Supporting Information for "Measuring carbon dioxide emissions from liquefied natural gas terminals with imaging spectroscopy"

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1. Table S2: Emission rate estimates of power plant CO_2 emission events.

Introduction

The Supporting Information provides detailed information of our method in the steps of CO_2 plume identification, artifacts masking and parameter values determination. It also contains the emission rate estimate results of both the power plant and the LNG terminal emissions dataset, and the life-cycle carbon intensity results of the LNG terminals.

Text S1. CO_2 plume identification

During detection, the CO_2 enhancement imagery resulted from column retrieval is then analyzed manually to identify the presence of a CO_2 plume. During this step, a Red, Green, Blue (RGB) image is generated from raw radiance data, and hourly wind data of this area is collected from the Dark Sky API (Apple Inc., 2023). The criteria to determine the presence of a CO_2 plume are as follows. First, the potential plume exhibits clear proximity to the known CO_2 emitting facility. Second, the potential plume demonstrates a clear shape that distinguishes it from surface feature artifacts, with its direction aligned with the wind direction, estimated from wind reanalysis data at the time of measurement. Finally, the potential plume shows a decrease in α values along the wind direction from its origin, indicating a gas diffusion effect. Based on the plume shape, the α values and the location of the point source infrastructure, the plume origin is also determined for further quantification purposes.

Text S2. Artifact masking

The artifact masking process aims to remove certain artifacts in close proximity to the plume source, such as roofs with white paint and gas flaring. These features can lead to high CO_2 mass enhancement due to the SWIR absorption by hydrocarbon from oil-based paints. The masking process consists of two steps. The first step masks out roof pixels with white paint based on their top-of-atmosphere reflectance values, and the second step masks out flaring effect by their radiance values. However, excluding these pixels from quantification may introduce low bias to the results if the emission is present at the same location of the artifacts. In this case, the CO_2 enhancement of these pixels is not only from artifacts – part of it is also from CO_2 emissions. Thus, excluding these pixels from quantification would lead to a smaller integrated mass enhancement (IME) of the CO_2 plume. If the plume length is not affected by this masking process (i.e., r_c is the same), then a low bias of the emission rate estimate would occur. How much the bias is depends on the plume IME and the IME of the excluded pixels resulted from emissions. One potential way of estimating the IME of the excluded pixels from emissions is to estimate the CO_2 enhancement of these pixels from artifacts. This could be achieved if we have spectroscopy data in the same area at another time with no emissions. However, because the CO_2 enhancement from multiple sources at the same location is not a simple summation of the CO_2 enhancement from each source, it is way more complex to estimate the IME from emissions based on the CO_2 enhancement from artifacts of the same pixels. Thus, erasing the low bias resulted from artifact pixels is out of scope of this study. Note that the low bias may explain the underestimation tendency of the power plant dataset emission rate estimation in this study.

Text S3. Quantification parameters

During quantification, we define that the pixels with their mix ratio length α within the range $\alpha_l - \alpha_h$ are CO_2 plume pixels. Therefore, the pixels outside this range are excluded from quantification. In this range, the lower bound (the minimum threshold) α_l is important as the pixel values above it are considered as strong CO_2 signals. Since different emission events may have different plume enhancements (strong/not strong CO_2

signals) and different background (noisy/not noisy), the α_l value should be adjusted accordingly. Therefore, α_l is defined as the median value of all the non-negative pixel values in the enhancement image to fit the enhancement distribution of each emission event. In our dataset, its value varies in 5,700-27,000 ppm-m. Additionally, the CO_2 plume pixel enhancement rarely exceeds 400,000 ppm-m in our dataset. So we define an upper bound (the maximum threshold) α_h as high as 900,000 ppm-m to ensure that all the CO_2 plume pixels are included in our mix ratio length range.

We also define a merge distance to allow for the presence of gaps (i.e., low CO_2 enhancement pixels) within the plume. Practically, a greater merge distance would introduce more low CO_2 enhancement pixels into quantification to ensure a complete plume shape. But more background noise could be included as well if the merge distance value becomes too high. We tested multiple values (e.g., 5 m, 10 m, 20 m and 30 m), and the plume figures based on 20 m show the most complete and clearest plume shapes with the least noise. So 20 m is used for all the emission events in this study.

References

Apple Inc. (2023). *Dark Sky API.* `https://darksky.net/dev`.

Cusworth, D. H., Duren, R. M., Thorpe, A. K., Eastwood, M. L., Green, R. O., Dennison, P. E., ... Miller, C. E. (2021). Quantifying global power plant carbon dioxide emissions with imaging spectroscopy. *AGU Advances*, *2*(2), e2020AV000350. doi: https://doi.org/10.1029/2020AV000350

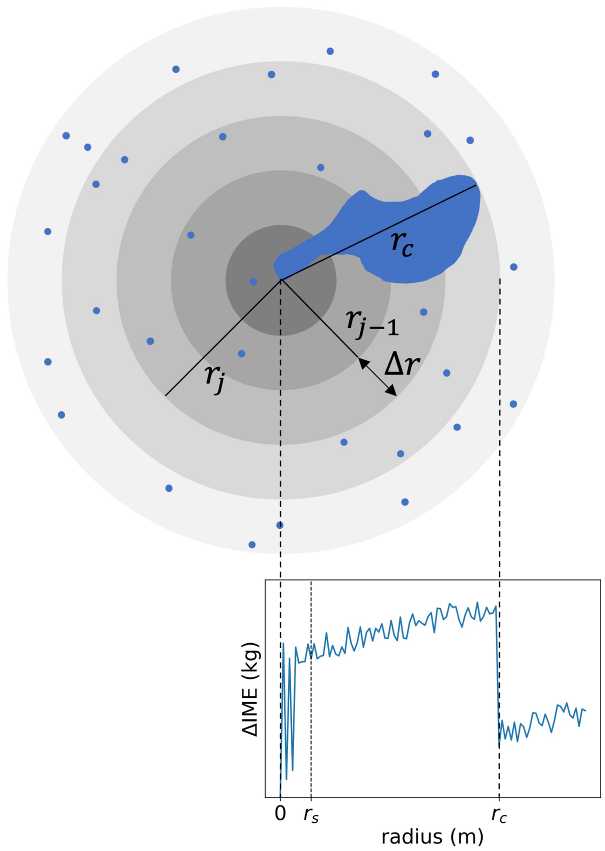

Figure S1. Illustration of the fetch radius calculation.

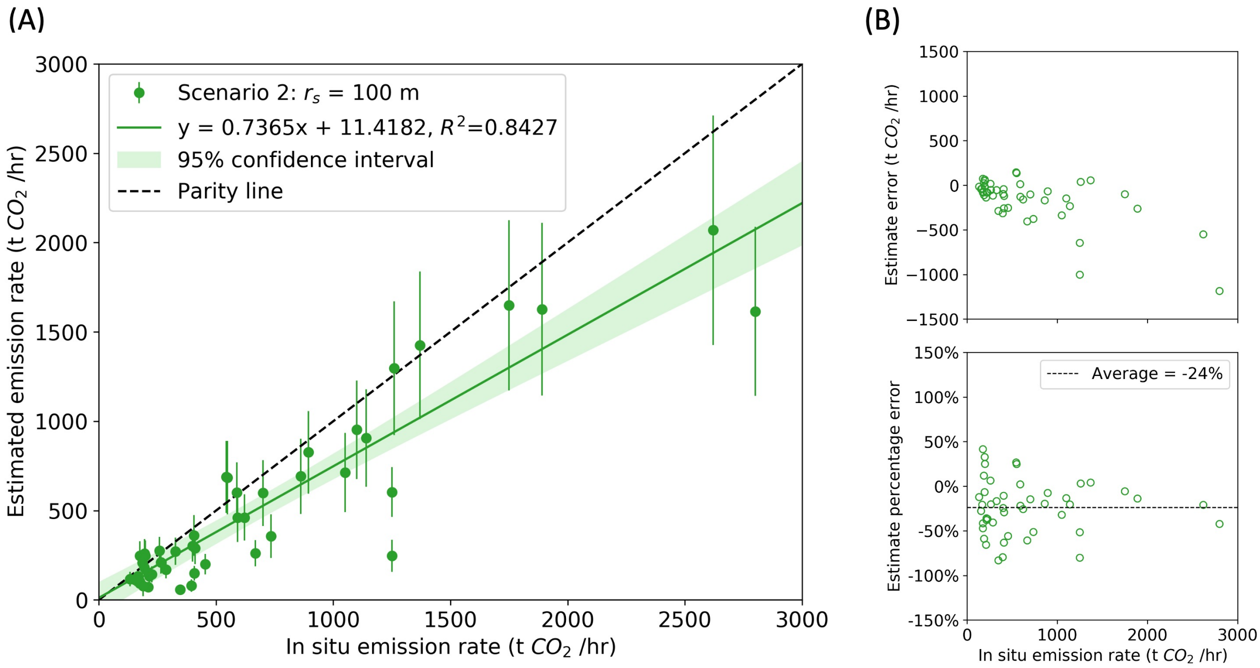

Figure S2. Power plant emission rate estimates compared to *in situ* emission rates in scenario 2: $r_s = 100$ m. (A): Emission rate estimates with ordinary least squares regression results. (B): Emission rate estimation errors.

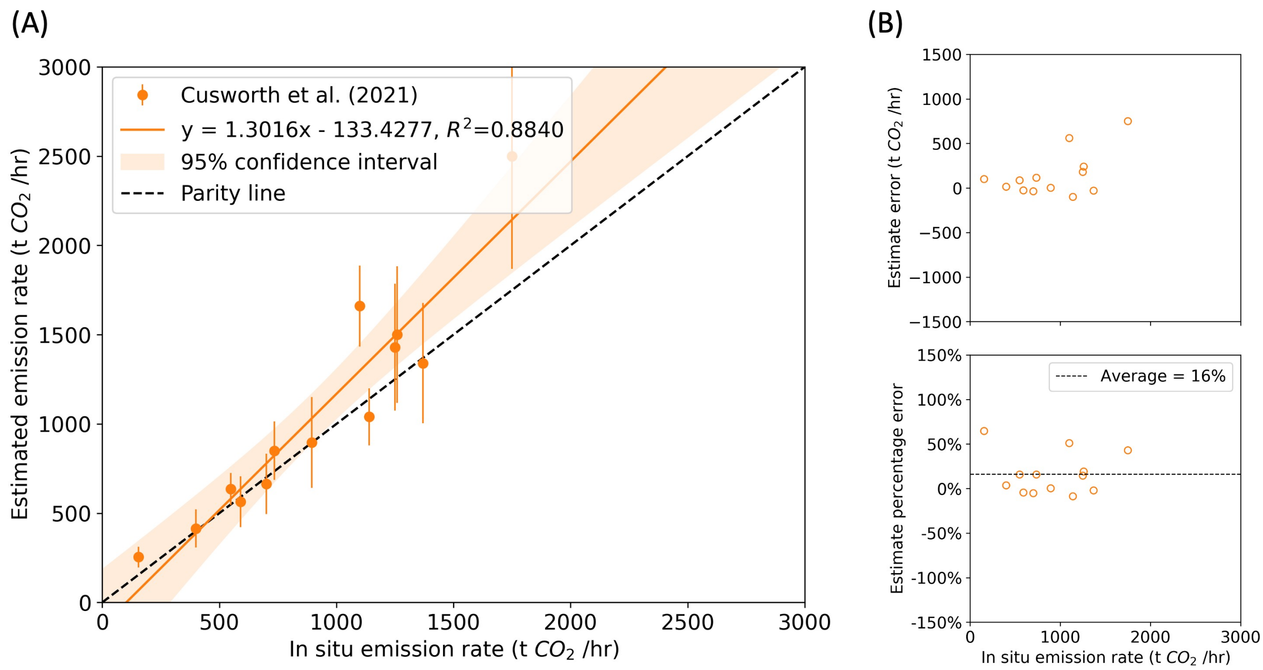

Figure S3. Power plant emission rate estimates from Cusworth et al. (2021) compared to *in situ* emission rates. (A): Emission rate estimates with ordinary least squares regression results. (B): Emission rate estimation errors.

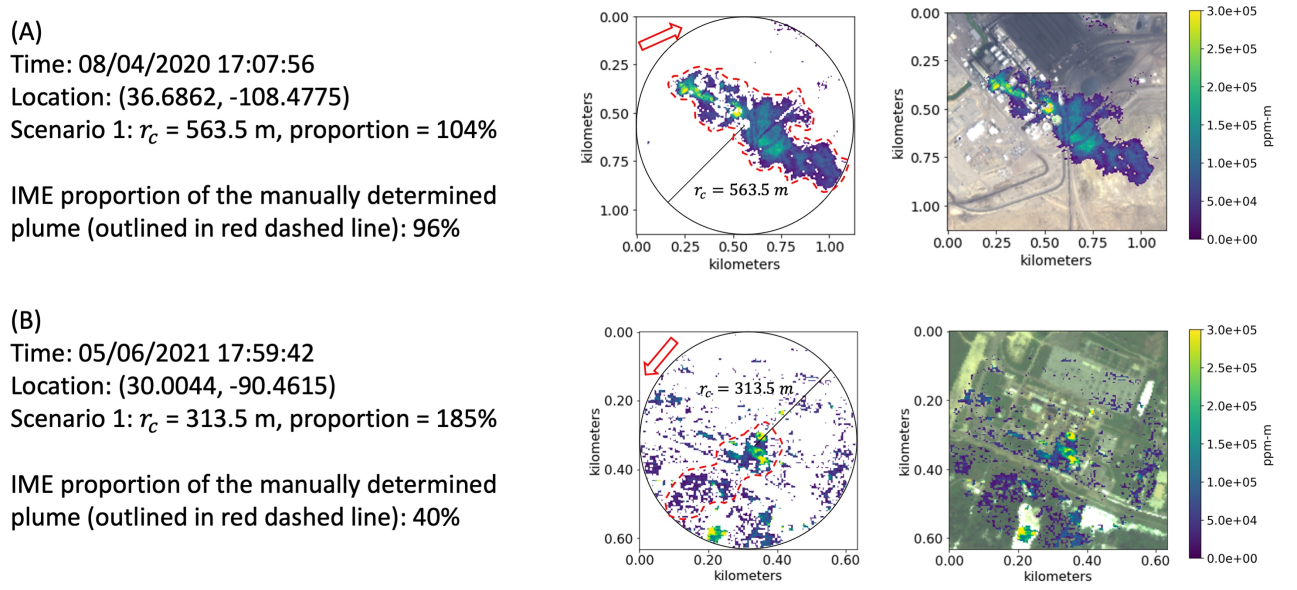

Figure S4. Examples of background noise effect on plume quantification. The manually determined plume is outlined by red dashed line based on the pixel values and wind direction (red angle). The pixels outside the red dashed line are likely to be background noise. (A) is the same example as Figure 1 of the main paper, where background noise has a negligible effect on its emission rate estimation; (B) is an example of overestimation due to a large proportion of background noise included into quantification.

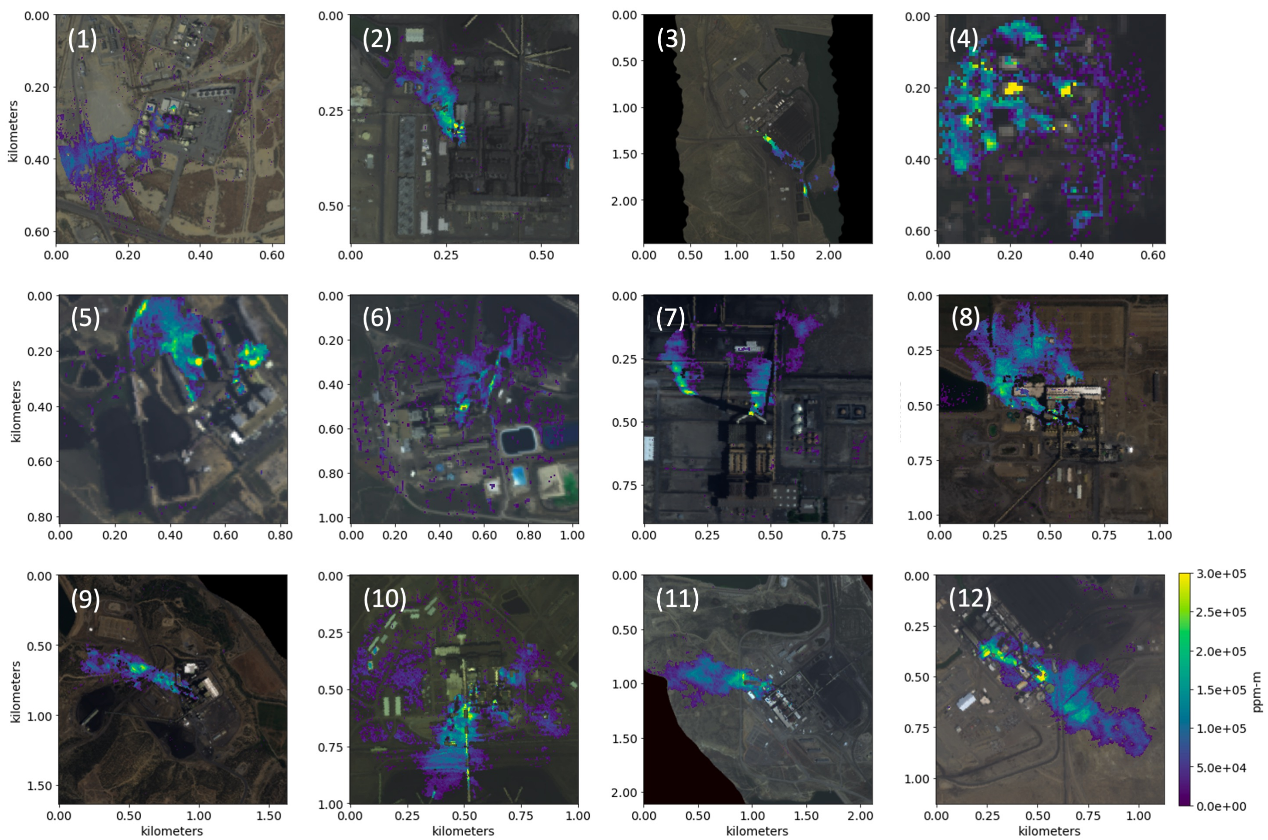

Figure S5. Power plant dataset plume figures (1)-(12).

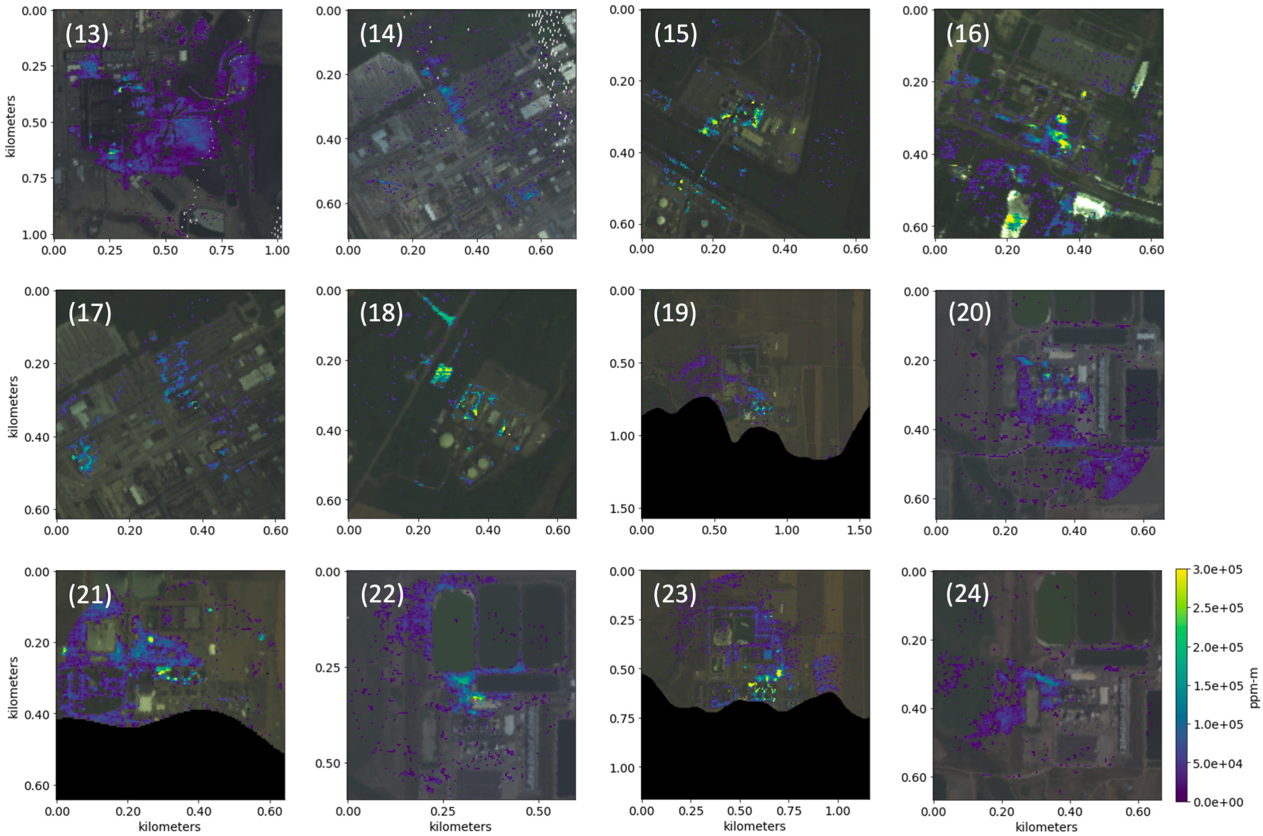

Figure S6. Power plant dataset plume figures (13)-(24).

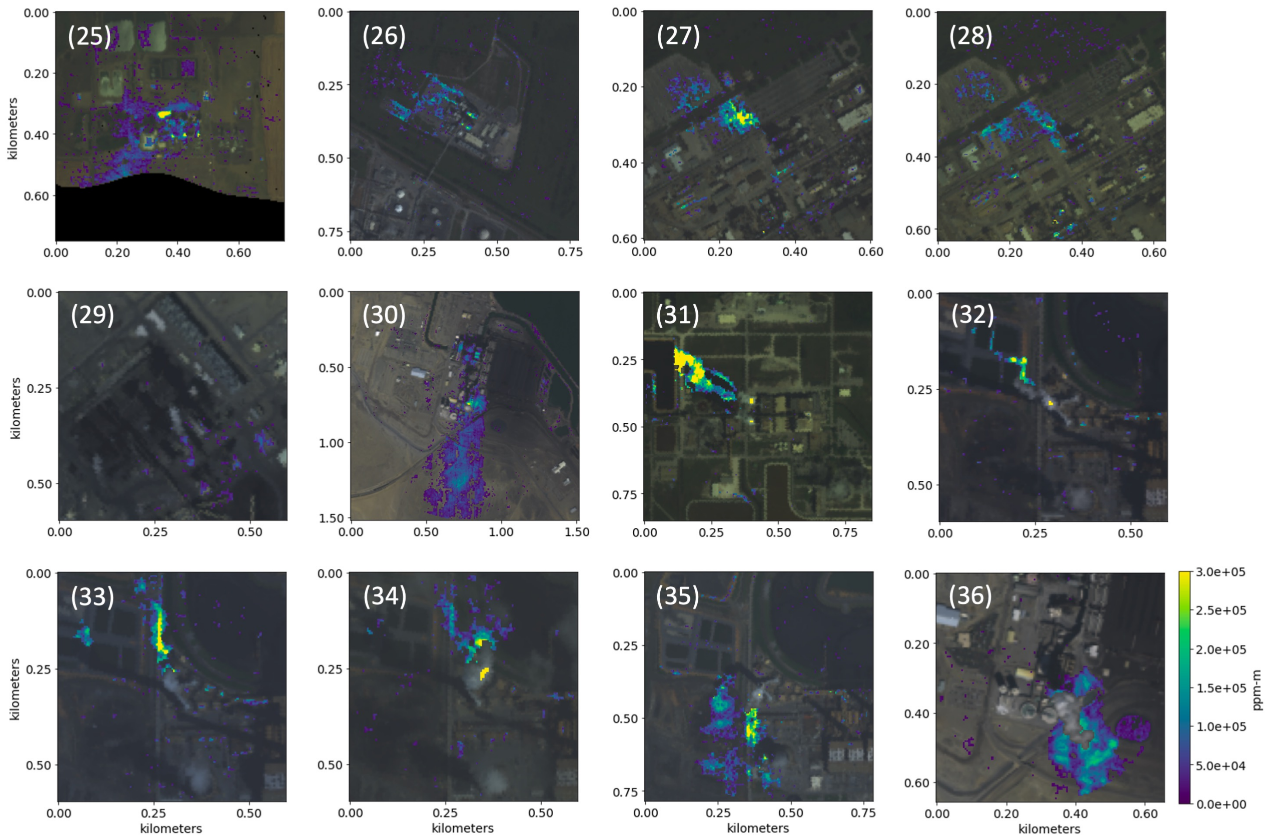

Figure S7. Power plant dataset plume figures (25)-(36).

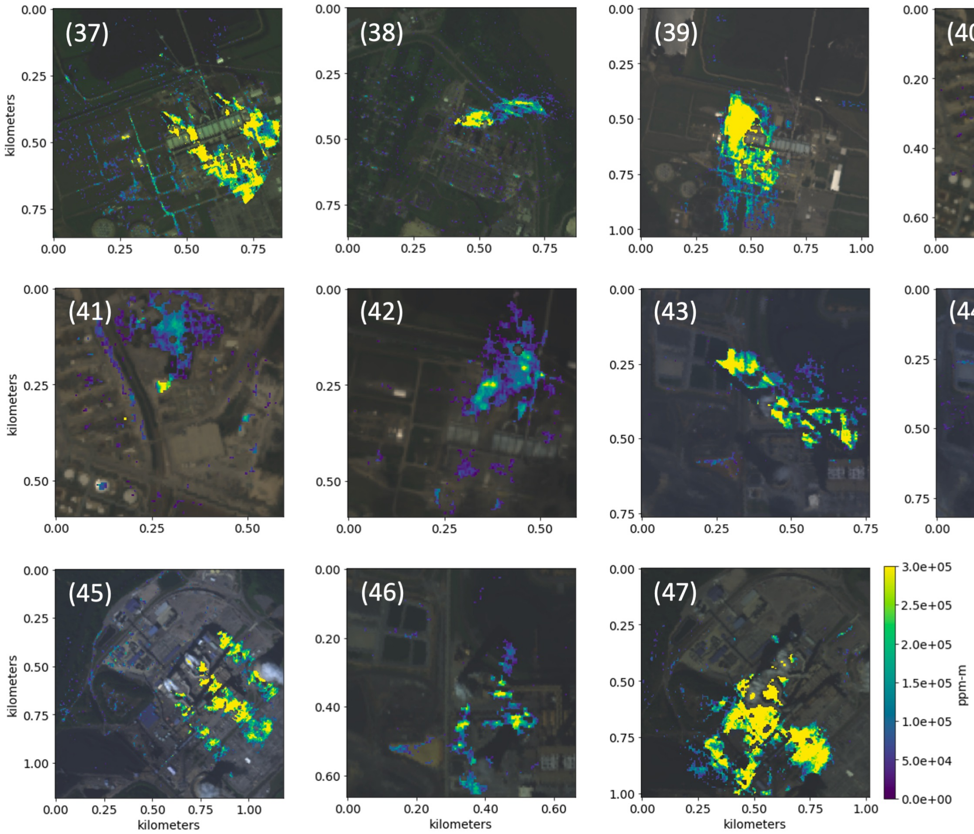

Figure S8. Power plant dataset plume figures (37)-(47).

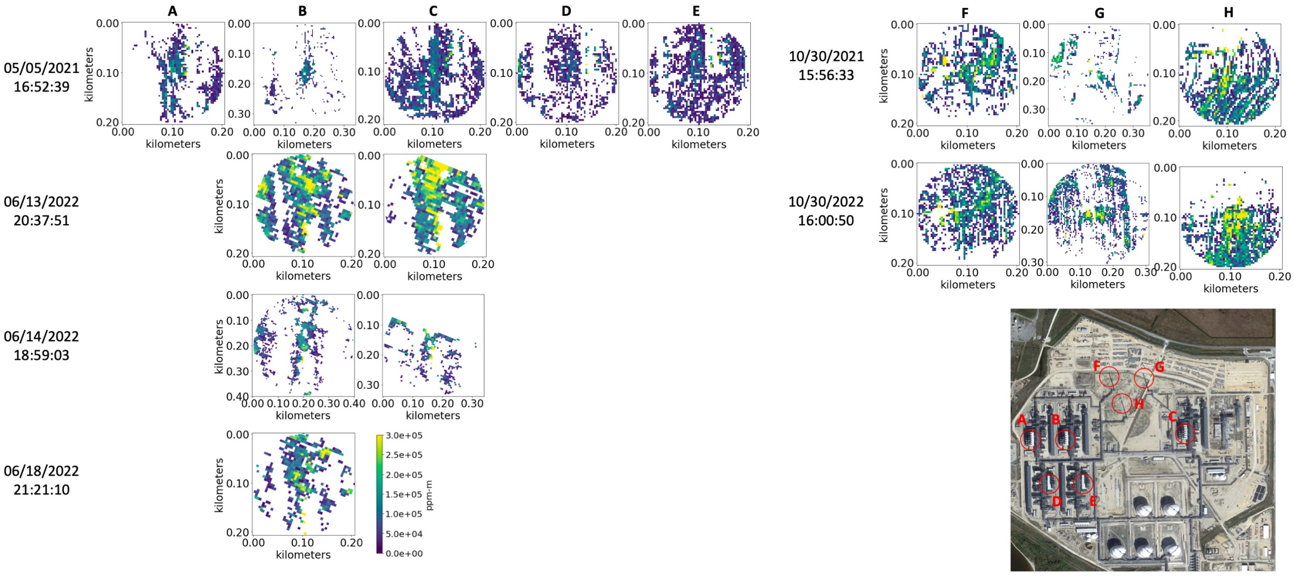

Figure S9. Sabine Pass LNG terminal plume figures.

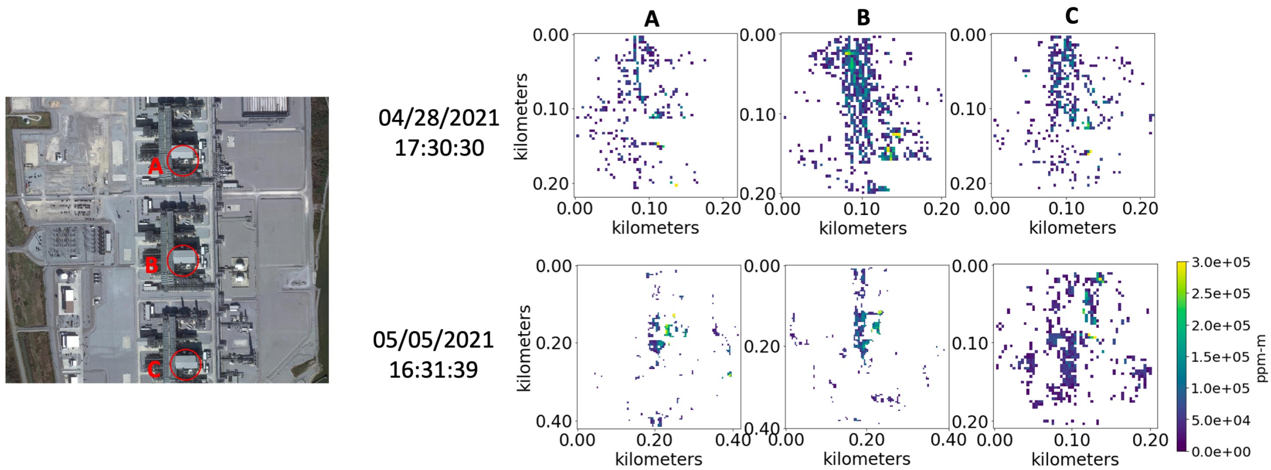

Figure S10. Cameron LNG terminal plume figures.

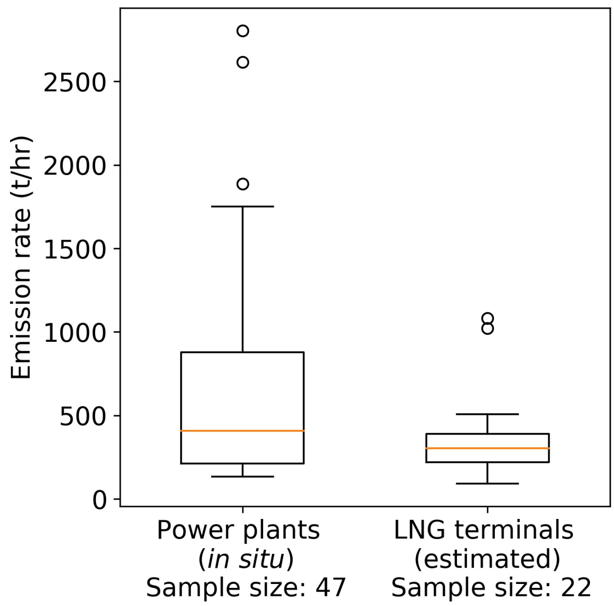

Figure S11. Box plots of the emission rate estimates for power plants and LNG terminals.

Table S1. Summary of existing industrial-scale LNG export terminals in the U.S.

Terminal	State	Exports (average of Jan-Jun 2022, Bcf/d)[a]	#Liquefaction trains	Operator
Sabine Pass	LA	4.05	6	Cheniere Energy
Corpus Christi	TX	2.09	3	Cheniere Energy
Cameron	LA	1.80	3	Sempra LNG
Freeport	TX	1.66	3	Freeport LNG Development, L.P.
Cove Point	MD	0.73	1	Berkshire Hathaway BHE GT&S
Calcasieu Pass/Venture Global	LA	0.52	18	Venture Global LNG
Elba Island	GA	0.29	10	Kinder Morgan

[a]The exports average is calculated from January to June 2022 instead of the whole year because of the eight-month full shutdown of Freeport due to a pipeline explosion in June 2022.

Table S3. Emission rate estimates of LNG terminal CO_2 emission events.

Terminal	Point source	Timestamp (UTC)	Emission rate estimate (t/hr)	2-sigma uncertainty (t/hr)
Sabine Pass	A	05/05/2021 16:52:39	224.34	62.95
	B	05/05/2021 16:52:39	269.59	77.89
		06/13/2022 20:37:51	1022.65	280.10
		06/14/2022 18:59:03	426.75	125.28
		06/18/2022 21:21:10	378.19	96.50
	C	05/05/2021 16:52:39	393.18	107.97
		06/13/2022 20:37:51	1083.22	308.06
		06/14/2022 18:59:03	323.61	99.28
	D	05/05/2021 16:52:39	219.69	54.95
	E	05/05/2021 16:52:39	283.89	72.41
	F	10/30/2021 15:56:33	335.16	85.98
		10/30/2022 16:00:50	378.25	103.22
	G	10/30/2021 15:56:33	247.75	84.62
		10/30/2022 16:00:50	344.55	108.11
	H	10/30/2021 15:56:33	431.32	122.71
		10/30/2022 16:00:50	508.44	137.29
Cameron	A	04/28/2021 17:30:30	100.13	26.39
		05/05/2021 16:31:39	180.53	52.85
	B	04/28/2021 17:30:30	265.61	67.80
		05/05/2021 16:31:39	195.08	58.20
	C	04/28/2021 17:30:30	154.33	43.43
		05/05/2021 16:31:39	91.64	25.81

Table S4. LNG terminal carbon intensity estimation

Terminal	Date	Emission rate (t/hr)	Exports (Mcf)	CI (g CO_2 eq/MJ)
Sabine Pass	05/05/2021	1390.69	3446252	9.18
	10/30/2021	1122.73[a]	3632365[b]	7.03
	06/13/2022	2105.87	3693437	12.97
	06/14/2022	750.36	3697785[c]	4.62
	06/18/2022	378.19	3505148	2.45
Cameron	04/28/2021	520.06	3517943[d]	3.36
	05/05/2021	467.24	3654576	2.91

[a]The emisson rate estimate is the average of two overpasses at the same day. [b,c,d]The exports data is at the closest date after the emission event (10/31/2022, 06/15/2022, 04/30/2021, respectively).