The U.S. GReenhouse gas And Air Pollutant Emissions System (GRA2PES)

Updated on: October 30, 2024

Temporal Extent: 2021

Temporal Resolution: Monthly, Weekday / weekend, Hourly

Spatial Extent: Contiguous United States

Horizontal Spatial Resolution: 4km x 4km

Vertical Spatial Resolution: 20 pressure levels (Table 3)

Data Units: For fossil fuel CO_2, CO_2, CO, NH_3, NO_x, SO_2, and speciated non-methane volatile organic compounds (NMVOC) species, the unit is moles per square kilometer per hour (moles/km^2/hr). For total NMVOC, $PM_{2.5}$, PM_{10}, and speciated PM, the unit is metric tons per square kilometer per hour (metric tons/km^2/hr) (Table 1).

Data type: Research

Summary

The GReenhouse gas And Air Pollutants Emissions System (GRA2PES) is an hourly high-resolution (4km x 4km) data product with resolved vertical distribution for emissions of both greenhouse gases and air pollutants developed in a consistent framework. The dataset contains emissions over the contiguous United States covering major anthropogenic sectors, including energy, industrial fuel combustion and processes, commercial and residential combustion, oil and gas production, on-road and off-road transportation, etc. (Table 2). Fossil fuel CO_2 ($ffCO_2$) emissions are developed along with those of air pollutants including CO, NH_3, NO_x, SO_2, NMVOC, PM_{10} and $PM_{2.5}$ with consistency in spatial and temporal distributions. Emissions by sectors are grouped into point and area sources, and then vertically distributed into 20 vertical layers (Table 3) based on stack information where applicable. Spatial-temporal surrogates are developed to distribute CO_2 emissions to grid cells to keep consistency between greenhouse gases and air quality species. Weekday-weekend and diurnal profiles are applied by sources to allocate emissions from month to hour.

The gridded data is prepared in NetCDF format, with 20 vertical layers (Table 3) for 95 (excluding methane) species (Table 1) and 17 sectors (Table 2), as well as international emissions in the domain. Total emissions for all sectors combined are also provided. The current version of GRA2PES is for 2021. Long-term emissions and more greenhouse gases species (e.g., methane) are under development and added in the future. GRA2PES is a collaborative research project, aiming to strengthen the community's ability to consistently model and map greenhouse gas and air pollutant emissions and associated uncertainties across the contiguous United States.

GRA2PES builds off of previously developed inventories such as the Fuel-based Oil and Gas (FOG) inventory (Gorchov Negron et al., 2018), the Fuel-based Inventory of Vehicle Emissions (FIVE) (McDonald et al., 2014, McDonald et al., 2018a), the Volatile Chemical Products (VCPs)

inventory (McDonald et al., 2018b,). These inventories have been updated over time; VCPs in Coggon et al., 2021, FIVE in Harkins et al., 2021, FOG in Francoeur et al., 2021. A full anthropogenic air quality inventory, with near-real-time adjustments was also developed in He et al., 2024. These inventories that GRA2PES builds off of have been extensively evaluated in air quality modeling studies and compared to satellite, aircraft and ground observations in multiple years (McDonald et al., 2018a, Li et al., 2021, He et al., 2024, Zhu et al., 2024).

Source Data Product Citation

The emissions data are deployed to the National Institute of Standards and Technology (NIST) data center with a doi of https://doi.org/10.18434/mds2-3520 .

Version History

The current version is V1.

- August 2024, the first version of GRA2PES data with ffCO_2 and air pollutants is developed and deployed to the NIST data center.

Data Download

The gridded emissions by sectors for all chemical species can be downloaded from the NIST data repository: https://data.nist.gov/od/id/mds2-3520 . There are three ways to download the emissions data efficiently.

1. **Web Interface.**

- Visit the NIST data repository.
- Add desired files to the "Data Cart" and download all selected files.

2. **Python Script.**

- Use the provided Python script on the website, pdrdownload.py, to download all files from the page.
- Requirements: Python 3
- Usage example:

```
python pdrdownload.py -D -C
```

3. **Wget Command.**

- Download files directly using wget.
- The command follows this format:

```
wget https://data.nist.gov/od/ds/mds2-3520/GRA2PESv1.0_[sector
name]_2021[M2].tar.gz
```

Replace `[sector name]` with the sector abbreviation as listed in Table 2.
Replace `[M2]` with the month number (e.g., `01`, `02`, ..., `12`).

- Example:

```
wget https://data.nist.gov/od/ds/mds2-
3520/GRA2PESv1.0_EGU_202101.tar.gz
```

Scientific Details

GRA2PES emissions are developed for both greenhouse gases and air pollutants under a consistent framework. For fuel combustion sources, fuel combustion and CO_2 emission factors at a state level are estimated, with facility-level information integrated. Emissions of electricity generation units are developed by matching point sources from different inventories. Air pollutants emissions derived from the national emissions inventory are used to develop spatial-temporal surrogates to distribute CO_2 emissions to 4km x 4km grid cells. A series of emission inventories that have been comprehensively evaluated based on field campaign from oil and gas production, on-road vehicles, cooking and volatile chemical products are integrated into GRA2PES (Table 2).

Table 1: Full Species List

ID	Species	Description	Unit
1	ffCO2	Fossil Fuel Carbon Dioxide	mole km^-2 hr^-1
2	CO2	Carbon Dioxide	mole km^-2 hr^-1
3	CO	Carbon Monoxide	mole km^-2 hr^-1
4	NH3	Ammonia	mole km^-2 hr^-1
5	NOX	Nitrogen Oxides (NOX)	mole km^-2 hr^-1
6	SO2	Sulfur Dioxide	mole km^-2 hr^-1
7	VOC	Total NMVOC Emissions	metric tons km^-2 hr^-1
8	PM25-PRI	Total Primary PM2.5 Emissions	metric tons km^-2 hr^-1
9	PM10-PRI	Total Primary PM10 Emissions	metric tons km^-2 hr^-1
10	HC01	Methane (Not included in this V1 release, under development)	mole km^-2 hr^-1
11	HC02	Ethane+Alkanes with k(OH)< 500 ppm^-1-min^-1	mole km^-2 hr^-1
12	HC03	Alkanes with 500<k(OH)<2500 ppm^-1-min^-1, EXCLUDE(C3H8, C2H2, ethanol, acids)	mole km^-2 hr^-1
13	HC04	Alkanes with 2500<k(OH)<5000 ppm^-1-min^-1, EXCLUDE(butanes)	mole km^-2 hr^-1
14	HC05	Alkanes with 5000<k(OH)<10000 ppm^-1-min^-1, EXCLUDE(pentanes)	mole km^-2 hr^-1
15	HC06	Alkanes with k(OH)>10000 ppm^-1-min^-1, EXCLUDE(ethylene glycol)	mole km^-2 hr^-1
16	HC07	Ethylene	mole km^-2 hr^-1
17	HC08	Alkenes with k(OH)<20000 ppm^-1-min^-1	mole km^-2 hr^-1
18	HC09	Alkenes with k(OH)>20000 ppm^-1-min^-1, EXCLUDE(dienes and styrenes)	mole km^-2 hr^-1
19	HC10	Anthropogenic Isoprene	mole km^-2 hr^-1
20	HC11	Anthropogenic Terpenes (VCPs)	mole km^-2 hr^-1
21	HC12	Aromatics with k(OH)<20000 ppm^-1-min^-1, EXCLUDE(benzene and toluene)	mole km^-2 hr^-1
22	HC13	Aromatics with k(OH)<20000 ppm^-1-min^-1, EXCLUDE(xylenes)	mole km^-2 hr^-1
23	HC14	Formaldehyde	mole km^-2 hr^-1
24	HC15	Acetaldehyde	mole km^-2 hr^-1
25	HC16	>C2 aldehydes	mole km^-2 hr^-1
26	HC17	Benzaldehyde	mole km^-2 hr^-1
27	HC18	Acetone	mole km^-2 hr^-1
28	HC19	Methylethyl ketone	mole km^-2 hr^-1
29	HC20	PRD2 SAPRAC species (aromatic ketones)	mole km^-2 hr^-1
30	HC21	Methanol	mole km^-2 hr^-1
31	HC22	Glyoxal	mole km^-2 hr^-1
32	HC23	Methylglyoxal	mole km^-2 hr^-1
33	HC24	Biacetyl	mole km^-2 hr^-1
34	HC25	Phenols	mole km^-2 hr^-1
35	HC26	Cresols	mole km^-2 hr^-1
36	HC27	Methacrolein	mole km^-2 hr^-1
37	HC28	Methylvinyl ketone	mole km^-2 hr^-1
38	HC29	IPRD SAPRAC species (>C4 unsaturated aldehydes)	mole km^-2 hr^-1
39	HC30	Formic Acid	mole km^-2 hr^-1
40	HC31	Acetic Acid	mole km^-2 hr^-1
41	HC32	>C2 Acids	mole km^-2 hr^-1
42	HC33	Xylenols	mole km^-2 hr^-1
43	HC34	Catechols	mole km^-2 hr^-1
44	HC35	NonVolatile Compounds	mole km^-2 hr^-1
45	HC36	Propylene	mole km^-2 hr^-1
46	HC37	Acetylene	mole km^-2 hr^-1
47	HC38	Benzene	mole km^-2 hr^-1
48	HC39	Butanes	mole km^-2 hr^-1
49	HC40	Pentanes	mole km^-2 hr^-1
50	HC41	Toluene	mole km^-2 hr^-1
51	HC42	m-Xylene	mole km^-2 hr^-1
52	HC43	o-Xylene	mole km^-2 hr^-1
53	HC44	p-Xylene	mole km^-2 hr^-1
54	HC45	Propane	mole km^-2 hr^-1

55	HC46	Dienes	mole km^-2 hr^-1
56	HC47	Styrenes	mole km^-2 hr^-1
57	HC48	Ethanol	mole km^-2 hr^-1
58	HC49	Ethylene Glycol	mole km^-2 hr^-1
59	HC50	Unidentified_Unknown VOC	mole km^-2 hr^-1
60	HC51	Isopropyl Alcohol (OVCP)	mole km^-2 hr^-1
61	HC52	Propylene Glycol (OVCP)	mole km^-2 hr^-1
62	HC53	Glycerol (OVCP)	mole km^-2 hr^-1
63	HC54	D4-Siloxane	mole km^-2 hr^-1
64	HC55	D5-Siloxane	mole km^-2 hr^-1
65	HC56	Other Siloxane	mole km^-2 hr^-1
66	HC57	NROG	mole km^-2 hr^-1
67	HC58	PCBTF	mole km^-2 hr^-1
68	HC59	PDCBZ	mole km^-2 hr^-1
69	HC60	Propanal	mole km^-2 hr^-1
70	HC61	Butanal	mole km^-2 hr^-1
71	HC62	Pentanal	mole km^-2 hr^-1
72	HC63	Hexanal	mole km^-2 hr^-1
73	HC64	Heptanal	mole km^-2 hr^-1
74	HC65	Octanal	mole km^-2 hr^-1
75	HC66	Nonanal	mole km^-2 hr^-1
76	HC67	Unsaturated Aldehydes	mole km^-2 hr^-1
77	HC68	C10+ Aldehydes	mole km^-2 hr^-1
78	PM01	Nonspeciated Primary PM2.5 (sum of PM08-PM19)	metric tons km^-2 hr^-1
79	PM02	Sulfate PM2.5	metric tons km^-2 hr^-1
80	PM03	Nitrate PM2.5	metric tons km^-2 hr^-1
81	PM04	Organic Carbon PM2.5	metric tons km^-2 hr^-1
82	PM05	Elemental Carbon PM2.5	metric tons km^-2 hr^-1
83	PM06	Non-Carbon Organic PM2.5	metric tons km^-2 hr^-1
84	PM07	Ammonium PM2.5	metric tons km^-2 hr^-1
85	PM08	Aluminum PM2.5	metric tons km^-2 hr^-1
86	PM09	Calcium PM2.5	metric tons km^-2 hr^-1
87	PM10	Iron PM2.5	metric tons km^-2 hr^-1
88	PM11	Water PM2.5	metric tons km^-2 hr^-1
89	PM12	Magnesium PM2.5	metric tons km^-2 hr^-1
90	PM13	Other PM2.5	metric tons km^-2 hr^-1
91	PM14	Potassium PM2.5	metric tons km^-2 hr^-1
92	PM15	Manganese PM2.5	metric tons km^-2 hr^-1
93	PM16	Chloride PM2.5	metric tons km^-2 hr^-1
94	PM17	Sodium PM2.5	metric tons km^-2 hr^-1
95	PM18	Titanium PM2.5	metric tons km^-2 hr^-1
96	PM19	Silicon PM2.5	metric tons km^-2 hr^-1

Table 2: Full Sector List

Sectors	$ffCO_2$ data source	AQ data source	Publications	Abbreviation in Filename
Industrial fuel	GHGI17 + GHGRP	NEI17 + GHGRP	He et al., 2024	INDF
Industrial processes	GHGRP	NEI17 + GHGRP	He et al., 2024	INDP
Commercial	GHGI17	NEI17	He et al., 2024	COMM
Residential	GHGI17	NEI17	He et al., 2024	RES
Railroad	EIA	NEI17	He et al., 2024	RAIL
EGU	CEMS (CO2)	NEI17+CEMS (NOx, SO2 only)	He et al., 2024	EGU
Airport	N/A	NEI17	He et al., 2024	AVIATION
Waste	N/A	NEI17		WASTE
Agricultural	N/A	NEI17		AG
Fugitives	N/A	NEI17	He et al., 2024	FUG
Oil and Gas	GHGRP + FOG	GHGRP + NEI17 + FOG	Gorchov Negron et al., 2018 Francoeur et al. 2021	OG
On-road Gasoline	FIVE	FIVE	McDonald et al., 2014 McDonald et al., 2018a Harkins et al., 2021	ONROAD_GAS
On-road Diesel				ONROAD_DSL
Nonroad				OFFROAD
VCP	N/A	VCP	McDonald et al., 2018b Coggon et al., 2021 He et al., 2024	VCP
Cooking	N/A	Observations + gridded population	Coggon et al., 2024 Zhu et al., 2024 (under review)	COOKING
Shipping	CAMSv4.2	CAMSv4.2	Granier et al., 2019	SHIPPING
International	CAMSv4.2	CAMSv4.2	Granier et al., 2019	INTERNATIONAL
All sectors combined				total

Key Publications

Lyu, C., Harkins, C., Li, M., Mueller, K., McDonald, B. et al.: Developing the United States GReenhouse gas And Air Pollutants Emissions System (GRA2PES), *to be submitted*.

Gorchov Negron, A., McDonald, B. C., McKeen, S. A., Peischl, J., Ahmadov, R., de Gouw, J. A., Frost, G. J., Hastings, M. G., Pollack, I. B., Ryerson, T. B., Thompson, C., Warneke, C., and Trainer, M.: Development of a fuel-based oil and gas inventory of nitrogen oxides emissions, *Environmental Science & Technology*, 10.1021/acs.est.8b02245, 2018.

Francoeur, C. B., McDonald, B. C., Gilman, J. B., Zarzana, K. J., Dix, B., Brown, S. S., de Gouw, J. A., Frost, G. J., Li, M., McKeen, S. A., Peischl, J., Pollack, I. B., Ryerson, T. B., Thompson, C., Warneke, C., and Trainer, M.: Quantifying Methane and Ozone Precursor Emissions from Oil and Gas Production Regions across the Contiguous US*, Environmental Science & Technology*, 55, 9129-9139, 10.1021/acs.est.0c07352, 2021.

McDonald, B. C., McBride, Z. C., Martin, E. W., Harley, R. A.: High-resolution mapping of motor vehiclecarbon dioxide emissions. *J. Geophys. Res.Atmos*. 119, 10.1002/2013JD021219, 2014.

McDonald, B. C., McKeen, S. A., Cui, Y. Y., Ahmadov, R., Kim, S.-W., Frost, G. J., Pollack, I. B., Peischl, J., Ryerson, T. B., Holloway, J. S., Graus, M., Warneke, C., Gilman, J. B., de Gouw, J. A., Kaiser, J., Keutsch, F. N., Hanisco, T. F., Wolfe, G. M., and Trainer, M.: Modeling Ozone in the Eastern U.S. using a Fuel-Based Mobile Source Emissions Inventory, *Environmental Science & Technology*, 52, 7360-7370, 10.1021/acs.est.8b00778, 2018a.

Harkins, C., McDonald, B. C., Henze, D. K., and Wiedinmyer, C.: A fuel-based method for updating mobile source emissions during the COVID-19 pandemic, *Environmental Research Letters*, 16, 065018, 10.1088/1748-9326/ac0660, 2021.

McDonald, B. C., de Gouw, J. A., Gilman, J. B., Jathar, S. H., Akherati, A., Cappa, C. D., Jimenez, J. L., Lee-Taylor, J., Hayes, P. L., McKeen, S. A., Cui, Y. Y., Kim, S.-W., Gentner, D. R., Isaacman-VanWertz, G., Goldstein, A. H., Harley, R. A., Frost, G. J., Roberts, J. M., Ryerson, T. B., and Trainer, M.: Volatile chemical products emerging as largest petrochemical source of urban organic emissions, *Science*, 359, 760-764, 10.1126/science.aaq0524, 2018b.

Coggon, M. M., Gkatzelis, G. I., McDonald, B. C., Gilman, J. B., Schwantes, R. H., Abuhassan, N., Aikin, K. C., Arend, M. F., Berkoff, T. A., Brown, S. S., Campos, T. L., Dickerson, R. R., Gronoff, G., Hurley, J. F., Isaacman-VanWertz, G., Koss, A. R., Li, M., McKeen, S. A., Moshary, F., Peischl, J., Pospisilova, V., Ren, X., Wilson, A., Wu, Y., Trainer, M., Warneke, C.: Volatile chemical product emissions enhance ozone and modulate urban chemistry, *Proc Natl Acad Sci*, 118 (32) e2026653118, 10.1073/pnas.2026653118, 2021

Coggon, M. M., Stockwell, C. E., Xu, L., Peischl, J., Gilman, J. B., Lamplugh, A., Bowman, H. J., Aikin, K., Harkins, C., Zhu, Q., Schwantes, R. H., He, J., Li, M., Seltzer, K., McDonald, B., and Warneke, C.: Contribution of cooking emissions to the urban volatile organic compounds in Las Vegas, NV, *Atmospheric Chemistry Physics*, 24, 4289-4304, 10.5194/acp-24-4289-2024, 2024.

Zhu, Q., Schwantes, R., Stockwell, C., Harkins, C., Lyu, C., Coggon, M., Yu, K., Warneke, C., Schnell, J., He, J., Pye, H., Li, M., Ahmadov, R., Pfannerstill, E., Place, B., Wooldridge, P., Schulze, B., Arata, C., Bucholtz, A., Seinfeld, J., Xu, L., Zuraski, K., Robinson, M., Neuman, J., Gilman, J., Lamplugh, A., Veres, P., Peischl, J., Rollins, A., Brown, S., Goldstein, A., Cohen, R.,

and McDonald, B.: Co-benefits of Zero-Emission Vehicle Adoption on CO2 Emissions and O3 Pollution in Los Angeles, *Nat. Sustain*, under review.

Granier, C., Darras, S., Denier van der Gon, H., Doubalova, J., Elguindi, N., Galle, B., Gauss, M., Guevara, M., Jalkanen, J.-P., Kuenen, J., Liousse, C., Quack, B., Simpson, D., Sindelarova, K.: The Copernicus Atmosphere Monitoring Service global and regional emissions (April 2019 version), 10.24380/d0bn-kx16, 2019

Other Relevant Publications

He, J., Harkins, C., O'Dell, K., Li, M., Francoeur, C., Aikin, K., Anenberg, S., Baker, B., Brown, S. S., Coggon, M. M., Frost, G. J., Gilman, J. B., Kongdragunta, S., Lamplugh, A., Lyu, C., Moon, Z., Pierce, B., Schwantes, R.H., Stockwell, C.E., Warneke, C., Yang, K., McDonald, B. C.: COVID-19 perturbation on US air quality and human health impact assessment. *PNAS Nexus*. 3 (1). https://doi.org/10.1093/pnasnexus/pgad483, 2024.

Li, M., McDonald, B. C., McKeen, S. A., Eskes, H., Levelt, P., Francoeur, C., Harkins, C., He, J., Barth, M., Henze, D. K., Bela, M. M., Trainer, M., de Gouw, J. A., & Frost, G. J.: Assessment of Updated Fuel-Based Emissions Inventories Over the Contiguous United States Using TROPOMI NO2 Retrievals. *Journal of Geophysical Research*: Atmospheres, 126(24), e2021JD035484. https://doi.org/10.1029/2021JD035484, 2021.

Zhu, Q., Schwantes, R. H., Coggon, M., Harkins, C., Schnell, J., He, J., Pye, H. O. T., Li, M., Baker, B., Moon, Z., Ahmadov, R., Pfannerstill, E. Y., Place, B., Wooldridge, P., Schulze, B. C., Arata, C., Bucholtz, A., Seinfeld, J. H., Warneke, C., Stockwell, C. E., Xu, L., Zuraski, K., Robinson, M. A., Neuman, J. A., Veres, P. R., Peischl, J., Brown, S. S., Goldstein, A. H., Cohen, R. C., and McDonald, B. C.: A better representation of volatile organic compound chemistry in WRF-Chem and its impact on ozone over Los Angeles, *Atmos. Chem. Phys*., 24, 5265-5286, https://doi.org/10.5194/acp-24-5265-2024, 2024.

Vertical Grid Information

The altitude above ground level corresponding to the vertical grid in these emission files is spatially varying but the average altitude range of each vertical level in the domain is listed below.

Table 3: Vertical level information

Vertical Level	Height above Ground Level Range
Level 0	0-23 meters
Level 1	23-47 meters
Level 2	47-74 meters
Level 3	74-103 meters
Level 4	103-136 meters
Level 5	136-173 meters
Level 6	173-214 meters
Level 7	214-261 meters
Level 8	261-313 meters
Level 9	313-372 meters
Level 10	372-440 meters
Level 11	440-515 meters
Level 12	515-603 meters
Level 13	603-701 meters
Level 14	701-814 meters
Level 15	814-940 meters
Level 16	940-1083 meters
Level 17	1083-1244 meters
Level 18	1244-1425 meters
Level 19	1425-1627 meters

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