GeoHealth

Supporting Information for

# A Refined Satellite-based Emissions Estimate from Onshore Oil and Gas Flaring and Venting Activities in the United States and their Impacts on Air Quality and Health

Huy Tran[1], Erin Polka[2], Jonathan J. Buonocore[2], Ananya Roy[3], Beth Trask[3], Hillary Hull[3], Saravanan Arunachalam[1*]

*[1] Institute for the Environment, University of North Carolina at Chapel Hill*
*[2] Department of Environmental Health, Boston University School of Public Health*
*[3] Environmental Defense Fund*

## Contents of this file



## List of Figures



## List of Tables

## S.1. Flaring emission estimates from VIIRS flared gas volume (FGV)

The following governing equation is used to estimate emissions from flaring:

$$E\left(\frac{tons}{yr}\right) = V\left(\frac{BCM}{yr}\right) \times \frac{10^9 m^3}{BCM} \times \frac{26700 \pm 114000\ BTU}{m^3} \times EF\left(\frac{lb}{BTU}\right) \times \frac{tons}{2000\ lbs} \quad (1)$$

where $\boldsymbol{V}$ is annual natural gas flared volume for individual flare location from VIIRS in 2019; $\boldsymbol{E}$ is annual emission and $\boldsymbol{EF}$ is emission factor which will be discussed for each pollutant explicitly in the below section.

Various studies reported wide range of EF. To characterize the uncertainties associated with EF and the above heating value (26,700±114,000 BTU), we performed Monte-Carlo simulations with the following approach:

- In each Monte Carlo integration, a heating value and an EF were randomly selected,
- Emission for each VIIRS-detected flare location was estimated using equation 1,
- Repeat the above steps for 5,000 integrations,
- Calculated mean and standard deviation from 5,000 estimates.

The Eq.(1) is also applied to estimate emissions for flared gas volume reported by Rystad Energy (2022) for individual counties in Texas, New Mexico, North Dakota, Wyoming and Colorado.

### NOx emissions

Table 13.5-1 of AP42 (EPA, 2022) lists EF of $NO_X$ as 0.068 lb/MMBtu. Francoeur et al. (2021) apply 0.065 ± 0.038 lb NOx/MMBtu which we applied in this study. Since there is not much differences in these values, we applied EF for $NO_X$ from Francoeur et al. (2021) in this study to Eq.1 to estimate $NO_X$ emissions for each VIIRS-detected flare.

### CO emissions

EF of CO at 0.31 lb/MMBtu from Table 13.5-1 of AP42 (EPA, 2022) is commonly applied for estimating CO emissions. We applied this EF to Eq. (1) to estimate CO emission from VIIRS-detected flare.

### VOC emissions

As discussed in the main text, VOC emissions from flare are taken as VOC emissions from venting of the associated flare-SCC nonpoint sources. Default VOC speciation profiles in the NEI 2017 were applied for VOC emission from flaring and venting (F&V).

### $SO_2$ emissions

$SO_2$ emissions are only estimated for certain flare-SCCs in the NEI 2017. In Texas, $SO_2$ is only estimated for SCCs 2310011450 and 2310021450 (oil and gas well casinghead) based on county-level weight percentage of hydrogen sulfide ($H_2S$) in the flared gas and a 98% conversion of $H_2S$ to $SO_2$.

In this study, EF for $SO_2$ emissions from VIIRS-detected flare is estimated as:

$$EF_{SO_2}\left(\frac{lb}{BTU}\right) = MW * W_{H_2S} * 0.98$$

where MW is molecular weight of flared gas and $W_{H2S}$ is weight percentage of $H_2S$ in flared gas. The $EF_{SO2}$ assumes 98% conversion of $H_2S$ to $SO_2$. In each Monte Carlo simulations, a pair of MW and $W_{H2S}$ values from one of the 8 O&G production fields in Texas (Table S5) is randomly selected to determine $EF_{SO2}$ which is then applied to Eq.(1) to estimate $SO_2$ emissions.

From the above treatment F&V SO2 emissions are accounted for about 82% of total O&G $SO_2$ emissions in the CONUS, and the total SO2 emissions from O&G jumped from ~49,000 tpy in NEI 2017 to ~115,500 tpy in wFlare2 scenario. This may look like a significant jump. However, the pre-release version of the NEI 2020[12] also shows more than three times increase in O&G $SO_2$ emissions in 2020 (257,572 tpy) from NEI 2017 (73,250 tpy) as a result of updating $SO_2$ emission factors based on recent field surveys in the O&G production fields. This also implies that O&G $SO_2$ emissions are underestimated in the NEI 2017.

### $PM_{10}$ and $PM_{2.5}$ emissions

Emissions of $PM_{10}$ and $PM_{2.5}$ is not estimated for flare-SCCs in the NEI 2017. From our personal communication with emission inventory experts at EPA and TCEQ, PM emissions from flare are assumed to be low. Table 13.5-1 of AP42 (EPA, 2022) only lists emissions for soot from flare but is in concentrations unit (µg/L) and thus are not applicable for estimating PM emissions.

Our search for prior studies on EF for PM emissions from flare yielded limited results. For studies performed over the Bakken basin, EF for black carbon emissions from flaring is reported by Weyant et al. (2016) at 0.13±0.36 g/m$^3$ and by Schwarz et al. (2015) at 0.57±0.14 g/m$^3$. We applied these two EFs to Eq.(1) and Monte-Carlo simulations to estimate black carbon emission from flaring. For this study, 100% of $PM_{2.5}$ and $PM_{10}$ emissions from flaring are attributed to black carbon which is mapped to CMAQ model as elemental carbon (EC) species.

### Stack parameters and temporal profiles

The combustion in flaring occurs at the flare stack's tips which differs from conventional stacks where combustion occurs in a combustion chamber and the exhausts are released through the stack. Therefore, the effective stack parameters of flaring are functions of physical stack height and diameter, heating value of flared gas and ambient wind velocity.

Stack parameters for VIIRS-detected flare are estimated using refined methods developed by San Joaquin Velley Air Pollution Control District (SJVAPCD, 2022) based on algorithms developed by American Petroleum Institute Standard 521 (API, 2014) and with several empirical flare parameters taken from Texas Commission on Environmental Quality (TCEQ, 2004). Figure S1 show the histogram of flare stack parameters estimated from this study.

In summary: the effective flare stack height $H_{eff}$, effective stack diameter $D_{eff}$, and effective stack exist velocity $V_{eff}$ are estimated as

$$H_{eff}(m) = 3.28084\frac{m}{ft} \times (h + \Delta y)$$
$$D_{eff}(m) = 0.000988 \times (Q \times 0.45 \times 239)^{0.5}$$

---

[1] https://gaftp.epa.gov/Air/emismod/2020/2020emissions_prerelease

[2] https://gaftp.epa.gov/Air/nei/2020/doc/supporting_data/nonpoint/oilgas/OIL_GAS_TOOL_v1.3

$$V_{eff}(m) = U_j \times 3.28084$$

The physical stack height $h$ = 20 ft and physical stack diameter $d$ = 0.254 m are assigned to all VIIRS-detected flares. It is assumed that 45% of net heat released from flaring, $Q$ *(kW/hr)*, is available for plume rise. $Q$ is determined as 25,076 kW/hr for flared gas comprised of 79% methane, 10% ethane, 5% propane and 1% butane. Stack exit temperature is assigned to VIIRS detected temperature of each VIIRS-detected flare.

The flame vertical length Δy is determined as:

$$\Delta y\ (ft) = L \times \left[-0.0392 + \frac{0.1267}{U^2} + \frac{0.0178}{U} - \frac{0.003}{U^{1.5}}\right]$$

$$L\ (m) = e^{(0.4562 \times log\ (Q)) - 5.3603}$$

U is unitless quantity representing flame distortion due to ambient wind velocity:

$$U = \frac{U_x}{U_j}$$

$$U_j(\frac{m}{s}) = \frac{4 \times F}{\pi \times d^2} \times 0.707$$

The actual volumetric flow rate of exhausted gas from flaring $F$ is determined as 0.56 $m^3$/s for average flared gas parameters: flow rate at 64,000 scf/hr; natural gas specific density 0.056 lb/scf; molecular weight 19.5 g/mole, and flowing gas temperature at 293.15 K. $U_X$ is ambient wind speed and is determined for each VIIRS-detected flare using reanalysis data from National Centers for Environmental Prediction (NCEP) for 2019[3].

To allocate the annual emissions estimated from Eq.(1) to monthly emissions, the monthly vented and flared gas data at state level were retrieved from U.S. Energy Information Administration (EIA, 2022). The monthly emissions are then evenly distributed to hourly emissions. In this approach, each state that has VIIRS-detected flares has its own temporal allocation, and all VIIRS-detected flares in a same state have identical temporal allocation.

[3] https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html

## S.2. Additional Health Impact Analyses

For childhood asthma outcomes, we used concentration response functions (CRFs) from two publications. One set was pulled from Orellano et al. (2017) which derived relationships between $PM_{2.5}$ and $NO_2$ and asthma outcomes; the other is from Alhanti et al. (2016) which derived relationships between asthma outcomes and the pollutants $PM_{2.5}$, $NO_2$, and ozone. We compare the results using the different CRFs to evaluate the sensitivity of results to different choices of CRFs.

We conducted an environmental justice analysis to estimate the distribution of health impacts in overburdened and underserved areas. We acquired a shapefile of Justice40 data, from the Climate and Economic Justice Screen Tool (CJEST)[4] , with environmental and economic justice demographic data, 2010 census tract IDs, and county names. We filtered tracts that were identified as 'low income' (i.e., census tracts that are 65$^{th}$ percentile or above for household income that is less than or equal to twice the federal poverty level, excluding students), and tract data for percent 'American Indian / Alaskan Native' and percent 'Hispanic or Latino'. (While we recognize 'American Indian / Alaskan Native' is used for official government documentation, these populations will be referred to as 'Native' for the remainder of this publication). Tracts with percent race/ethnicity data were categorized dichotomously, based on whether tract populations were above or below the 65$^{th}$ percentile. This cutoff was 2% for Native populations and 14% for Hispanic/Latino populations. The 65$^{th}$ percentile for Native populations was calculated by dropping all census tracts with 0% identified Native persons. Justice40 tracts were merged with the *wFlare2* health outcome polygons, grouped by Justice40 categories and aggregated by health outcome.

An "impact risk ratio" (IRR) was calculated for each aggregated health outcome by Justice40 category using Eq. (2), which is similar to the method used by Flores et al., (2022) to calculate whether persistently marginalized members of racial and ethnic groups were disproportionately impacted by power outages. This IRR serves as measurement if underserved tracts are disproportionately impacted by wFlare2 emissions.

$$IRR = \frac{\frac{Cases\ of\ health\ outcome\ occurring\ within\ J40\ designated\ tracts}{Population\ residing\ within\ J40\ designated\ tracts}}{\frac{Cases\ of\ health\ outcome\ occurring\ nationwide}{Population\ nationwide}} \quad (2)$$

[4] https://screeningtool.geoplatform.gov/en/downloads

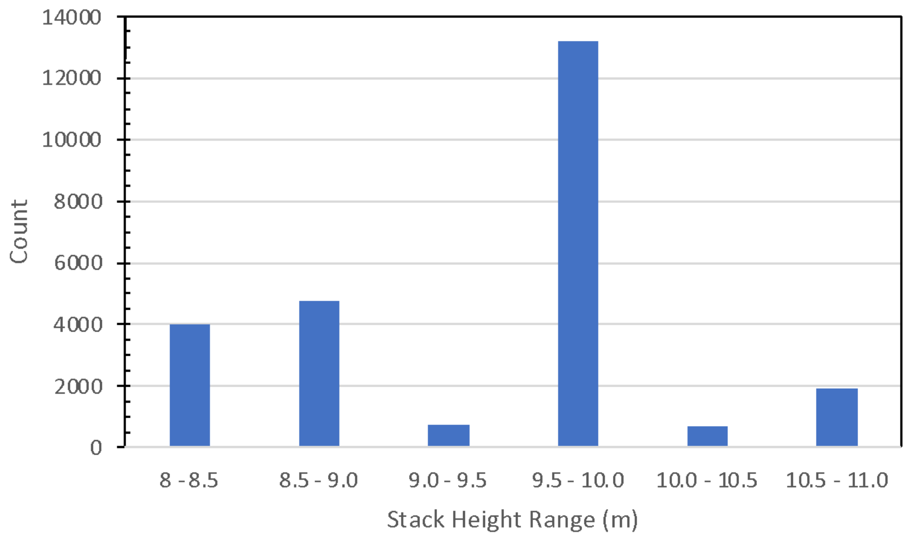
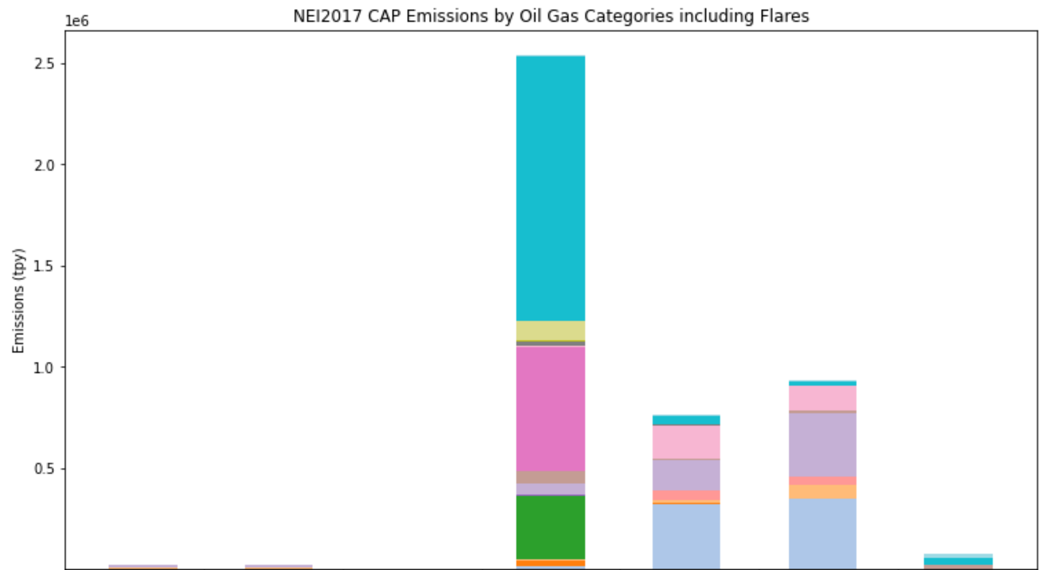
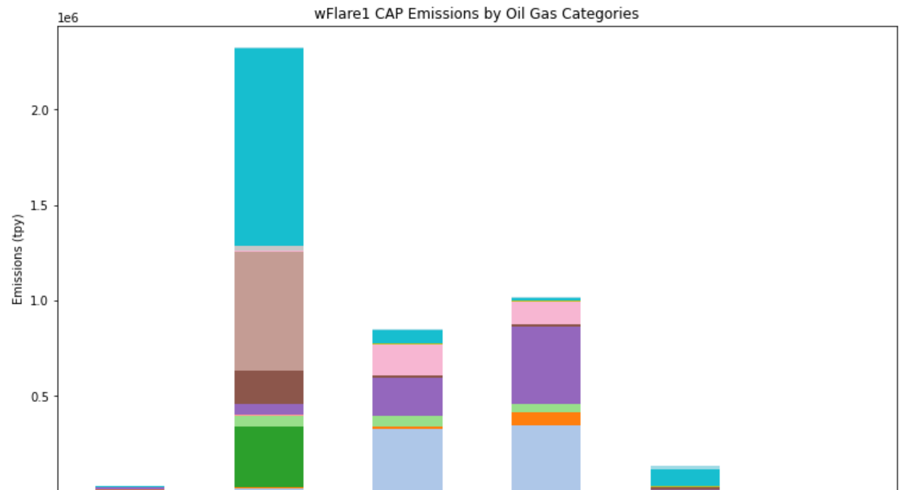



*Figure S1. Distribution of flare effective stack height*

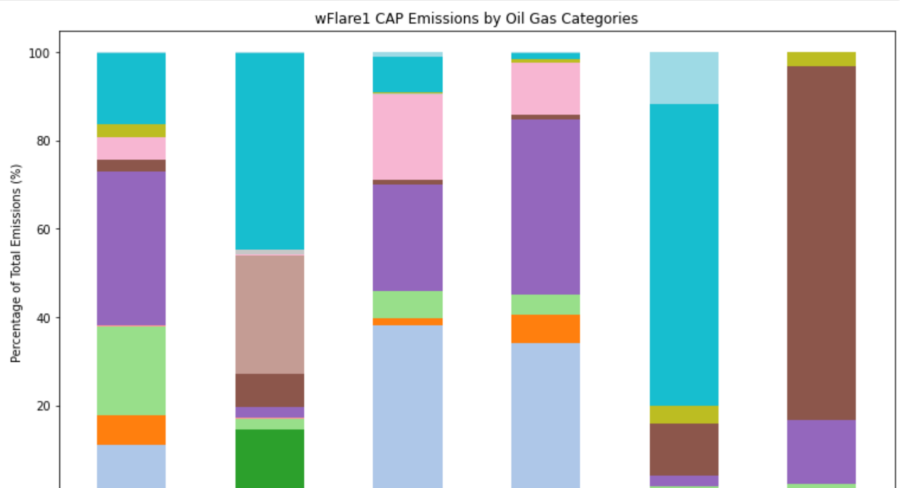



| | PM10-PRI | PM25-PRI | NH3 | VOC | CO | NOX | SO2 |
|---|---|---|---|---|---|---|---|
| ptFlare | 8.05E+01 | 7.82E+01 | 1.84E-01 | 4.59E+03 | 8.44E+03 | 2.71E+03 | 1.53E+04 |
| npFlare | 2.25E+02 | 2.22E+02 | 0.00E+00 | 1.31E+06 | 3.94E+04 | 1.87E+04 | 3.37E+04 |
| Waste_Disposal | 1.25E+01 | 5.25E+00 | 0.00E+00 | 9.89E+04 | 3.71E+01 | 4.08E+01 | 2.39E+01 |
| Turbine_Boiler | 7.30E+02 | 7.27E+02 | 6.09E+01 | 4.88E+02 | 3.20E+03 | 5.56E+03 | 5.17E+03 |
| Storage Tanks | 3.00E+00 | 2.93E+00 | 0.00E+00 | 2.44E+04 | 1.32E+03 | 5.35E+02 | 3.73E+01 |
| Pumpjack Engines | 1.42E+03 | 1.39E+03 | 0.00E+00 | 5.26E+03 | 1.64E+05 | 1.21E+05 | 7.16E+01 |
| Pneumatics | 2.61E-01 | 2.61E-01 | 4.66E-03 | 6.14E+05 | 6.38E+01 | 1.94E+02 | 1.56E-02 |
| Others | 8.28E+02 | 7.03E+02 | 1.76E+03 | 5.94E+04 | 1.01E+04 | 8.88E+03 | 1.54E+04 |
| Other_Engines | 8.61E+03 | 8.51E+03 | 3.23E+02 | 5.32E+04 | 1.47E+05 | 3.18E+05 | 1.41E+03 |
| Loading_Transport | 8.34E+01 | 5.50E+01 | 3.20E-01 | 5.90E+03 | 1.66E+02 | 9.27E+01 | 1.51E+00 |
| Heater_Separators | 5.36E+03 | 5.32E+03 | 3.89E+01 | 4.36E+03 | 5.01E+04 | 4.21E+04 | 1.19E+03 |
| GasPlant_Refinery_Others | 5.77E-01 | 5.77E-01 | 0.00E+00 | 7.34E+02 | 6.83E+00 | 1.25E+00 | 2.94E-01 |
| Fugitives | 2.85E+01 | 1.55E+01 | 5.00E-12 | 3.11E+05 | 2.45E+02 | 1.42E+02 | 3.42E+02 |
| Drilling_Completion | 1.87E+03 | 1.79E+03 | 6.55E+00 | 6.79E+03 | 1.40E+04 | 6.71E+04 | 4.32E+02 |
| Dehydrators | 6.67E+01 | 6.54E+01 | 1.23E-01 | 3.02E+04 | 1.16E+03 | 1.08E+03 | 1.46E+01 |
| Compressor_Engines | 2.98E+03 | 2.98E+03 | 0.00E+00 | 1.16E+04 | 3.24E+05 | 3.45E+05 | 1.16E+02 |

*Figure S2. Emissions of criteria pollutants from O&G categories in NEI 2017*

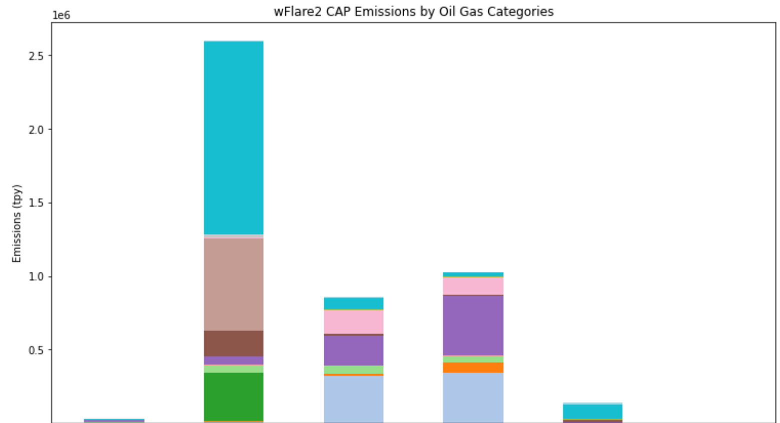



| | PM25-PRI | VOC | CO | NOX | SO2 | NH3 |
|---|---|---|---|---|---|---|
| ptOG_Flares | 8.38E+01 | 5.22E+03 | 8.95E+03 | 2.80E+03 | 1.53E+04 | 1.33E-01 |
| VIIRS_Flares | 4.34E+03 | 1.04E+06 | 6.79E+04 | 1.42E+04 | 8.96E+04 | 0.00E+00 |
| Turbine_Boiler | 7.43E+02 | 5.15E+02 | 3.50E+03 | 5.96E+03 | 5.19E+03 | 6.87E+01 |
| Storage Tanks | 2.93E+00 | 2.55E+04 | 1.32E+03 | 5.35E+02 | 3.73E+01 | 0.00E+00 |
| Pumpjack Engines | 1.39E+03 | 5.26E+03 | 1.64E+05 | 1.21E+05 | 7.16E+01 | 0.00E+00 |
| Pneumatics | 2.61E-01 | 6.24E+05 | 6.38E+01 | 1.94E+02 | 1.56E-02 | 4.66E-03 |
| Others | 7.11E+02 | 1.75E+05 | 1.02E+04 | 8.93E+03 | 1.55E+04 | 1.76E+03 |
| Other_Engines | 9.49E+03 | 5.52E+04 | 2.04E+05 | 4.05E+05 | 2.94E+03 | 3.23E+02 |
| Loading_Transport | 5.50E+01 | 6.19E+03 | 1.66E+02 | 9.27E+01 | 1.51E+00 | 3.20E-01 |
| Heaters_Dehydes | 5.43E+03 | 5.45E+04 | 5.26E+04 | 4.46E+04 | 1.38E+03 | 3.90E+01 |
| Fugitives | 1.55E+01 | 3.21E+05 | 2.45E+02 | 1.42E+02 | 3.42E+02 | 5.00E-12 |
| Drilling_Completion | 1.80E+03 | 6.84E+03 | 1.41E+04 | 6.76E+04 | 4.32E+02 | 6.55E+00 |
| Compressor_Engines | 2.98E+03 | 1.16E+04 | 3.24E+05 | 3.45E+05 | 1.16E+02 | 0.00E+00 |

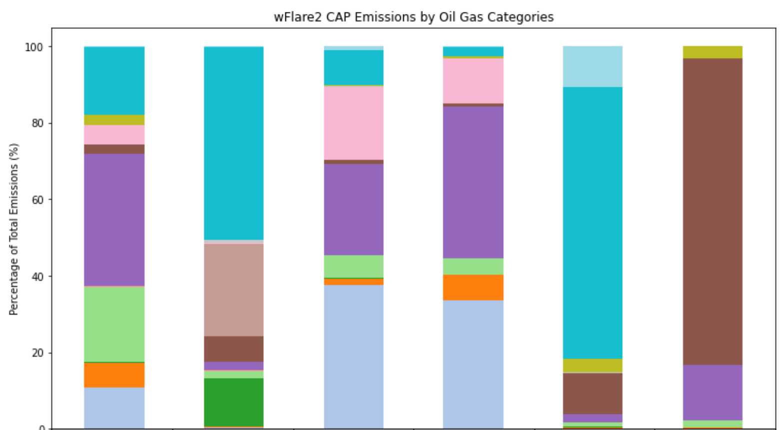



| | PM25-PRI | VOC | CO | NOX | SO2 | NH3 |
|---|---|---|---|---|---|---|
| ptOG_Flares | 0.31 | 0.22 | 1.05 | 0.28 | 11.67 | 0.01 |
| VIIRS_Flares | 16.07 | 44.51 | 7.98 | 1.40 | 68.49 | 0.00 |
| Turbine_Boiler | 2.75 | 0.02 | 0.41 | 0.59 | 3.96 | 3.13 |
| Storage Tanks | 0.01 | 1.10 | 0.15 | 0.05 | 0.03 | 0.00 |
| Pumpjack Engines | 5.14 | 0.23 | 19.30 | 11.91 | 0.05 | 0.00 |
| Pneumatics | 0.00 | 26.81 | 0.01 | 0.02 | 0.00 | 0.00 |
| Others | 2.63 | 7.53 | 1.19 | 0.88 | 11.81 | 80.07 |
| Other_Engines | 35.10 | 2.37 | 23.93 | 39.83 | 2.25 | 14.71 |
| Loading_Transport | 0.20 | 0.27 | 0.02 | 0.01 | 0.00 | 0.01 |
| Heaters_Dehydes | 20.08 | 2.34 | 6.18 | 4.39 | 1.05 | 1.78 |
| Fugitives | 0.06 | 13.81 | 0.03 | 0.01 | 0.26 | 0.00 |
| Drilling_Completion | 6.64 | 0.29 | 1.66 | 6.65 | 0.33 | 0.30 |
| Compressor_Engines | 11.01 | 0.50 | 38.08 | 33.98 | 0.09 | 0.00 |

*Figure S3. Emissions of criteria pollutants from O&G categories in wFlare1*




| | PM25-PRI | VOC | CO | NOX | SO2 | NH3 |
|---|---|---|---|---|---|---|
| ptOG_Flares | 8.38E+01 | 5.22E+03 | 8.95E+03 | 2.80E+03 | 1.53E+04 | 1.33E-01 |
| VIIRS_Rystad_NEI_Flares | 4.82E+03 | 1.31E+06 | 7.75E+04 | 2.33E+04 | 1.00E+05 | 0.00E+00 |
| Turbine_Boiler | 7.43E+02 | 5.15E+02 | 3.50E+03 | 5.96E+03 | 5.19E+03 | 6.87E+01 |
| Storage Tanks | 2.93E+00 | 2.55E+04 | 1.32E+03 | 5.35E+02 | 3.73E+01 | 0.00E+00 |
| Pumpjack Engines | 1.39E+03 | 5.26E+03 | 1.64E+05 | 1.21E+05 | 7.16E+01 | 0.00E+00 |
| Pneumatics | 2.61E-01 | 6.24E+05 | 6.38E+01 | 1.94E+02 | 1.56E-02 | 4.66E-03 |
| Others | 7.11E+02 | 1.75E+05 | 1.02E+04 | 8.93E+03 | 1.55E+04 | 1.76E+03 |
| Other_Engines | 9.49E+03 | 5.52E+04 | 2.04E+05 | 4.05E+05 | 2.94E+03 | 3.23E+02 |
| Loading_Transport | 5.50E+01 | 6.19E+03 | 1.66E+02 | 9.27E+01 | 1.51E+00 | 3.20E-01 |
| Heaters_Dehydes | 5.43E+03 | 5.45E+04 | 5.26E+04 | 4.46E+04 | 1.38E+03 | 3.90E+01 |
| Fugitives | 1.55E+01 | 3.21E+05 | 2.45E+02 | 1.42E+02 | 3.42E+02 | 5.00E-12 |
| Drilling_Completion | 1.80E+03 | 6.84E+03 | 1.41E+04 | 6.76E+04 | 4.32E+02 | 6.55E+00 |
| Compressor_Engines | 2.98E+03 | 1.16E+04 | 3.24E+05 | 3.45E+05 | 1.16E+02 | 0.00E+00 |




| | PM25-PRI | VOC | CO | NOX | SO2 | NH3 |
|---|---|---|---|---|---|---|
| ptOG_Flares | 0.30 | 0.20 | 1.04 | 0.27 | 10.79 | 0.01 |
| VIIRS_Rystad_NEI_Flares | 17.53 | 50.32 | 9.01 | 2.27 | 70.85 | 0.00 |
| Turbine_Boiler | 2.70 | 0.02 | 0.41 | 0.58 | 3.67 | 3.13 |
| Storage Tanks | 0.01 | 0.98 | 0.15 | 0.05 | 0.03 | 0.00 |
| Pumpjack Engines | 5.05 | 0.20 | 19.08 | 11.80 | 0.05 | 0.00 |
| Pneumatics | 0.00 | 24.00 | 0.01 | 0.02 | 0.00 | 0.00 |
| Others | 2.58 | 6.74 | 1.18 | 0.87 | 10.93 | 80.07 |
| Other_Engines | 34.49 | 2.12 | 23.66 | 39.48 | 2.08 | 14.71 |
| Loading_Transport | 0.20 | 0.24 | 0.02 | 0.01 | 0.00 | 0.01 |
| Heaters_Dehydes | 19.73 | 2.10 | 6.11 | 4.35 | 0.98 | 1.78 |
| Fugitives | 0.06 | 12.36 | 0.03 | 0.01 | 0.24 | 0.00 |
| Drilling_Completion | 6.53 | 0.26 | 1.64 | 6.60 | 0.31 | 0.30 |
| Compressor_Engines | 10.81 | 0.45 | 37.66 | 33.68 | 0.08 | 0.00 |

*Figure S4. Emission of criteria pollutants from O&G categories in wFlare2*

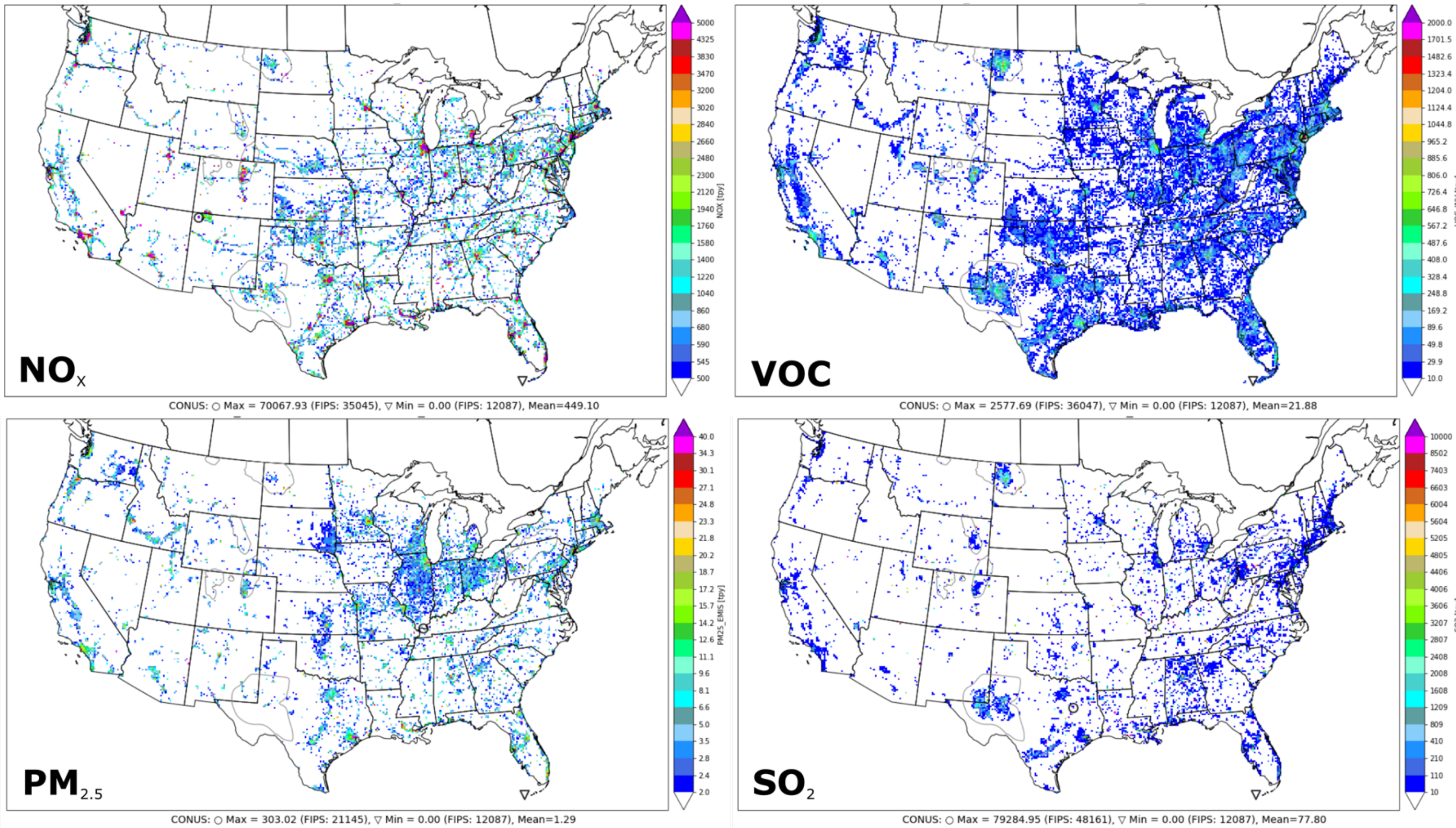



*Figure S5. Annual anthropogenic emissions (tpy) of criteria pollutants $NO_X$, VOC, $PM_{2.5}$ and $SO_2$ in wFlare2 scenario*

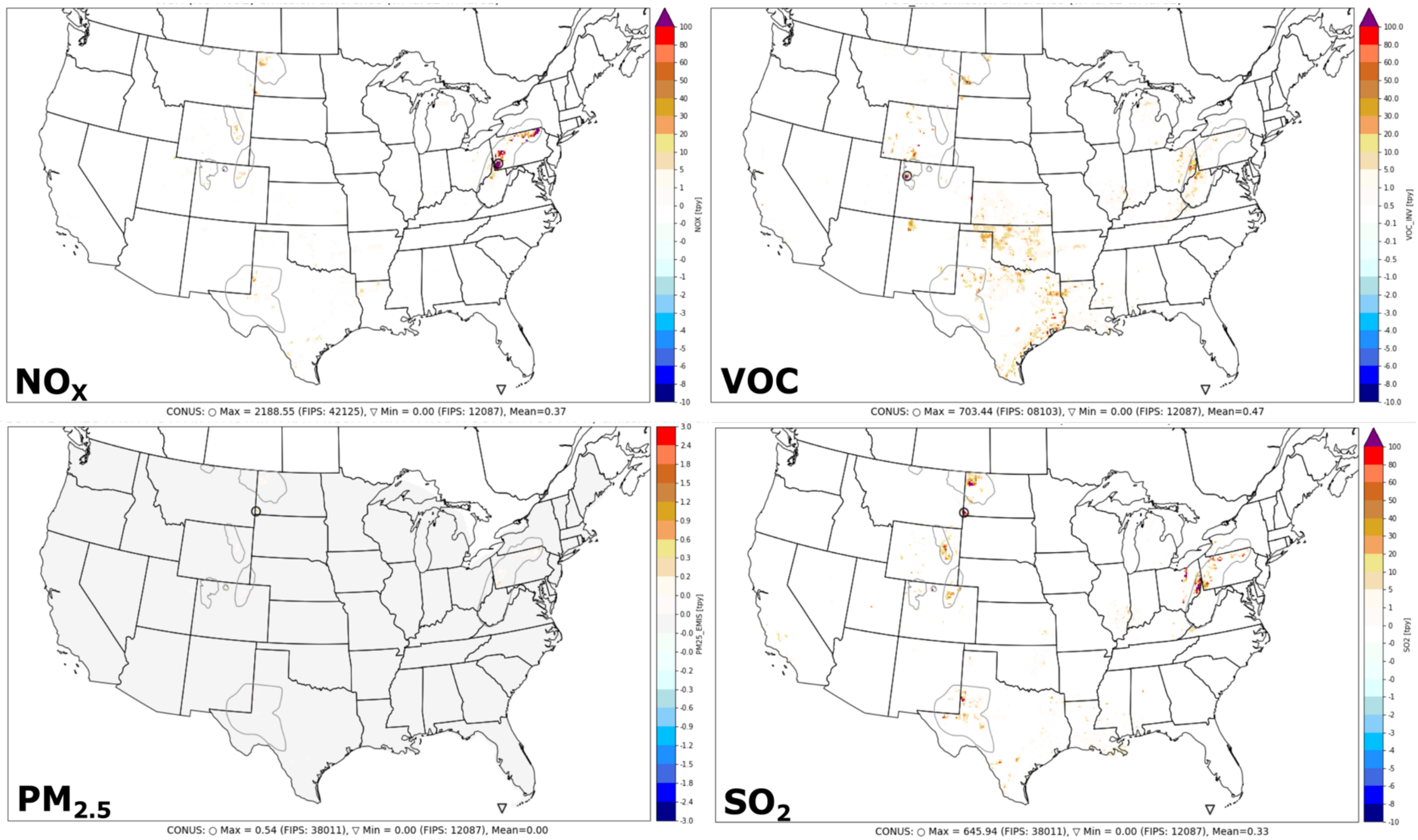



*Figure S6. Differences in annual anthropogenic emissions (tpy) of criteria pollutants $NO_X$, VOC, $PM_{2.5}$ and $SO_2$ counties between wFlare2-wFlare1 scenarios*

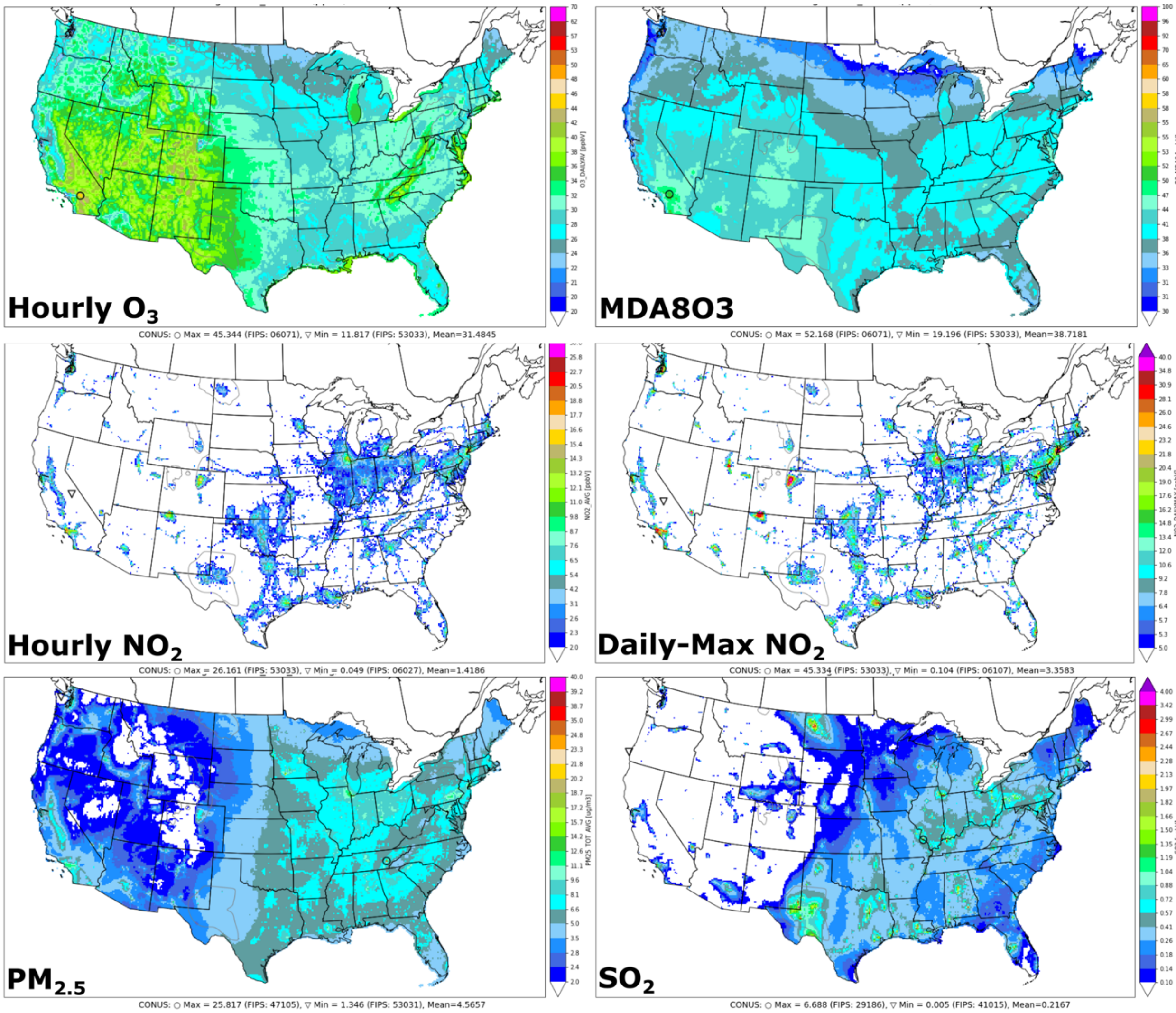



*Figure S7. Annual averaged concentrations of hourly $O_3$ and MDA8$O_3$ (ppb), daily-average and daily-max $NO_2$ (ppb), $PM_{2.5}$ (μg/$m^3$), and $SO_2$ (ppb) as simulated in wFlare2 scenario*

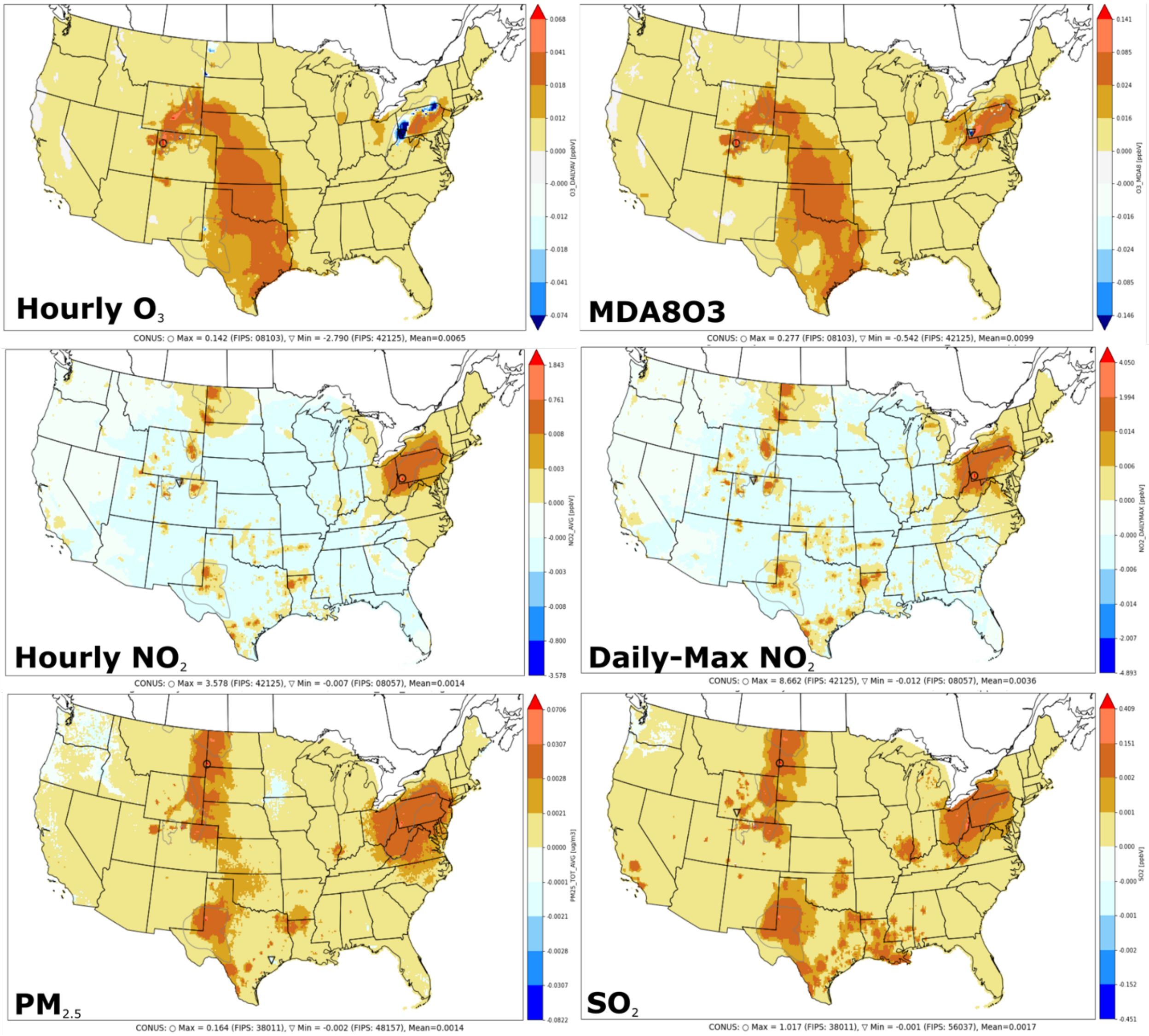



*Figure S8. Differences (wFlare2 - wFlare1) between the two F&V emission scenarios in annual averages of MDA8 Ozone (ppb), 24-hour average $PM_{2.5}$ ($\mu g/m^3$),daily-average and daily-maximum $NO_2$ concentrations (ppb), and $SO_2$ (ppb)*

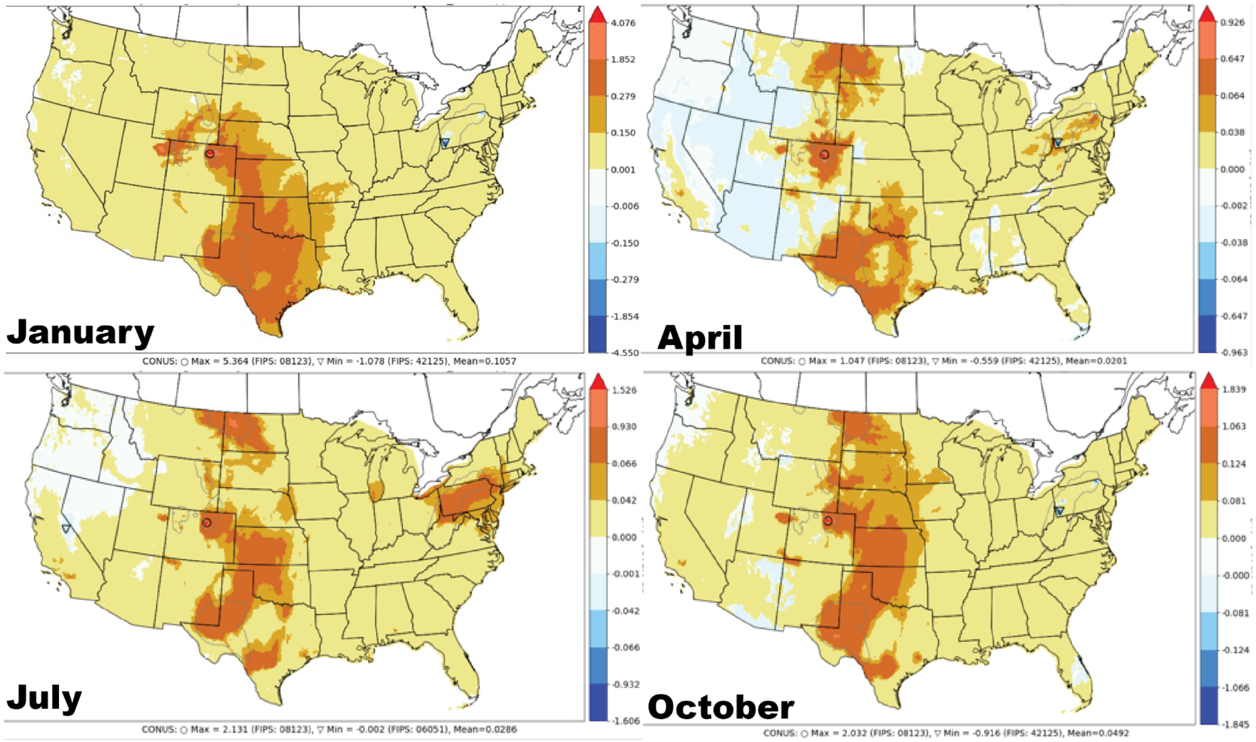



*Figure S9. Differences (wFlare2 - woFlare) of monthly average MDA8O3 (ppb)*

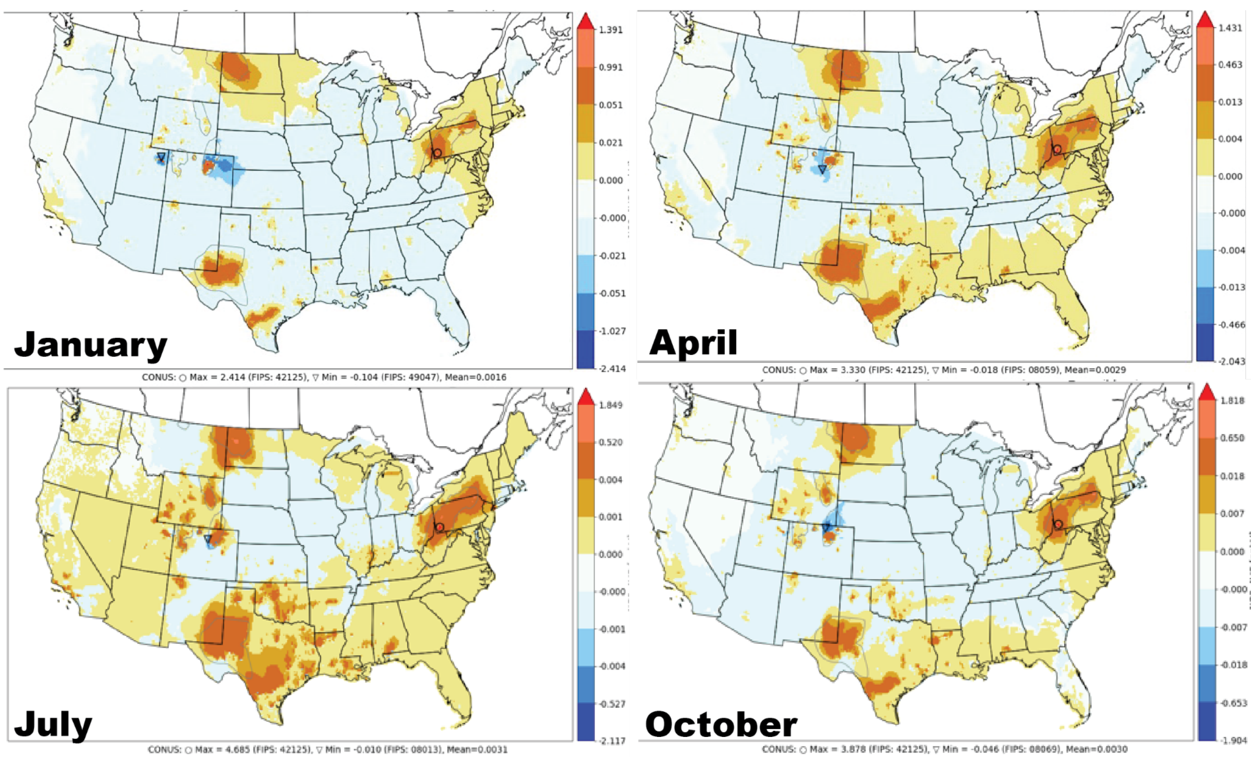



*Figure S10. Differences (wFlare2 – woFlare) of monthly average $NO_2$ (ppb)*

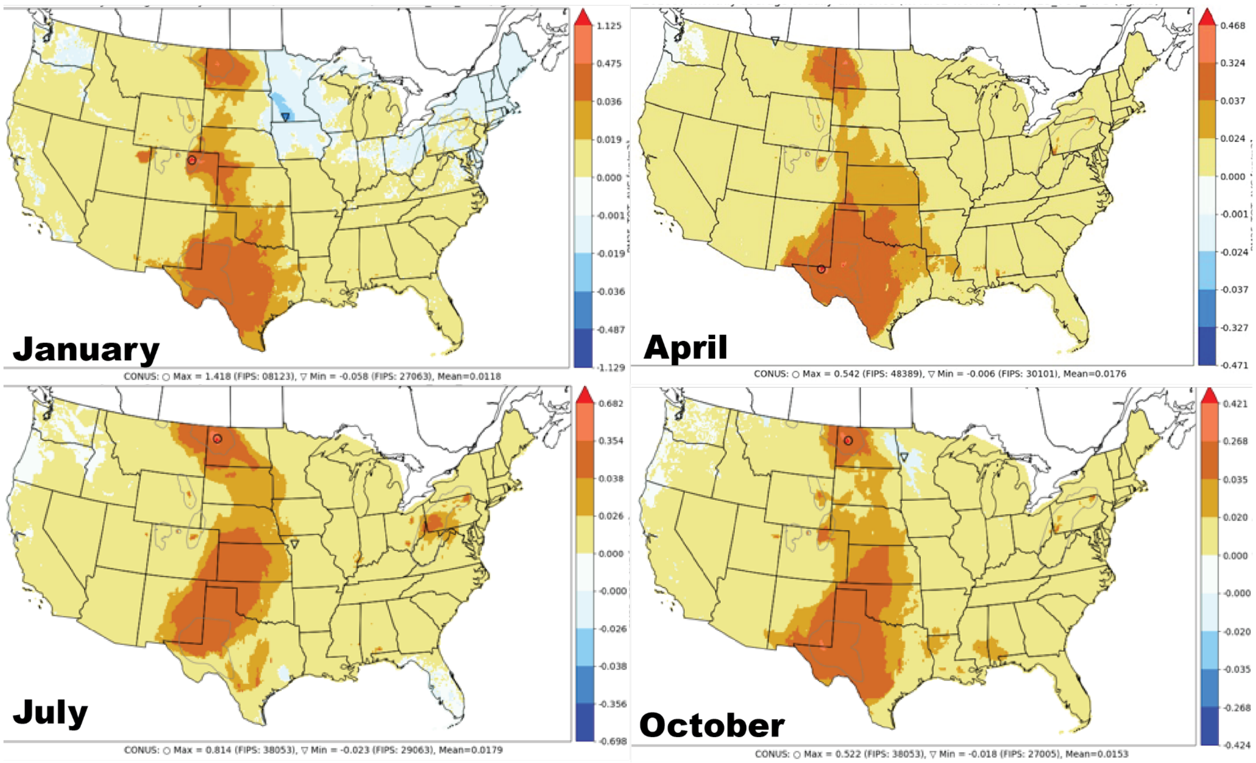


*Figure S11. Differences (wFlare2 – woFlare) of monthly average $PM_{2.5}$ ($\mu g/m^3$)*

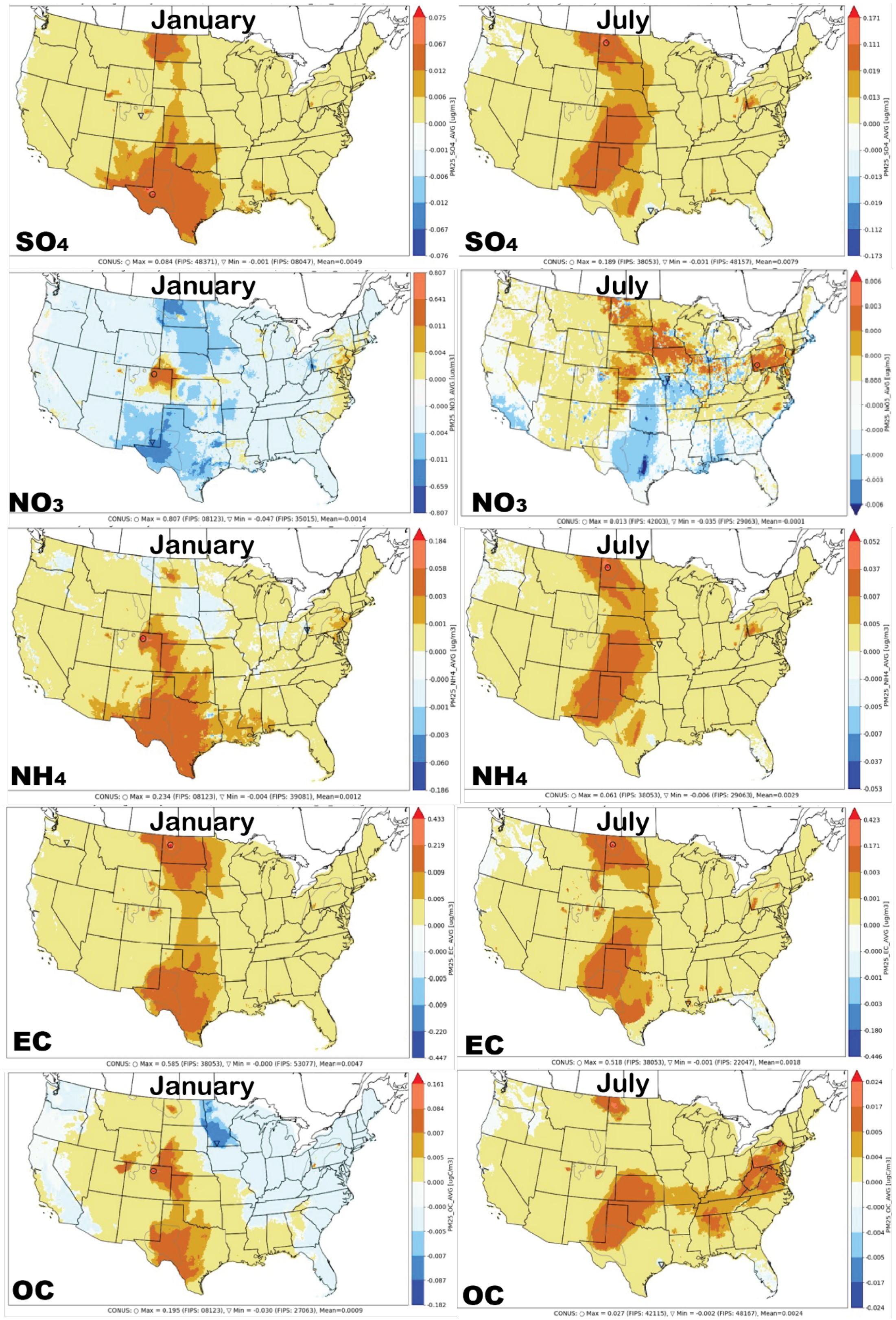



*Figure S12. Differences of monthly average $PM_{2.5}$ chemical components (wFlare2 – woFlare) in (left column) January and (right column) July*

*Table S1. Source Classification Codes (SCCs) associated with point O&G sources*

| SCC | Descriptions |
|---|---|
| 31000160 | Industrial Processes; Oil and Gas Production; Crude Oil Production; Flares |
| 31000205 | Industrial Processes; Oil and Gas Production; Natural Gas Production; Flares |
| 31000215 | Industrial Processes; Oil and Gas Production; Natural Gas Production; Flares Combusting Gases :1000 BTU/scf |
| 30600903 | Industrial Processes; Petroleum Industry; Flares; Natural Gas |
| 20190099 | Internal Combustion Engines; Electric Generation; Flares; Heavy Water |
| 30190022 | Industrial Processes; Chemical Manufacturing; Fuel Fired Equipment; Flare: Residual Oil |
| 30190023 | Industrial Processes; Chemical Manufacturing; Fuel Fired Equipment; Flare: Natural Gas |
| 30390023 | Industrial Processes; Primary Metal Production; Fuel Fired Equipment; Natural Gas: Flares |
| 30590023 | Industrial Processes; Mineral Products; Fuel Fired Equipment; Natural Gas: Flares |
| 30600401 | Industrial Processes; Petroleum Industry; Blowdown Systems; Blowdown System with Vapor Recovery System with Flaring |
| 30600904 | Industrial Processes; Petroleum Industry; Flares; Process Gas |
| 30600905 | Industrial Processes; Petroleum Industry; Flares; Liquified Petroleum Gas |
| 30600906 | Industrial Processes; Petroleum Industry; Flares; Hydrogen Sulfide |
| 30600999 | Industrial Processes; Petroleum Industry; Flares; Not Classified ** |
| 31000216 | Industrial Processes; Oil and Gas Production; Natural Gas Production; Flares Combusting Gases <1000 BTU/scf |
| 30990023 | Industrial Processes; Fabricated Metal Products; Fuel Fired Equipment; Natural Gas: Flares |
| 39990023 | Industrial Processes; Miscellaneous Manufacturing Industries; Miscellaneous Manufacturing Industries; Natural Gas: Flares |
| 39990024 | Industrial Processes; Miscellaneous Manufacturing Industries; Miscellaneous Manufacturing Industries; Process Gas: Flares |
| 40290023 | Chemical Evaporation; Surface Coating Operations; Fuel Fired Equipment; Natural Gas: Flares |
| 49090023 | Chemical Evaporation; Organic Solvent Evaporation; Fuel Fired Equipment; Flare: Natural Gas |
| 50100410 | Waste Disposal; Solid Waste Disposal - Government; Landfill Dump; Waste Gas Destruction: Waste Gas Flares |
| 50300601 | Waste Disposal; Solid Waste Disposal - Industrial; Landfill Dump; Waste Gas Flares |

*Table S2. Source Classification Codes (SCCs) associated with well completion flaring*

| **SCC** | **Short Descriptions** |
|---|---|
| 2310111700 | On-Shore Oil Exploration: Oil Well Completion: All Processes |
| 2310121700 | On-Shore Gas Exploration: Gas Well Completion: All Processes |
| 2310023600 | On-Shore CBM Exploration: CBM Well Completion: All Processes |
| 2310111701 | On-Shore Oil Exploration; Oil Well Completion: Flaring |
| 2310021500 | On-Shore Gas Production; Gas Well Completion - Flaring |

*Table S3. Source Classification Codes (SCCs) associated with nonpoint O&G sources*

| SCC | Descriptions |
|---|---|
| 2310011000 | On shore crude oil production all processes (casinghead gas) |
| 2310021000 | On shore gas production: all processes |
| 2310011020 | On shore oil production crude tanks (including flash) |
| 2310021010 | On-shore gas production: storage tanks: condensate (including flash) |
| 2310030220 | Gas Well Tanks - Flashing & Standing/Working/Breathing, Controlled |
| 2310023010 | On-shore gas production; Coal Bed Methane Natural Gas; Storage Tanks: Condensate |
| 2310021400 | On-shore gas production dehydrators |
| 2310011201 | On shore oil production truck/rail loading of crude |
| 2310021030 | On shore gas production truck and rail loading of condensate |
| 2310011001 | On-Shore Oil Production; Associated Gas Venting |
| 2310010200 | Oil & Gas Exploration & Production /Crude Petroleum /Oil Well Tanks - Flashing & Standing/Working/Breathing |
| 2310021603 | On-Shore Gas Production / Gas Well Venting - Blowdowns |
| 2310011450 | On-Shore Oil Production; Wellhead |
| 2310021450 | On-Shore Gas Production; Wellhead |

*Table S4. Annual natural gas flared volume (MCM/yr) as estimated by VIIRS and Rystad*

| States | VIIRS 2017 | VIIRS 2018 | VIIRS 2019 | VIIRS 2020 | RYSTAD 2019 |
|---|---|---|---|---|---|
| Texas | 4,850 | 6,753 | 8,958 | 6,577 | 5,851 |
| North Dakota | 3,230 | 5,180 | 6,093 | 3,809 | 5,815 |
| New Mexico | 644 | 1,169 | 1,394 | 1,026 | 1,048 |
| Louisiana | 194 | 202 | 276 | 356 | N/A |
| Alaska | 210 | 206 | 231 | 220 | N/A |
| Wyoming | 128 | 155 | 128 | 72 | 247 |
| Oklahoma | 102 | 150 | 99 | 80 | N/A |
| Montana | 11 | 69 | 86 | 54 | N/A |
| Utah | 35 | 54 | 57 | 45 | N/A |
| Mississippi | 73 | 65 | 44 | 39 | N/A |
| Colorado | 41 | 65 | 22 | 18 | 136 |
| Pennsylvania | 18 | 33 | 22 | 4 | N/A |

*Table S5. Flared gas parameters from O&G production fields in Texas*

| **Production fields** | **Molecular Weight of flared gas (g/mole)** | **$H_2S$ weight content ($W_{H2S}$)** |
|---|---|---|
| Anadarko | 21.8 | 0.06 |
| Fort Worth | 23.4 | 0.20 |
| Eagle Ford | 23.7 | 0.17 |
| East Texas | 21.7 | 0.95 |
| Marathon Thrust Belt | 28.6 | 0.01 |
| Palo Duro | 23.7 | 0.01 |
| Permian | 28.6 | 0.50 |

*Table S6. Annual emissions (tpy) of criteria pollutants from flaring and venting in top 5 states*

| | | $PM_{2.5}$ | VOC | CO | $NO_X$ | $SO_2$ |
|---|---|---|---|---|---|---|
| **Colorado** | *NEI 2017 point flare* | 1 | 1,800 | 1,150 | 348 | 23 |
| | *NEI 2017 nonpoint flare* | 0 | 81,900 | 0 | 868 | 0 |
| | *Total NEI2017 flare* | 1 | 83,700 | 1,150 | 1,220 | 23 |
| | *VIIRS + Rystad + NEI hybrid* | 39 (6.5%) | 83,672 (70.6%) | 1,728 5.7%) | 491 (1.1%) | 784 (69.6%) |
| | Ratio** | 29.2 | 1.0 | 1.5 | 0.4 | 34.2 |
| **Texas** | *NEI 2017 point flare* | 9 | 604 | 2,780 | 1,010 | 6,820 |
| | *NEI 2017 nonpoint flare* | 0 | 569,000 | 20,600 | 4,580 | 23,300 |
| | *Total NEI2017 flare* | 9 | 570,000 | 23,400 | 5,590 | 30,100 |
| | *VIIRS + Rystad + NEI hybrid* | 2,244 (29.8%) | 578,902 (63.1%) | 38,112 (18.4%) | 8,440 (3.0%) | 53,336 (91.5%) |
| | Ratio | 240.6 | 1.0 | 1.6 | 1.5 | 1.8 |
| **Wyoming** | *NEI 2017 point flare* | 4 | 385 | 338 | 264 | 2,130 |
| | *NEI 2017 nonpoint flare* | 0 | 54,600 | 652 | 2,610 | 56 |
| | *Total NEI2017 flare* | 4 | 55,000 | 990 | 2,870 | 2,190 |
| | *VIIRS + Rystad + NEI hybrid* | 69 (4.8%) | 55,964 (58.8%) | 1,361 (9.4%) | 479 (1.7%) | 3,487 (61.0%) |
| | Ratio | 15.9 | 1.0 | 1.4 | 0.2 | 1.6 |
| **New Mexico** | *NEI 2017 point flare* | 1 | 311 | 425 | 109 | 2,470 |
| | *NEI 2017 nonpoint flare* | 1 | 74,900 | 705 | 137 | 2,170 |
| | *Total NEI2017 flare* | 2 | 75,200 | 1,130 | 246 | 4,640 |
| | *VIIRS + Rystad + NEI hybrid* | 370 (29.1%) | 84,177 (52.0%) | 6,189 (9.4%) | 1,319 (2.4%) | 10,019 (77.5%) |
| | Ratio | 222.9 | 1.1 | 5.5 | 5.4 | 2.2 |
| **North Dakota** | *NEI 2017 point flare* | 2 | 17 | 115 | 27 | 532 |
| | *NEI 2017 nonpoint flare* | 0 | 308,000 | 11,200 | 2,110 | 2,490 |
| | *Total NEI2017 flare* | 2 | 308,000 | 11,300 | 2,140 | 3,020 |
| | *VIIRS + Rystad + NEI hybrid* | 1,713 (62.7%) | 307,755 (84.6%) | 26,886 (60.4%) | 5,638 (22.0%) | 35,900 (85.7%) |
| | Ratio | 1068.8 | 1.0 | 2.4 | 2.6 | 11.9 |
| **Continental USA** | *VIIRS + Rystad + NEI hybrid* | 4,907 (17.8%) | 1,312,511 (50.5%) | 86,484 (10.0%) | 26,067 (2.5%) | 115,505 (81.6%) |

** Numbers in parentheses indicate percentage of emissions from FV to total emissions from O&G*

*** Ratio of VIIRS + Rystad + NEI hybrid-flare emissions over NEI 2017 flare*

*Table S7. Contribution of FV to NAAQS exceedances in 2016*

| **States** | **MDA8O3 > 70 ppbV** | **24-hour $PM_{2.5}$ > *35 μg/m³*** | **Daily Max $NO_2$ > 60 ppbV*** | **Annual $PM_{2.5}$ > 10 *μg/m³* **** |
|---|---|---|---|---|
| *Colorado* | 65 | 0 | 9 | 0 |
| *Texas* | 31 | 0 | 0 | 0 |
| *California* | 20 | 0 | 0 | 0 |
| *Pennsylvania* | 17 | 1 | 0 | 3 |
| *Michigan* | 13 | 0 | 0 | 0 |
| *North Dakota* | 0 | 0 | 0 | 0 |
| *New Mexico* | 0 | 0 | 0 | 0 |
| *Wyoming* | 0 | 0 | 0 | 0 |
| *Remaining CONUS* | 64 | -1 | 1 | 1 |

** Showing hypothesized daily-maximum $NO_2$ exceedances if the current ambient standard (100 ppbV) is lowered to 60 ppbV.*
*** Showing hypothesized annual PM2.5 exceedances if the current annual standard (12 μg/m³) is lowered to 10 μg/m³ as being considered in latest EPA's proposal (EPA, 2023).*

*Table S8: Baseline health data for included health outcomes, associated pollutants, sources, years, and spatial resolution*

| Health Outcome | Pollutant | Background Prevalence/Incidence Data | | |
|---|---|---|---|---|
| | | Source | Year | Spatial Resolution |
| Mortality | $PM_{2.5}$ | U.S. Centers for Disease Control Wide-ranging Online Database for Epidemiological Research (CDC WONDER)[5] | 1999 - 2016 | County |
| Mortality | $O_3$ | U.S. Centers for Disease Control Wide-ranging Online Database for Epidemiological Research (CDC WONDER) | 1999 - 2016 | County |
| Mortality | $NO_2$ | U.S. Centers for Disease Control Wide-ranging Online Database for Epidemiological Research (CDC WONDER) | 1999 - 2016 | County |
| Respiratory Hospitalizations | $PM_{2.5}$ | BenMAP and Health Care Utilization Project (HCUP)[6] | 2011 - 2014, varies by outcome | State |
| Cardiovascular Hospitalizations | $PM_{2.5}$ | BenMAP and Health Care Utilization Project (HCUP) | 2011 - 2014, varies by outcome | State |
| Heart Attacks (acute non-fatal) | $PM_{2.5}$ | BenMAP and Health Care Utilization Project (HCUP) | 2011 - 2014, varies by outcome | State |
| Heart Attacks (acute non-fatal) | $NO_2$ | BenMAP and Health Care Utilization Project (HCUP) | 2011 - 2014, varies by outcome | State |
| Respiratory Hospitalizations | $O_3$ | BenMAP and Health Care Utilization Project (HCUP) | 2011 - 2014, varies by outcome | State |
| Asthma Incidence | $PM_{2.5}$ | Winer et al. (2012) | 2006 - 2008 | National |
| Asthma Incidence | $NO_2$ | Winer et al. (2012) | 2006 - 2008 | National |

[5] https://wonder.cdc.gov
[6] https://hcup-us.ahrq.gov

| Health Outcome | Pollutant | Background Prevalence/Incidence Data | | |
|---|---|---|---|---|
| | | Source | Year | Spatial Resolution |
| Asthma Exacerbations | $PM_{2.5}$ | State Prevalence: https://ephtracking.cdc.gov/DataExplorer/<br><br>National Prevalence: https://www.cdc.gov/asthma/nhis/2017/table4-1.htm<br><br>Exacerbation Rate: Ostro et al., 2001 | 1993 | State and National |
| Asthma Exacerbations | $NO_2$ | State Prevalence: https://ephtracking.cdc.gov/DataExplorer/<br><br>National Prevalence: https://www.cdc.gov/asthma/nhis/2017/table4-1.htm<br><br>Exacerbation Rate: Ostro et al., 2001 | 1993 | State and National |
| Preterm Birth | $PM_{2.5}$ | U.S. Centers for Disease Control Wide-ranging Online Database for Epidemiological Research (CDC WONDER) | 2018 | State and National |
| Low Birth Weight | $PM_{2.5}$ | U.S. Centers for Disease Control Wide-ranging Online Database for Epidemiological Research (CDC WONDER) | 2018 | State and National |

*Table S9. Concentration response functions for all health outcomes*

| | | Concentration-Response Function | | | |
|---|---|---|---|---|---|
| **Health Outcome** | **Population at risk** | **Study** | **Pollutant** | **Metric** | **CRF central estimate (95% CI)** |
| Mortality | Adults ≥ 25 years of age | (Vodonos et al., 2018) | $PM_{2.5}$ | Annual Average $PM_{2.5}$ (µg/ $m^3$) | 1.29% (1.09 - 1.5%) [note: slope at 10µg/m3] |
| Mortality | Adults ≥ 25 years of age | (Turner et al., 2016) | $O_3$ | Annual Average of the 8hr Maximum Daily Average (ppb) | 0.2% (0.1 - 0.4%) |
| Mortality | Adults ≥ 25 years of age | (Faustini et al., 2014) | $NO_2$ | Annual Average (µg/ $m^3$) | 0.4% (0.2% - 0.6%) |
| Respiratory Hospitalizations | Adults ≥ 65 years of age | (Levy et al., 2012; Zanobetti et al., 2009) | $PM_{2.5}$ | Daily Average (µg/ $m^3$) | 0.11% (0.057 - 0.16%) |
| Cardiovascular Hospitalizations | Adults ≥ 65 years of age | (Levy et al., 2012; Zanobetti et al., 2009) | $PM_{2.5}$ | Daily Average (µg/m $m^3$) | 0.094% (0.065 - 0.12) |
| Heart Attacks (acute non-fatal) | Adults ≥ 18 years of age | (Mustafic et al., 2012) | $PM_{2.5}$ | Daily Average (µg/ $m^3$) | 0.25% (0.15 - 0.36%) |
| Heart Attacks (acute non-fatal) | Adults ≥ 18 years of age | (Mustafic et al., 2012) | $NO_2$ | Daily Average (µg/ $m^3$) | 0.11% (0.06 - 0.16%) |
| Respiratory Hospitalizations | Adults ≥ 65 years of age | (Ji et al., 2011) | $O_3$ | Annual Average of the 8-hr max (ppb) | 0.16% (0.058 - 0.26%) |
| Asthma Incidence | Children 5 -17 years of age | (Khreis et al., 2017) | $PM_{2.5}$ | Annual Average (µg/ $m^3$) | 3.0% (1.0 - 4.9%) |
| Asthma Incidence | Children 5 -17 years of age | (Khreis et al., 2017) | $NO_2$ | Annual Average (µg/ $m^3$) | 1.2% (0.5 - 1.7%) |
| Asthma Exacerbations | Children 5 -17 years of age | (Orellano et al., 2017) | $PM_{2.5}$ | Annual Average (µg/ $m^3$) | 0.22% (0 - 0.44%) |
| Asthma Exacerbations | Children 5 -17 years of age | (Orellano et al., 2017) | $NO_2$ | Annual Average (µg/ $m^3$) | 0.39% (0.01 - 0.78%) |
| Asthma Exacerbations | Children 5 -17 years of age | (Alhanti et al., 2016) | $PM_{2.5}$ | Annual Average (µg/ $m^3$) | 0.25% (0.13 - 0.5%) |
| Asthma Exacerbations | Children 5 -17 years of age | (Alhanti et al., 2016) | $O_3$ | Annual Average of the 8hr Maximum Daily Average (ppb) | 0.25% (0.14 - 0.36%) |

| | | Concentration-Response Function | | | |
|---|---|---|---|---|---|
| **Health Outcome** | **Population at risk** | **Study** | **Pollutant** | **Metric** | **CRF central estimate (95% CI)** |
| Asthma Exacerbations | Children 5 -17 years of age | (Alhanti et al., 2016) | $NO_2$ | Annual Average of the 1hr Maximum Daily Average (ppb) | 0.42% (0.33 - 0.58%) |
| Asthma ED Visits | Children 5 -17 years of age | (Alhanti et al., 2016) | $PM_{2.5}$ | Annual Average (µg/m$^3$) | 0.25% (0.13 - 0.5%) |
| Asthma ED Visits | Children 5 -17 years of age | (Alhanti et al., 2016) | $O_3$ | Annual Average of the 8hr Maximum Daily Average (ppb) | 0.25% (0.14 - 0.36%) |
| Asthma ED Visits | Children 5 -17 years of age | (Alhanti et al., 2016) | $NO_2$ | Annual Average of the 1hr Maximum Daily Average (ppb) | 0.42% (0.33 - 0.58%) |
| Asthma Hospitalizations | Children 5 -17 years of age | (Alhanti et al., 2016) | $PM_{2.5}$ | Annual Average (µg/m$^3$) | 0.25% (0.13 - 0.5%) |
| Asthma Hospitalizations | Children 5 -17 years of age | (Alhanti et al., 2016) | $O_3$ | Annual Average of the 8hr Maximum Daily Average (ppb) | 0.25% (0.14 - 0.36%) |
| Asthma Hospitalizations | Children 5 -17 years of age | (Alhanti et al., 2016) | $NO_2$ | Annual Average of the 1hr Maximum Daily Average (ppb) | 0.42% (0.33 - 0.58%) |
| Preterm Birth | Infants | (Sun et al., 2015) | $PM_{2.5}$ | Annual Average (µg/m$^3$) | 1.2% (0.29 - 2.1%) |
| Low Birth Weight | Infants | (Sun et al., 2016) | $PM_{2.5}$ | Annual Average (µg/m$^3$) | 0.86% (0.31 - 1.4%) |
| Autism Spectrum Disorder | Infants | (Becerra et al., 2013) | $PM_{2.5}$ | Annual Average (µg/m$^3$) | 0.014% (0 - 0.03%) |

*Table S10. Valuation functions for all outcomes evaluated*

| Health Outcome | Pollutant | Valuation ($2016 USD) | |
|---|---|---|---|
| | | **Value (low - high, if it exists)** | **Source** |
| Mortality | $PM_{2.5}$ | $10.3 million ($6.2 - $14.5 million) | U.S. EPA BenMAP |
| Mortality | $O_3$ | $10.3 million ($6.2 - $14.5 million) | U.S. EPA BenMAP |
| Mortality | $NO_2$ | $10.3 million ($6.2 - $14.5 million) | U.S. EPA BenMAP |
| Respiratory Hospitalizations | $PM_{2.5}$ | $36,000 | U.S. EPA BenMAP, Health Care Utilization Project, Agency for Healthcare Research and Quality |
| Cardiovascular Hospitalizations | $PM_{2.5}$ | $30,000 | U.S. EPA BenMAP, Health Care Utilization Project, Agency for Healthcare Research and Quality |
| Heart Attacks (acute non-fatal) | $PM_{2.5}$ | $70,000 | U.S. EPA BenMAP, Health Care Utilization Project, Agency for Healthcare Research and Quality |
| Heart Attacks (acute non-fatal) | $NO_2$ | $70,000 | U.S. EPA BenMAP, Health Care Utilization Project, Agency for Healthcare Research and Quality |
| Respiratory Hospitalizations | $O_3$ | $36,000 | U.S. EPA BenMAP, Health Care Utilization Project, Agency for Healthcare Research and Quality |
| Asthma Incidence | $PM_{2.5}$ | $58,000 (24,000 - 93,000) | Nurmagambetov et al. (2018) |
| Asthma Incidence | $NO_2$ | $58,000 (24,000 - 93,000) | Nurmagambetov et al. (2018) |
| Asthma Exacerbations | $PM_{2.5}$ | $60 ($22 - $99) | U.S. EPA BenMAP, Health Care Utilization Project, Agency for Healthcare Research and Quality |
| Asthma Exacerbations | $NO_2$ | $60 ($22 - $99) | U.S. EPA BenMAP, Health Care Utilization Project, Agency for Healthcare Research and Quality |
| Preterm Birth | $PM_{2.5}$ | $330,000 | Institute of Medicine (2007), Kerr-Wilson et al. (2012) |
| Low Birth Weight | $PM_{2.5}$ | $16,000 | Russell et al. (2007) |

*Table S11: Case counts and health impact valuation due to FV*

| Health Outcome | Pollutant | Cases | Value (2016 USD) |
|---|---|---|---|
| Deaths (Vodonos et al.) | $PM_{2.5}$ | 360<br>(300 - 420) | \$3,700,000,000<br>(\$1,900,000,000 - \$6,000,000,000) |
| Deaths (Turner et al.) | $O_3$ | 230<br>(120 - 470) | \$2,400,000,000<br>(\$720,000,000 - \$6,800,000,000) |
| Deaths (Faustini et al.) | $NO_2$ | 120<br>(61 - 180) | \$1,300,000,000<br>(\$380,000,000 - \$2,700,000,000) |
| Cardiovascular Hospitalizations (Levy & Zanobetti Pooled) | $PM_{2.5}$ | 18<br>(12 - 24) | \$650,000<br>(\$440,000 - \$850,000) |
| Respiratory Hospitalizations (Levy & Zanobetti Pooled) | $PM_{2.5}$ | 19<br>(9.8 - 28) | \$570,000<br>(\$290,000 - \$840,000) |
| Respiratory Hospitalizations (Ji et al.) | $O_3$ | 110<br>(40 - 180) | \$3,400,000<br>(\$1,200,000 - \$5,500,000) |
| Heart Attacks (Mustafić et al.) | $PM_{2.5}$ | 16<br>(9.7 - 23) | \$1,100,000<br>(\$680,000 - \$1,600,000) |
| Heart Attacks (Mustafić et al.) | $NO_2$ | 6.9<br>(3.7 - 10) | \$480,000<br>(\$260,000 - \$700,000) |
| Asthma Incidence (Khreis et al.) | $PM_{2.5}$ | 140<br>(47 - 230) | \$8,200,000<br>(\$1,100,000 - \$22,000,000) |
| Asthma Incidence (Khreis et al.) | $NO_2$ | 47<br>(19 - 65) | \$2,800,000<br>(\$460,000 - \$6,100,000) |
| Asthma Hospitalizations (Orellano et al.) | $PM_{2.5}$ | 1.1<br>(0 - 2.2) | \$20,000<br>(\$0 - \$41,000) |
| Asthma Hospitalizations (Orellano et al.) | $NO_2$ | 2.1<br>(0.053 - 4.1) | \$38,000<br>(\$960 - \$75,000) |
| Asthma ED Visits (Orellano et al.) | $PM_{2.5}$ | 11<br>(0 - 22) | \$5,000<br>(\$0 - \$10,000) |
| Asthma ED Visits (Orellano et al.) | $NO_2$ | 17<br>(0.43 - 34) | \$7,700<br>(\$190 - \$16,000) |
| Asthma Exacerbations (Orellano et al.) | $PM_{2.5}$ | 8,500<br>(0 - 17,000) | \$500,000<br>(\$0 - \$1,700,000) |
| Asthma Exacerbations (Orellano et al.) | $NO_2$ | 13,000<br>(340 - 26,000) | \$790,000<br>(\$7,300 - \$2,600,000) |

| Health Outcome | Pollutant | Cases | Value (2016 USD) |
|---|---|---|---|
| Asthma Hospitalizations (Alhanti et al.) | $PM_{2.5}$ | 1.3 (0.63 - 2.5) | $23,000 ($12,000 - $46,000) |
| Asthma Hospitalizations (Alhanti et al.) | $O_3$ | 5.7 (3.2 - 8.1) | $100,000 ($59,000 - $150,000) |
| Asthma Hospitalizations (Alhanti et al.) | $NO_2$ | 3.2 (2.5 - 4.5) | $58,000 ($46,000 - $81,000) |
| Asthma ED Visits (Alhanti et al.) | $PM_{2.5}$ | 13 (6.3 - 25) | $5,700 ($2,700 - $12,000) |
| Asthma ED Visits (Alhanti et al.) | $O_3$ | 54 (31 - 77) | $24,000 ($13,000 - $36,000) |
| Asthma ED Visits (Alhanti et al.) | $NO_2$ | 25 (20 - 36) | $11,000 ($8,800 - $17,000) |
| Asthma Exacerbations (Alhanti et al.) | $PM_{2.5}$ | 9,700 (4,900 - 19,000) | $580,000 ($110,000 - $1,900,000) |
| Asthma Exacerbations (Alhanti et al.) | $O_3$ | 43,000 (24,000 - 61,000) | $2,500,000 ($530,000 - $6,000,000) |
| Asthma Exacerbations (Alhanti et al.) | $NO_2$ | 21,000 (16,000 - 29,000) | $1,200,000 ($360,000 - $2,800,000) |
| Low Birth Weight (Sun et al.) | $PM_{2.5}$ | 25 (8.9 - 40) | $390,000 ($140,000 - $630,000) |
| Preterm Birth (Sun et al.) | $PM_{2.5}$ | 64 (16 - 110) | $21,000,000 ($5,100,000 - $37,000,000) |
| Autism Spectrum Disorder (Becerra et al.) | $PM_{2.5}$ | 18 (0 - 36) | $44,000,000 ($0 - $110,000,000) |
| Deaths | All Three | 710 (480 - 1,100) | $7,300,000,000 ($3,000,000,000 - $16,000,000,000) |
| Asthma Incidence | $PM_{2.5}$and $NO_2$ | 190 (66 - 300) | $11,000,000 ($1,600,000 - $28,000,000) |
| Asthma Hospitalizations Orellano | $PM_{2.5}$and $NO_2$ | 3.2 (0.053 - 6.3) | $58,000 ($960 - $120,000) |
| Asthma ED Visits Orellano | $PM_{2.5}$and $NO_2$ | 28 | $13,000 |

| Health Outcome | Pollutant | Cases | Value (2016 USD) |
|---|---|---|---|
| | | (0.43 - 56) | ($190 - $26,000) |
| Asthma Exacerbations Orellano | $PM_{2.5}$and $NO_2$ | 22,000<br>(340 - 43,000) | $1,300,000<br>($7,300 - $4,300,000) |
| Asthma Hospitalizations Alhanti | All Three | 10<br>(6.4 - 15) | $180,000<br>($120,000 - $280,000) |
| Asthma ED Visits Alhanti | All Three | 92<br>(58 - 140) | $42,000<br>($25,000 - $65,000) |
| Asthma Exacerbations Alhanti | All Three | 73,000<br>(46,000 - 110,000) | $4,300,000<br>($990,000 - $11,000,000) |
| Respiratory Hospitalizations | $PM_{2.5}$ and $O_3$ | 130<br>(50 - 210) | $3,900,000<br>($1,500,000 - $6,400,000) |
| Heart Attacks | $PM_{2.5}$ and $NO_2$ | 23<br>(13 - 33) | $1,600,000<br>($940,000 - $2,300,000) |
| Grand Total* | | | $7,400,000,000<br>($3,000,000,000 - $16,000,000,000) ** |

*Grand Total includes summations of: Deaths, Asthma Incidence, Asthma Hospitalizations (Alhanti), Asthma Exacerbations (Alhanti), Asthma ED Visits (Alhanti), Respiratory Hospitalizations, and Heart Attacks
**Sums may not add up perfectly due to independent rounding

*Table S12. Flaring and Venting Impacts on Disadvantaged Populations*

| **Justice 40 Category** | **Health outcome** | **Cases occurring within Justice40 tracts** | **All attributable *wFlare2* cases** | **% of Health Impact Cases occurring within Justice 40 tracts** |
|---|---|---|---|---|
| Is Low Income (tracts in 65th percentile or above of household income 200% below Federal Poverty Limit, excluding students)? | Adult Premature Mortality | 220 | 710 | 31% |
| | Childhood Asthma Exacerbations | 22,000 | 73,000 | 30% |
| Native-identified Tracts (Greater than or equal to the 65th percentile for "American Indian/Alaska Native" as a percent of total reported population) | Adult Premature Mortality | 65 | 710 | 9% |
| | Childhood Asthma Exacerbations | 6,600 | 73,000 | 9% |
| Hispanic/Latino-identified Tracts (Greater than or equal to the 65th percentile for "Hispanic / Latino" as a percent of total reported population) | Adult Premature Mortality | 230 | 710 | 32% |
| | Childhood Asthma Exacerbations | 29,000 | 73,000 | 40% |

*Table S13: Impact Risk Ratio (IRR) of Flaring and Venting Impacts on Disadvantaged Populations**

| | | Adult Premature Mortality | Childhood Asthma Exacerbations |
|---|---|---|---|
| Is Low Income (tracts in 65th percentile or above of household income 200% below Federal Poverty Limit, excluding students)? | Proportion of cases occurring in this category of tract | 0.31 | 0.30 |
| | Proportion of populations in age groups at risk in this category of tract | 0.30 | 0.33 |
| | **How disproportionate is the impact (IRR)** | **1.0** | **0.92** |
| Native-identified Tracts (Greater than or equal to the 65th percentile for "American Indian/Alaska Native" as a percent of total reported population) | Proportion of cases occurring in this category of tract | 0.091 | 0.091 |
| | Proportion of populations in age groups at risk in this category of tract | 0.077 | 0.082 |
| | **How disproportionate is the impact (IRR)** | **1.2** | **1.1** |
| Hispanic/Latino-identified Tracts (Greater than or equal to the 65th percentile for "Hispanic / Latino" as a percent of total reported population) | Proportion of cases occurring in this category of tract | 0.32 | 0.4 |
| | Proportion of populations in age groups at risk in this category of tract | 0.33 | 0.36 |
| | **How disproportionate is the impact (IRR)** | **0.97** | **1.1** |

**All numbers have been independently rounded to 2 significant figures*