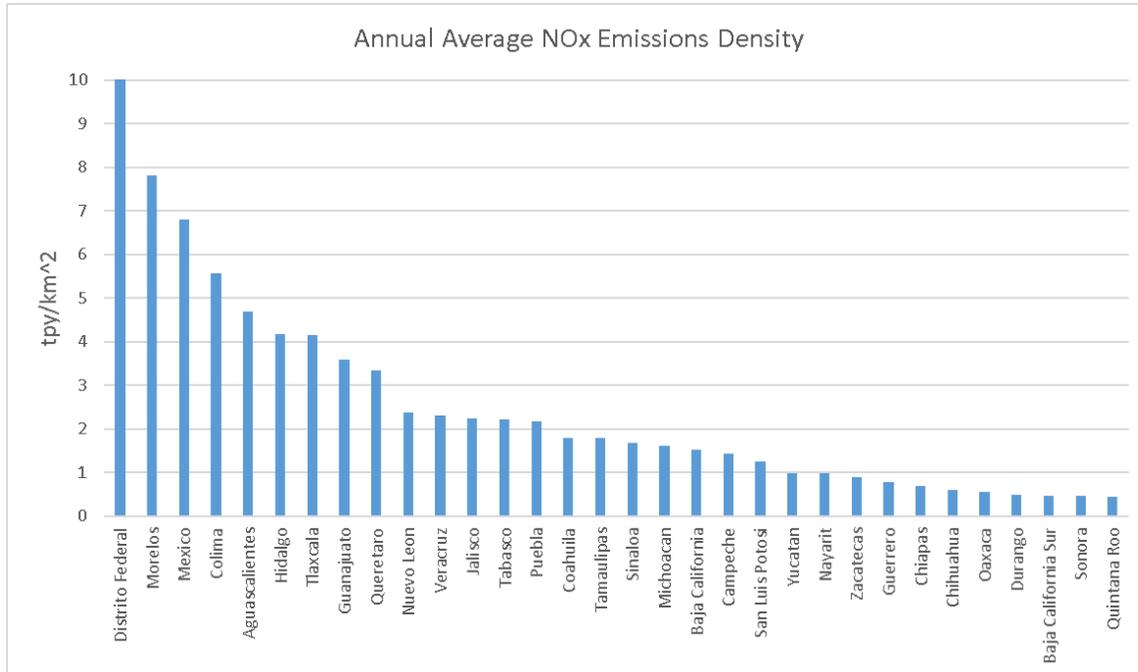
In this section, we compare the state-level emissions in the EPA inventory and satellite NO<sub>2</sub> columns averages for each state. The purpose is to see if there are any notable discrepancies, and if so, investigate those discrepancies. This is to identify any potential issues in the EPA Mexico inventory at state level.

First, we ranked the states in terms of 2008 – 2017 average tropospheric NO<sub>2</sub> columns from low to high as shown in Figure 4-12. As seen previously, Distrito Federal has the largest NO<sub>2</sub> columns followed by Mexico State and then Hidalgo State. Tlaxcala and Morelos are the states with the 4<sup>th</sup> and 5<sup>th</sup> highest NO<sub>2</sub> columns. These states all surround the Distrito Federal and can be seen in Figure 4-10. The state with the lowest annual average NO<sub>2</sub> tropospheric column is Quintana Roo, the eastern most State of Mexico, with an average column value of  $0.47 \times 10^{15}$  molec.cm<sup>-2</sup>. Note that the variation between minimum and maximum state-level average columns is a factor of 12. The states with the lowest NO<sub>2</sub> columns (Quintana Roo, Campeche, Chiapas, Oaxaca, Baja California Sur and Yucatan) are all coastal states which generally have low NO<sub>x</sub> emissions in the surrounding region. The minimum NO<sub>2</sub> column value may reflect NO<sub>2</sub> concentrations in the upper tropospheric layer and be less related to surface emissions. Many inland states have average tropospheric NO<sub>2</sub> columns value of  $\sim 1 \times 10^{15}$  molec.cm<sup>-2</sup>.



**Figure 4-12. Annual Average Tropospheric NO<sub>2</sub> Columns by State.**

Next, we ranked the states in terms of 2011 NO<sub>x</sub> emissions density and plotted in Figure 4-13 in the unit of tons per year per km<sup>2</sup>. The NO<sub>x</sub> emissions are based on the 2011 EPA inventory. Distrito Federal has the highest emissions density (920 tpy/km<sup>2</sup> which exceeds the maximum value of the y-axis on the plot), which is consistent with observed tropospheric NO<sub>2</sub> columns. The highest density for the Distrito Federal is due to high emissions for a relatively small area. Quintana Roo has the lowest emissions density. These maximum and minimum emissions density states are also the maximum and minimum NO<sub>2</sub> column states.



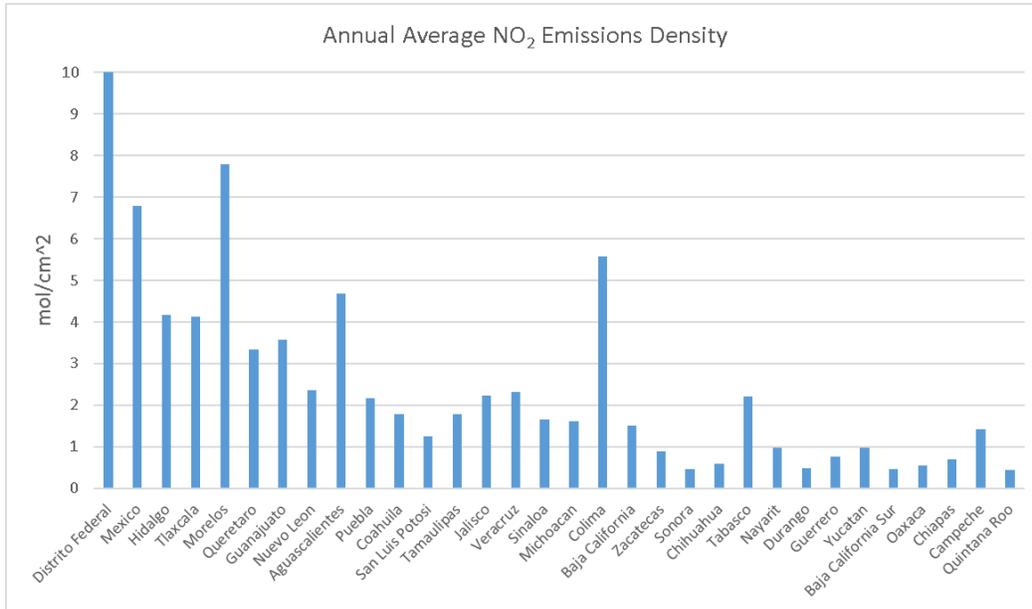
**Figure 4-13. Annual Average NOx emissions Density by State.**

To more readily identify potential discrepancies between NO<sub>x</sub> emission density and NO<sub>2</sub> column data, we reordered the emission densities to match the ranked order of the NO<sub>2</sub> columns. The reordered emissions densities are shown in Figure 4-14. The emissions density for Morelos State is higher than expected based on tropospheric NO<sub>2</sub> columns rankings. We examined the emissions inventory for the state which did not reveal any obvious inconsistencies. The Morelos State discrepancy is not particularly high and close inspection of the NO<sub>2</sub> column data gridcells reveals that the sampling method (i.e. gridcell-center-based) may impact the Morelos State NO<sub>2</sub> columns average to be biased low, as shown in Figure 4-15. Therefore, we do not believe the discrepancy warrants further investigation into the emissions inventory.

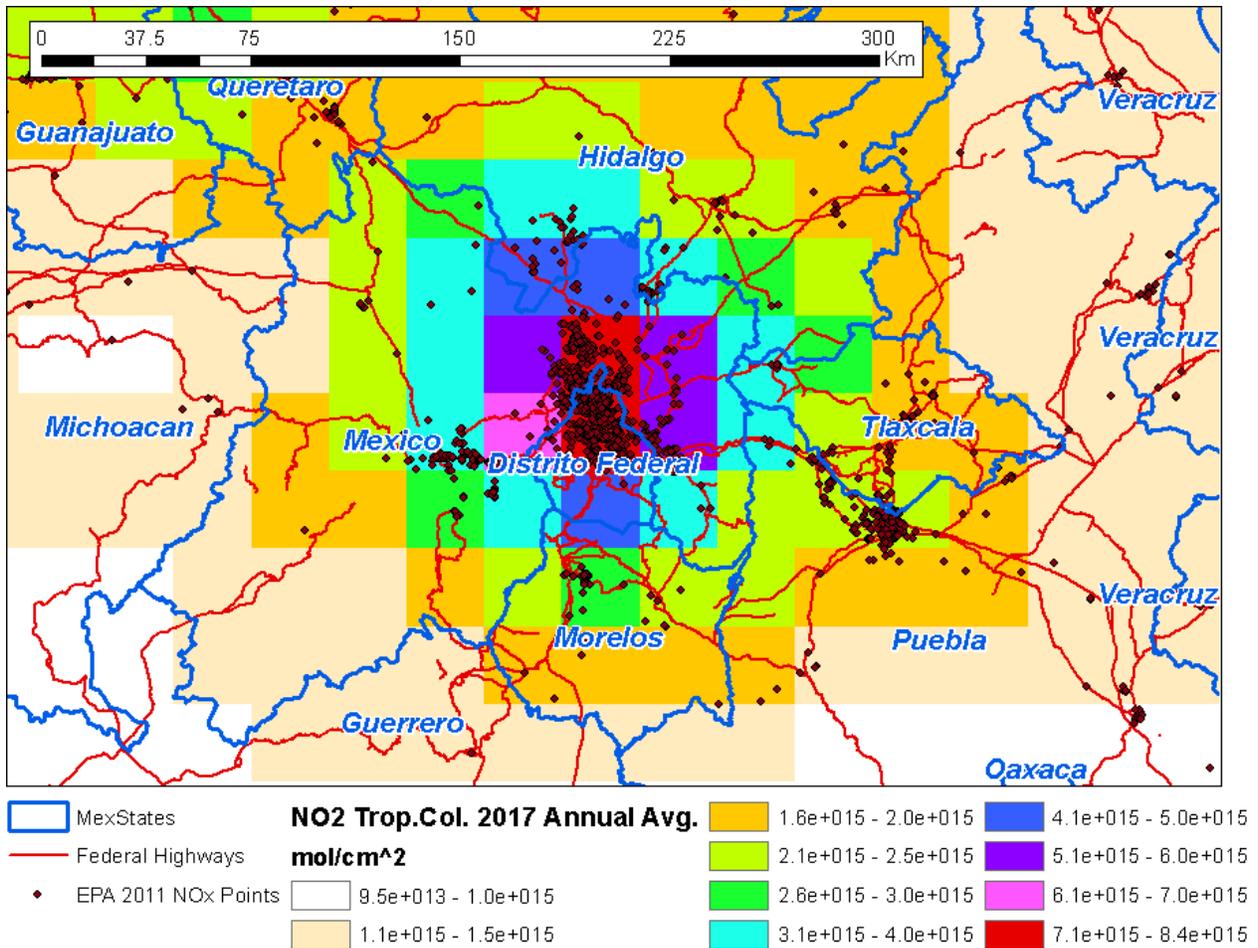
Emissions density for Colima State is also higher than might be expected based on NO<sub>2</sub> column rankings. We compared Colima State emissions with emissions from other states and found that Tlaxcala and Morelos (both close to Distrito Federal) have comparable emissions and are of similar size—and therefore have comparable emissions densities. The NO<sub>2</sub> columns for Tlaxcala and Morelos are much higher than for Colima and hence are located further left on the ranked plot and that is why Colima appears as an outlier in Figure 4-14. However, due to the close proximity of Tlaxcala and Morelos to the Distrito Federal- which has by far the highest emissions density of all states - transport of NO<sub>x</sub> emissions from Distrito Federal to Tlaxcala and Morelos likely influences the NO<sub>2</sub> columns for the neighbouring states. In contrast, Colima is surrounded by states with much lower emissions densities and the tropospheric columns are not likely to be as influenced by NO<sub>x</sub> emissions from surrounding states. Therefore, the difference in location of Colima (compared to Tlaxcala and Morelos) likely explains the

discrepancy and we do not believe further investigation into the emissions inventory for Colima is warranted based on this analysis.

Tabasco and Campeche both have higher emissions densities than might be expected from the ranked NO<sub>2</sub> column plot. The NO<sub>2</sub> columns for these states are less than  $1 \times 10^{15}$  molec.cm<sup>-2</sup>. We do not have very high confidence in the NO<sub>2</sub> column values for these states. Given that the discrepancies are moderate and could be attributable to limitations in the satellite retrievals, we do not believe further investigation into this discrepancy is warranted.



**Figure 4-14. Annual Average NO<sub>x</sub> emissions Density by State sorted in decreasing order of NO<sub>2</sub> columns from left to right.**



**Figure 4-15. Spatial Distribution of Tropospheric NO<sub>2</sub> Columns Zoomed around Mexico City Area.**

#### 4.6 Findings from the satellite NO<sub>2</sub> columns

- Generally, there is good spatial agreement between the EPA NO<sub>x</sub> emissions inventory and satellite NO<sub>2</sub> columns.
- The large NO<sub>x</sub> point sources are observed in the NO<sub>2</sub> columns.
- The satellite data show NO<sub>2</sub> reductions have occurred in regions with high NO<sub>2</sub> columns in 2008 – including the Mexico City area, Carbon Power plant, Monterrey and the Cantarell oil field in the Bay of Campeche. For the Distrito Federal and Mexico state, these decreasing trends are statistically significant.

## 5.0 GLOBAL GAS FLARING OBSERVED FROM SPACE

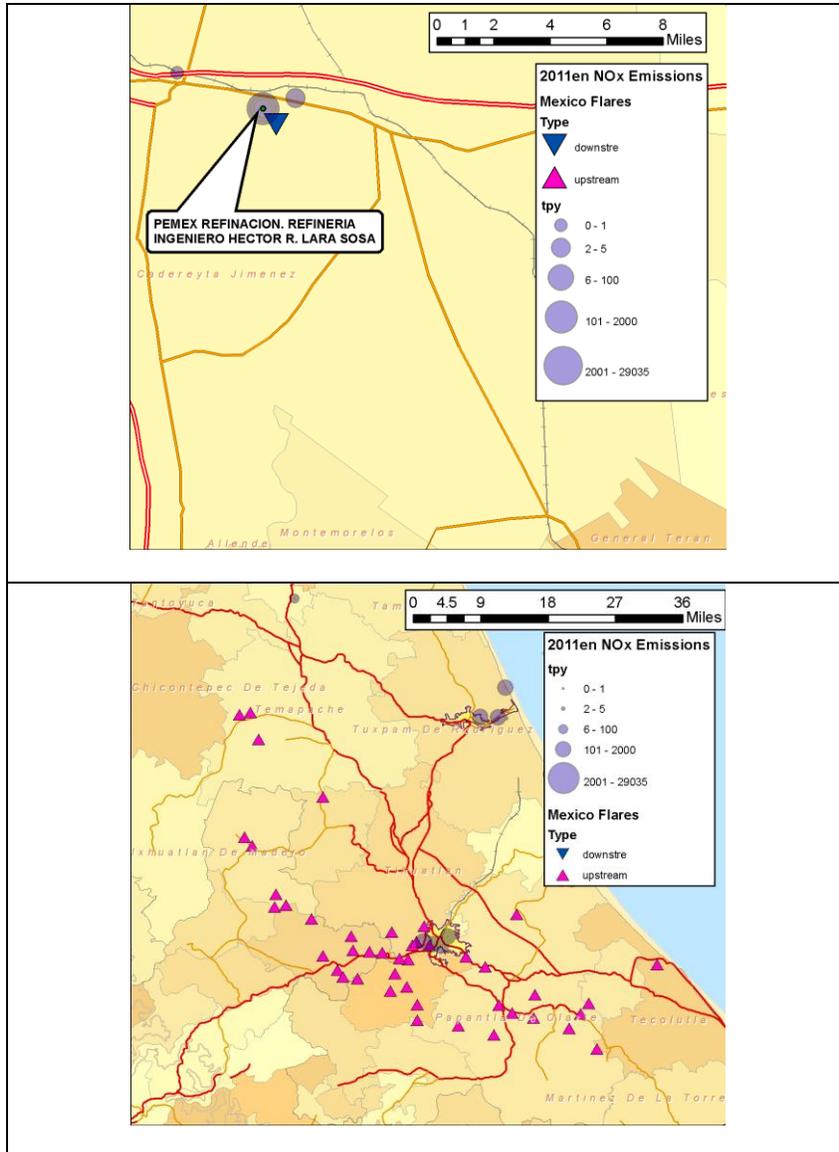
Flares are widely used to abate venting of natural gas and other combustible gases as a safety measure and to reduce environmental impacts. Elvidge et al. (2015) identify flares from space using their infrared emission signatures and then estimate the volume of gas flared from the radiant energy observed by satellite. The data includes satellite-derived gas flaring estimates using night time data collected by the Visible Infrared Imaging Radiometer Suite (VIIRS)<sup>18</sup>. The global flare data provides VIIRS-derived gas flaring estimates and location by country and source categories. The global flare data are divided into three categories: upstream in oil and gas production areas, downstream at refineries and transport facilities, and industrial (e.g., coal mines, landfills, water treatment plants, etc.). In Mexico, there are only upstream and downstream flares with predominance of upstream flaring.

### 5.1 Comparing EPA Inventory Data with Global Flare Data

We first extracted flares for Mexico using the Country attribute in the VIIRS data on flared gas volumes. To compare the global flaring data and EPA inventory, we overlaid satellite-detected flares and point sources in the EPA inventory using ArcGIS to determine whether these detected flares are accounted for in the EPA inventory. The NOAA's flaring data include attributes such as location coordinates (lat/lon), source categories (upstream or downstream), and Billion Cubic Meters (BCM) of gas flared for each flare. Using the ArcGIS software, we scanned Mexican flares to see if they were accounted for in the EPA inventory. In Figure 5-1, the top panel shows downstream flares (blue down arrows) that have a matching EPA point source and the bottom panel shows number of upstream flares (pink up arrows) with no matching EPA point sources. As illustrated in Figure 5-1, the downstream flares were accounted for in the EPA inventory but most upstream flares were not accounted for in the EPA inventory.

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<sup>18</sup> [https://www.ngdc.noaa.gov/eog/viirs/download\\_global\\_flare.html](https://www.ngdc.noaa.gov/eog/viirs/download_global_flare.html)



**Figure 5-1. Example snapshot views of the Satellite Observed Flaring Data Overlaid with the EPA Inventory Data.**

Figure 5-2 shows countrywide satellite observed flaring data for Mexico. The downstream sources (blue down arrows) are co-located with EPA inventory point sources, which are indicated as greyish circles, but the upstream sources (pink up arrows) are not co-located with EPA inventory point sources. The offshore upstream flares in the Bay of Campeche agree with point sources in the EPA inventory in terms of location. Many of the upstream flaring sources are missing from the EPA inventory. In the next section, we provide details on how we developed emission estimates for the missing upstream O&G flaring sources.

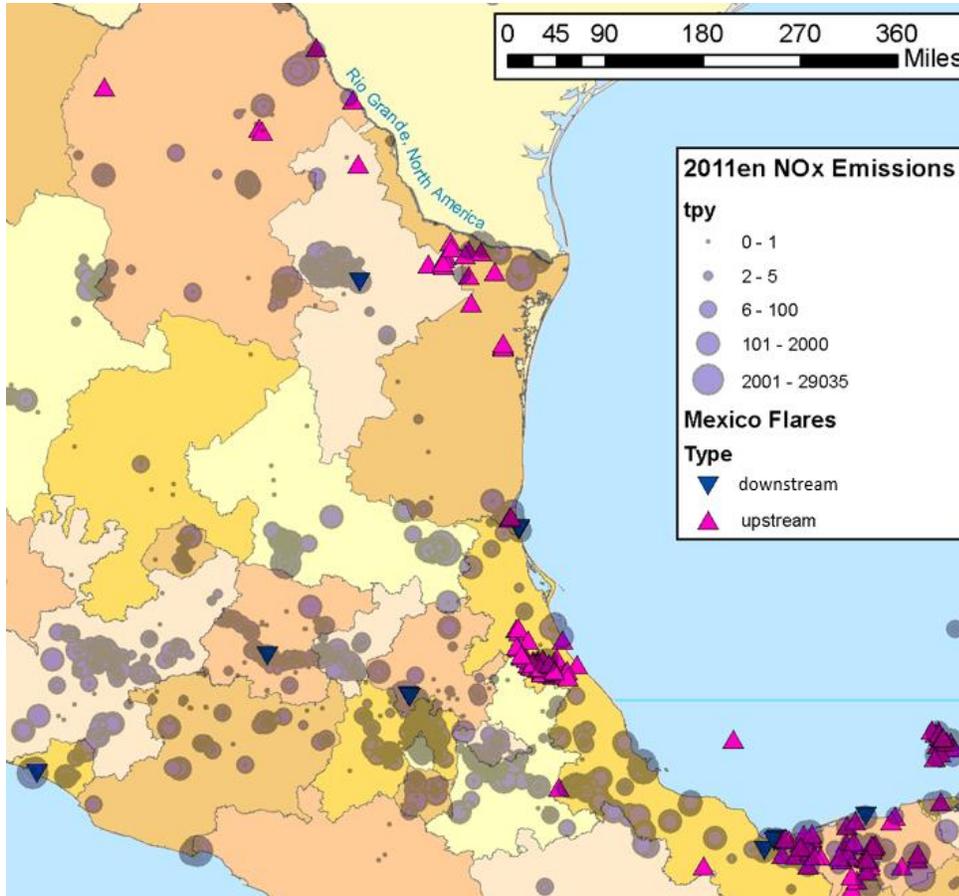


Figure 5-2. Mexico Flaring Data Overlaid with the EPA Inventory data.

## 5.2 Develop Flaring Emission Estimates

We developed screening level emission estimates for the upstream O&G flares using flared gas volumes, energy content of the flared gas, and emission factors from AP-42 (US EPA, 2018) and EPA NEI O&G Tool<sup>19</sup>. Emission factors for NO<sub>x</sub>, VOC, and CO were obtained from AP-42; and SO<sub>2</sub> emission factor was based on the EPA NEI O&G Tool Permian Basin H<sub>2</sub>S concentration for casinghead gas that is flared at oil wells. Table 5-1 provides emission factors and heating value used in emissions calculation for the upstream O&G flares.

<sup>19</sup> EPA Oil and Gas Tool, 2014 NEI Version 2.1 – Production Activities Module, 2017

**Table 5-1. Emission Factors for flare operation.**

VOC	332 lb/MMSCF gas burned
NOx	0.068 lb/MMBTU
CO	0.31 lb/MMBTU
Heating Value	1400 BTU/SCF
SO <sub>2</sub>	1049 lb/MMSCF

The screening level flaring emission estimates show substantial flaring emissions in Mexico as presented in Table 5-2. The NOx flaring emissions are comparable to the estimates Ramboll made for the Williston Basin which includes substantial casinghead gas and tank flaring from the Bakken formation.

**Table 5-2. Emission Estimates for upstream O&G flares in Mexico.**

Pollutant	Emissions (tpy)
VOC	23,005
NOx	6,597
CO	30,073
SO <sub>2</sub>	72,666

### 5.3 Develop EPS3 Inputs

Ramboll developed a full EPS3 run stream that includes inputs, cross-reference files, userin files, message files, and EPS3 outputs ready for input to CAMx for the upstream O&G flares. We assigned SCC of “31000160: Crude Oil Production /Flares” and stack parameters shown in Table 5-3 to the upstream O&G flares based on SCC-level default stack parameters available in SMOKE.

**Table 5-3. Stack Parameters for the upstream O&G flares.**

Height (m)	10.67
Diam (m)	0.18
Temp (K)	838.8
Exit Vel (m/s)	3.85

## 6.0 CONCLUSIONS AND RECOMMENDATIONS

Below, we provide a summary of findings of this study and recommendations to improve the existing emissions inventory.

### 6.1 Summary of Findings and Recommendations

1. Even though 12US2 emissions cover the northern part of Mexico only, EPA inventory data cover all 32 states of Mexico
2. EPA inventory data trend for Mexico looks reasonable when comparing with growth indicators like population and in the light of future vehicle/fuel standards
3. TCEQ can linearly interpolate available inventory data sets from EPA to develop emissions for their modeling years
4. There are some large VOC differences between MOBILE6 and MOVES estimates for Mexico on-road sources. Avoid mix and match of EPA on-road inventory based on different model (i.e MOBILE6-Mexico vs. MOVES-Mexico) for interpolation.
5. Mexico inventory data from EPA are generally in good agreement with a new global inventory data developed with the Community Emissions Data System (CEDS)
6. TCEQ can use either RCP4.5 or RCP6.0 for 2064 projections. If RCP4.5 is used, consider over-riding the increase in point source VOC that looks inconsistent with other species.
7. Add the Popocatepetl volcano near Mexico City to the inventory because it is not captured in the EPA inventory. Use annual SO<sub>2</sub> emissions for this source from the satellite data for large SO<sub>2</sub> sources.
8. Add the La Caridad copper smelter to the inventory. Scale Potosi copper smelter emissions to match satellite SO<sub>2</sub> estimate for 2011, use the same scaling factor for other pollutants.
9. Remove Potosi copper smelter facility emissions from inventory for 2011 and onwards.
10. Generally, there is good spatial agreement between the EPA NO<sub>x</sub> emissions inventory and satellite NO<sub>2</sub> columns.
11. The large NO<sub>x</sub> point sources are observed in the NO<sub>2</sub> columns.
12. The satellite data show NO<sub>2</sub> reductions have occurred in regions with high NO<sub>2</sub> columns in 2008 – including the Mexico City area, Carbon Power plant, Monterrey and the Cantarell oil field in the Bay of Campeche. For the Distrito Federal and Mexico state, these decreasing trends are statistically significant.
13. Add upstream O&G flaring emissions to the inventory. Flaring accounts for only some of the emission at oil and gas sources. We recommend developing a comprehensive inventory of Mexico's upstream oil and gas sector.
14. We developed and provided a full EPS3 run stream for sources not captured in the EPA inventory, including Popocatepetl volcano, Sonora copper smelter and upstream O&G flares. The EPS3 run streams include inputs, cross-reference files, userin files, message files, and EPS3 outputs ready for input to CAMx.

## 6.2 Recommendations for Future Work

1. TCEQ should keep track of TROPOMI data becoming readily usable. Figure 6-1 shows a sample plot of TROPOMI-detected Formaldehyde concentrations across the globe.
  - TROPOMI is more useful than OMI because TROPOMI provides 6x better spatial resolution: 7 km x 7 km (compared to OMI's 13x24). Also, OMI suffers from an internal obstruction ("row anomaly") issue that reduces its spatial coverage by approximately 50% for any given swath. Other TROPOMI improvements like better identification/screening of cloudy pixels and better signal/noise ratio will also likely result in better data quality.
  - In looking at this image, keep in mind that Nov to June includes winter in the Northern Hemisphere which will reduce the biogenic contribution to secondary formaldehyde in the Northern Hemisphere
  - Biomass and other open burning likely contributes to high formaldehyde over central Africa and South Asia
2. Research data to develop temporal profile for volcano emissions

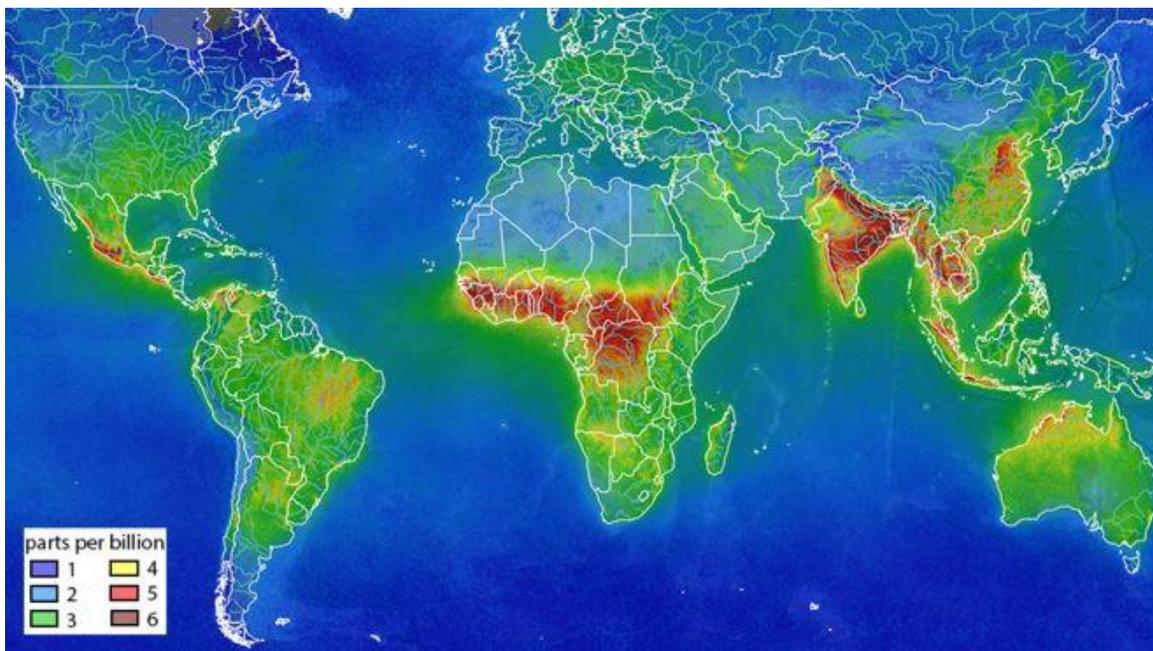


Figure 6-1. Formaldehyde concentrations across the globe as measured by TROPOMI, Nov-2017 to June-2018.

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