Comparison of global high-resolution fossil fuel CO_2 emissions data products to Vulcan v4.0: sector differences and methodological guidance

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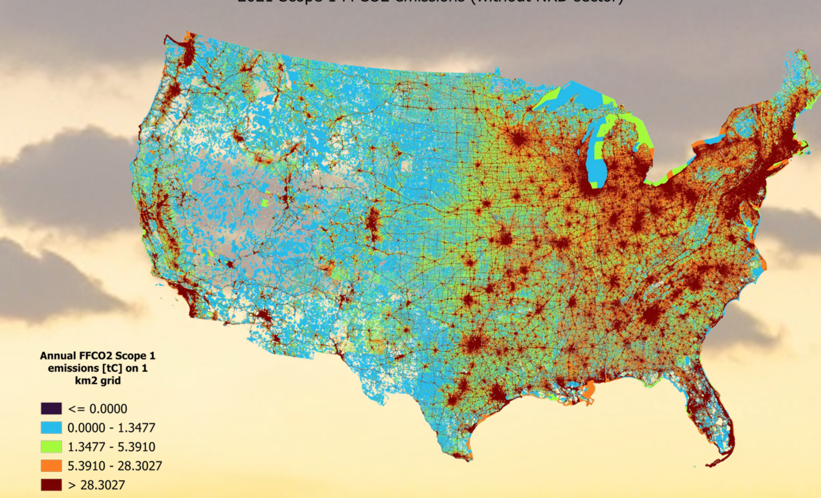
Vulcan v4

The Vulcan v4 (successor to Vulcan v3) is nearing public release (Gurney et al., 2020). Vulcan v4 quantifies all fossil fuel CO2 emissions in the US by sector, fuel, technology and attributes down to the spatial resolution of points, lines, and polygons (US Census blocks) for every hour from 2010 to 2021 (with 2022 added soon).

Vulcan follows an activity-based approach and draws from roughly two dozen federal datasets optimizing and harmonizing overlapping data elements. It has been compared to atmospheric CO2 inversions at the national and urban scales showing consistency (within 1.4% and 3% respectively) [Basu et al., 2020; Lauvaux et al., 2019].

Here, we compare Vulcan output with two recently produced global data products, **Climate Trace** and **GRACED**. We use a series of standard statistics for comparing totals and spatial results. Our aim is to assist and illuminate discrepancies and improvement pathways for all granular $FFCO_2$ estimation efforts.

2021 Scope 1 FFCO2 emissions (without NRD sector)



Vulcan v4 versus Climate Trace powerplants

Climate Trace, co-founded and promoted by former Vice President Al Gore, is a new effort using, in part, artificial intelligence (AI) approaches to estimate asset-scale GHG emissions. Climate Trace recently released a database of global powerplant CO2 emissions at the facility-scale that uses both AI and non-AI estimation approaches [Freeman et al., 2023].

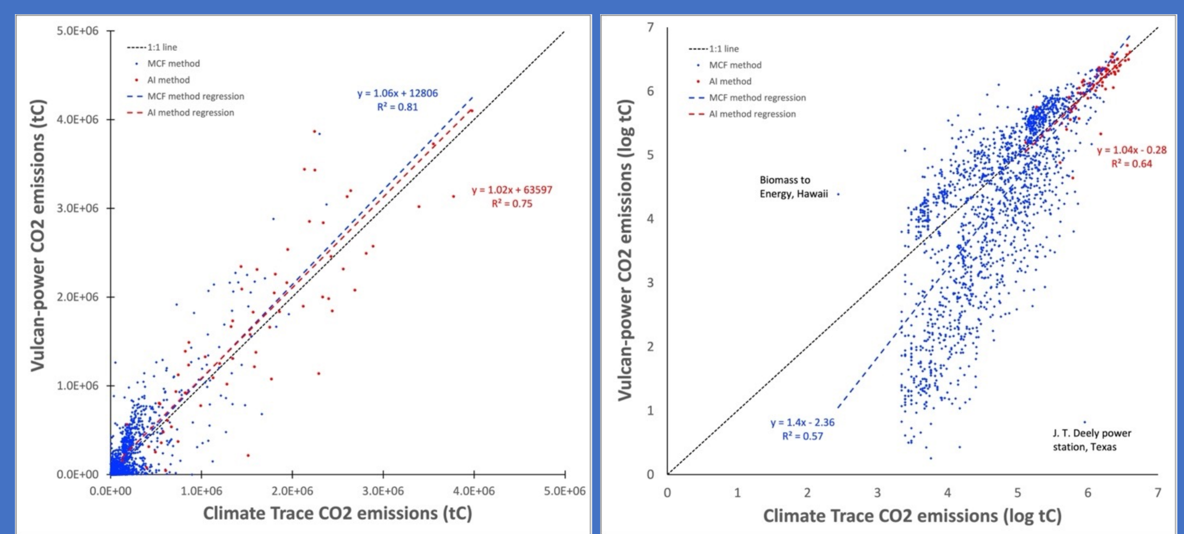
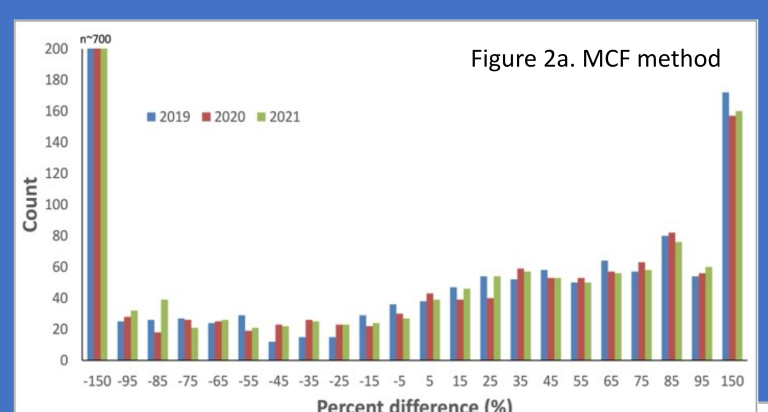


***Figure 1.** Comparison of facility-scale Vulcan v4.0 to Climate Trace powerplant carbon dioxide emissions in the year 2019. a) unscaled paired emissions, 1:1 line (solid black) and regression line/equation (dashed blue) included; b) log-scaled paired emission values. Red symbols: Facilities estimated with AI techniques by Climate Trace ("AI method"). Blue symbols: Facilities estimated with non-AI techniques ("MCF method").*

***Table 1.** comparison statistics for the paired power plant facilities in the Climate Trace and Vulcan-power datasets.**

Approach	Year	N pairs	Total emit CT (tC)	Total emit Vulcan (tC)	TD (MtC)	TRD (%)	MD (tC)	MAD (tC)	MRD (%)	MRD StDev (%)	SD (MtC)	SAD (MtC)	Pearson Correlation
AI method	2019	65	106.33	112.68	-6.35	-5.8%	97650	421190	-1.1	46.4	6.3	27.4	0.87
	2020	62	89.15	93.30	-4.14	-4.5%	66821	380493	-3.1	42.1	4.1	23.6	0.85
	2021	60	98.06	104.36	-6.30	-6.2%	104999	409442	-0.2	38.6	6.3	24.6	0.84
MCF method	2019	1682	243.33	281.82	-38.49	-14.7%	22885	102505	**-49.4**	117.7	38.5	172.4	0.83
	2020	1685	226.50	263.33	-36.83	-15.0%	22252	103382	**-50.5**	116.9	27.3	171.1	0.80
	2021	1687	233.61	271.00	-37.40	-14.8%	22816	98127	**-46.2**	114.0	30.0	160.8	0.85

[a] differences are calculated as Climate Trace minus Vulcan-power
TD = total emission difference
TRD = total emission relative difference
MD = mean facility difference
MAD = mean absolute facility difference
MRD = mean facility relative difference: Calculated as (CT-Vulcan)/avg(CT,Vulcan)
SD = summed facility difference
SAD = summed absolute facility difference



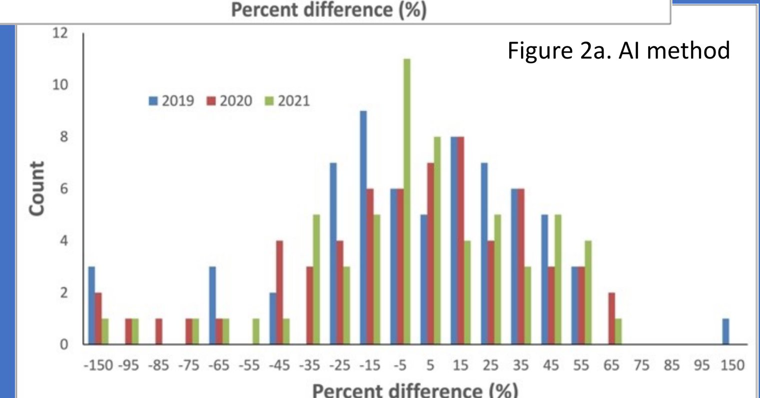


Figure 2a-b shows the frequency distribution of individual facility paired relative differences using the MCF method. Many paired differences (>700) are greater than the -95% relative difference frequency bin. Similarly, many paired differences are greater than the +95% relative difference frequency bin. The much larger negative individual relative difference values account for the large negative mean relative difference (-49.4% for the year 2019 – see Table 1).

Figure 2b shows the same but for the facilities that used the AI method. Here, agreement is much improved with a mean relative difference (-1.1% - see Table 1)

Why the large differences?

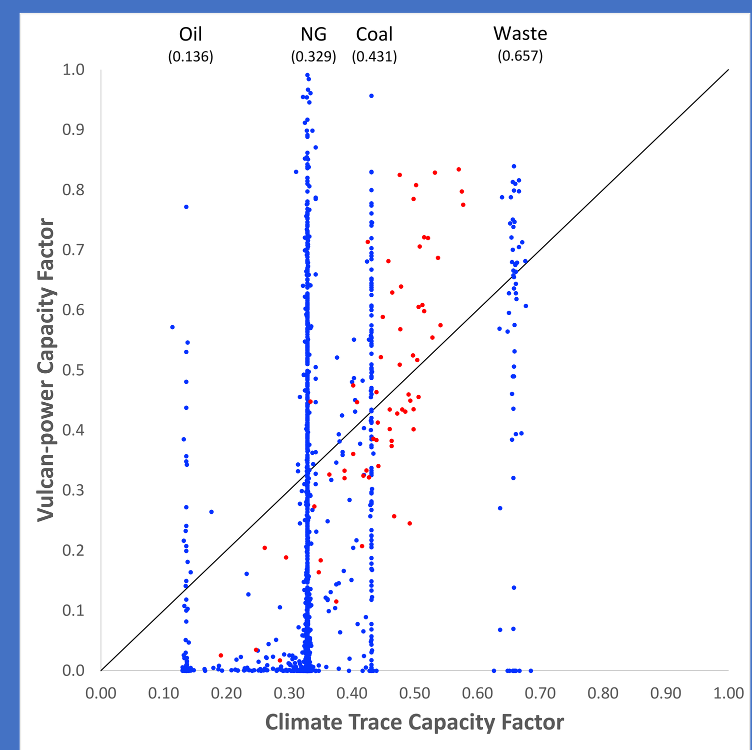


Figure 3. Comparison of individual US power plant capacity factors from Vulcan-power (y-axis) and the Climate Trace (x-axis). Red and blue symbols represent the AI versus MCF Climate Trace estimation method, respectively.

Noted on the figure are the mode values from the frequency distribution of Climate Trace capacity factors and the associated dominant fuel type.

Capacity factor = generation/maximum generation

Or percent of maximum output

Figure 3 shows the Climate Trace versus Vulcan power plant capacity factors. The country-average capacity factors used by Climate Trace for each fuel type category (i.e. coal, oil, natural gas, waste) is evident from the large number of individual facilities with an identical capacity factor. These facilities are nearly all estimated using the MCF method. The second group of paired facilities (red) showing greater correspondence are dominated by facilities estimated using the AI method or represent a combustion fuel mix (and hence, averaging of multiple fuel type-specific capacity factors occurred).

Figure 4a-d shows the frequency distribution of Vulcan capacity factors by fuel type (coal, NG, oil, waste). On each panel is the apparent Climate Trace capacity factor. In the case of natural gas and oil, the apparent Climate Trace capacity factor does not capture the dominant mode value (bias). In the case of coal and waste burning facilities, the Climate Trace apparent capacity factor is closer to the distribution mode. Regardless of whether or not the mean Climate Trace capacity factor value comes close to the reported mean/mode of the capacity factor distribution, the use of a single mean value will miss the individual facility variation and hence, is inadequate for individual facility emissions estimation.

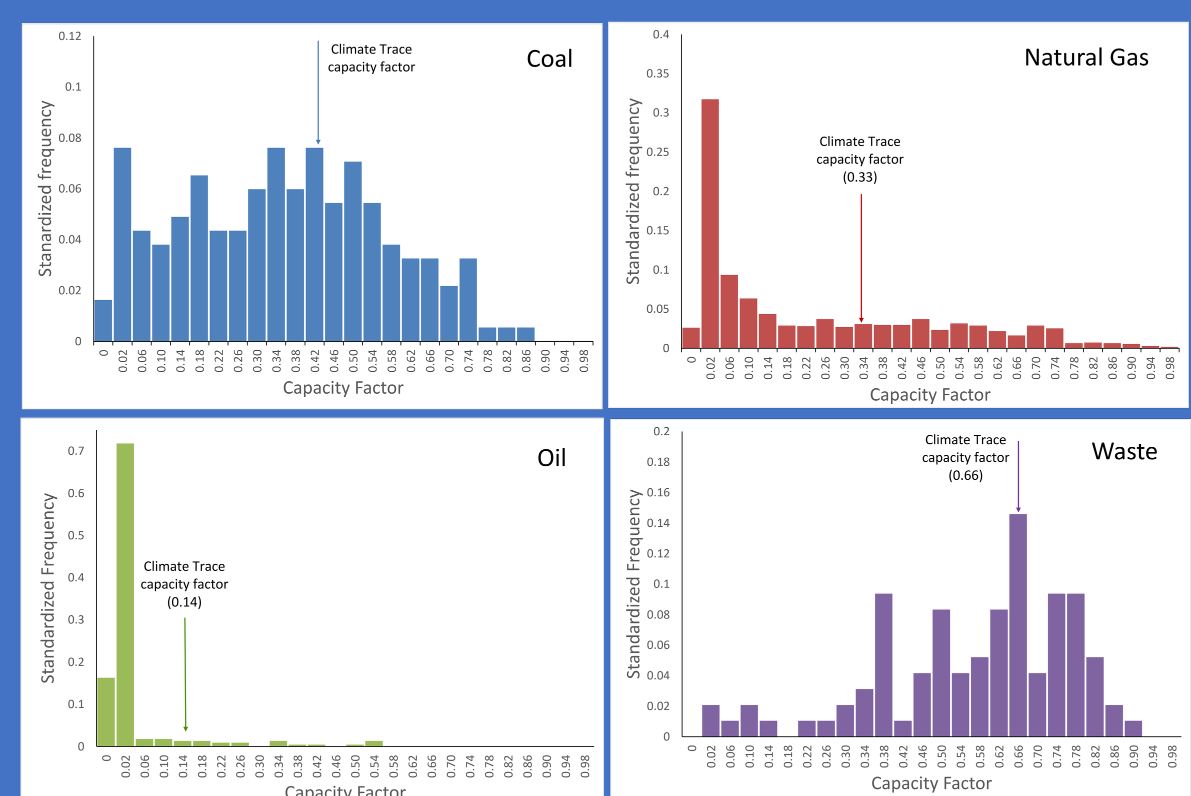


Figure 4. Frequency distribution of Vulcan-power capacity factors versus Climate Trace capacity factors for non-AI estimate power plant facilities in the US.

Vulcan v4 versus GRACED

The Global Gridded Daily CO2 Emissions Dataset (GRACED) is a near real time FFCO2 (and cement) emissions estimate with a spatial resolution of 0.1 x 0.1 and a temporal resolution of one day (Dou et al., 2022).

It is based on the daily national CO2 emissions from the Carbon Monitor data product, the spatial patterns of point source emission dataset Global Energy Infrastructure Emissions Database (GID), Emission Database for Global Atmospheric Research (EDGAR), and spatiotemporal patters of satellite nitrogen dioxide (NO2) retrievals.

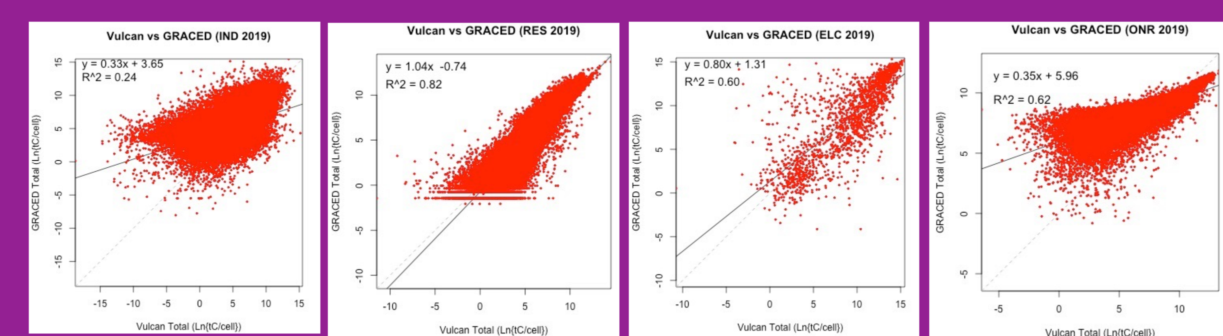
***Table 2.** comparison statistics for the paired gridcells in the GRACED and Vulcan V4 datasets.**

2019	TRD(%)	SAD(MtC)	SADFT(%)	SC[no 0]	GAMRD	difference	Vulcan	GRACED
RES	6.55%	88.51	57.8%	0.81[0.83]	0.81	10.4	153.2	163.6
IND	31.9%	315.1	162%	0.19[0.19]	1.44	73.9	194.7	268.6
ONR	6.36%	369.3	88.5%	0.86[0.87]	1.39	27.4	417.4	444.8
ELC	-8.18%	328.5	70.1%	0.76[0.80]	1.22	-36.8	468.7	431.9
TOT	5.89%	850.5	68.9%	0.72[0.73]	1.30	75	1234	1309

[a] differences are calculated as GRACED minus Vulcan V4.

The GRACED total across all of the comparable emissions sectors is larger (+5.9%) than the Vulcan estimates other than electricity production (-8.2% smaller). On a relative and absolute magnitude basis, the industrial sectors shows the largest difference.

On a gridcell basis, larger differences emerge. In general Vulcan shows a larger range of values, particularly for smaller emitting gridcells. The residential sector shows the greatest correlation (R2=0.82 while the industrial sector shows the smallest (R^2=0.24).



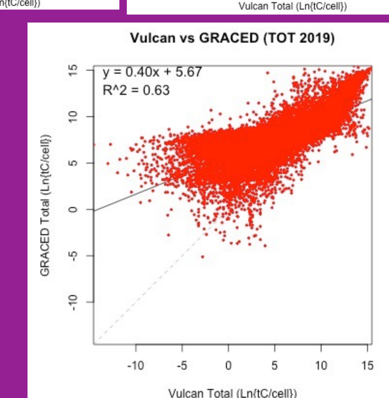


Figure 5. Comparison of paired gridcells from Vulcan V4 (x-axis) and GRACED (y-axis) for the four comparable sectors and the total. All plots use a natural log transformation.

Regression equation and R^2 values are provided.

Vulcan v4 versus GRACED continued

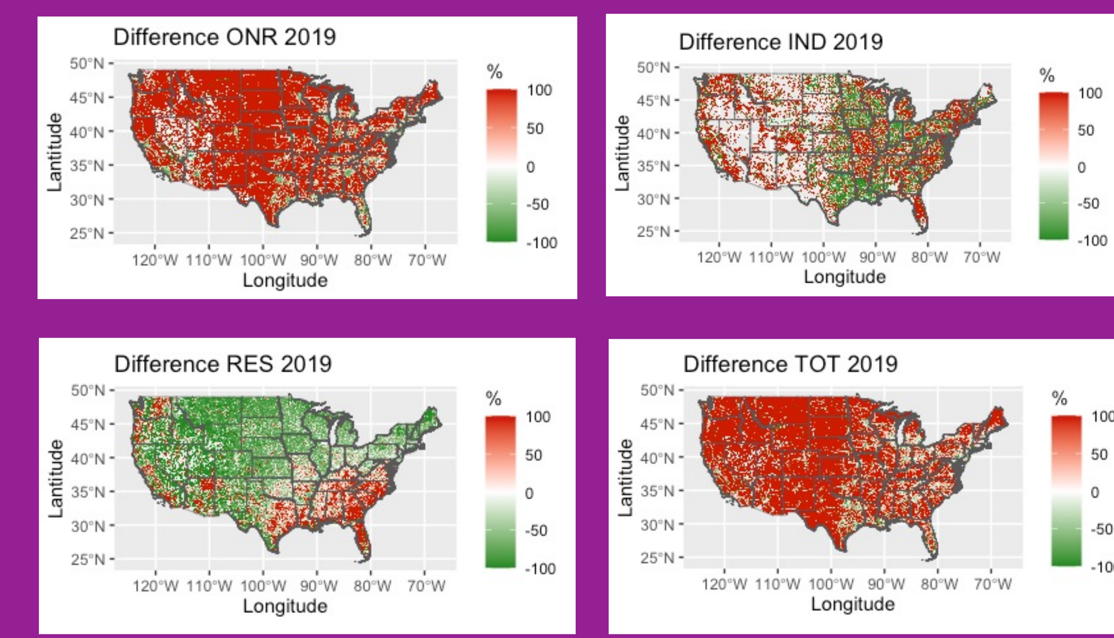


Figure 6. Gridcell by gridcell relative difference between the Vulcan V4 and GRACED data products for three sectors (electricity production not shown) and the total. Difference calculated as GRACED – Vulcan/(average(GRACED,Vulcan).

The difference maps (Figure 6) show systematic spatial patterns. In the onroad sector, GRACED has larger values through the rural dominated gridcells but generally smaller values in urban areas. This suggests a non-optimal allocation scheme between rural versus urban roadways.

The residential sector difference map shows the influence of the GRACED spatialization approach using the HDD/CDD metric. The positive/negative dipole is reminiscent of the winter mean North American Temp gradient (warm areas overestimating, cold areas underestimating emissions).

CONCLUSIONS:

The Climate Trace comparison provides 2 conclusions:

1) The mean capacity factor approach is inadequate to estimate individual power plant CO2 emissions.
2) Climate Trace power plant CO2 estimation is not ready to be used by stakeholders.

The GRACED comparison shows:

1) The onroad spatialization method has a large urban/rural bias.
2) The residential/commercial spatialization method needs additional spatial allocation information beyond the use of HDD/CDD.

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