Supporting Information for

Methane Emissions from Superemitting Coal Mines in Australia Quantified Using TROPOMI Satellite Observations

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Supporting information includes:

24 pages; 5 sections; 6 figures; 4 tables; and 1 animation
Section S1: Uncertainty estimates and sensitivity analysis

We compute the uncertainty in the daily emission rate by accounting for (a) the uncertainty in the mean enhancement due to variation in XCH₄ across each valid transect and in the upwind background (equation 1a), and (b) the uncertainty in the pressure-weighted average boundary layer ERA5 wind speed. We also account for an additional uncertainty of 16% (0.17/1.05) in the effective wind speed based on the relation \( U_{\text{eff}} = (1.05 \pm 0.17)U_{\text{blh}} \) derived by Varon et al.,¹ These uncertainties are represented as relative standard deviations (RSD) i.e., the ratio of the standard deviation to the mean (\( \sigma/\mu \)) and added in quadrature to compute the uncertainty in the daily emission rate (equation 1b). To calculate the uncertainty in the two-year mean emission rates, we combine the uncertainty of individual emission rates as shown below in equation 1c:

\[
\sigma_{\text{enhancement}} = \sqrt{\sigma_{\text{transect}}^2 + \sigma_{\text{background}}^2} \quad (1a)
\]

\[
RSD_{ij} = \sqrt{RSD_{\text{enhancement}}^2 + RSD_{\text{windspeed}}^2 + RSD_{U_{\text{eff}}-U_{\text{blh}}}^2} \quad (1b)
\]

\[
\sigma_j = \sqrt{\frac{\sum_i^n (Q_{ij} \times RSD_{ij})^2}{n^2}} \quad (1c)
\]

where \( \sigma_j \) is the one standard deviation of the mean emission estimate of the \( j^{th} \) source. \( RSD_{ij} \) is the error on individual daily source rates \( Q_{ij} \), where \( i \) represents one out of \( n \) orbits containing source \( j \).

The uncertainty in the source rate includes uncertainties from the emission flux calculated across each valid transect in a plume as it reflects the variability in source enhancement sampled at different intervals. We estimate relative standard deviations as high as 98% in the daily emission source rate for non-negative enhancements. This uncertainty range was found to be even higher (>100%) for lower source rates, in this case less than 10 t hr⁻¹, similar to that found in Varon et al.². Such high uncertainties can be explained by the selection of background observations, as other potential methane sources in the background area increase the spread of XCH₄ observations, increasing the uncertainty in the mean background XCH₄. Secondly, for <20 pixels in the upwind background, the median of the domain is used as mean XCH₄ background, which may introduce large uncertainties. The error in the wind speed has contributions from the hourly representation of the ERA5 winds, and the coarse resolution (0.25° × 0.25°) of the meteorology datasets. The
relative standard deviation in daily source rates due to windspeed variations within ± 2 hours of the overpass time amounts to 48%.

To further test the robustness of our emission estimates, sensitivity tests have been performed varying the number of valid transects, calculating the enhancements by subtracting the median of the study domain instead of the upwind background mean, applying different quality flags and using the operational instead of the scientific TROPOMI XCH₄ data product. Supporting figure S5 shows that the total annual emission from the three sources are not sensitive to the number of valid transects used. As expected, we see a decrease in number of orbits considered for emission quantification as the required number of valid transects increases. Similarly, Table S1 tabulates the emissions computed using the operational data product of TROPOMI and relaxed quality flag qa > 0 combined with aerosol optical thickness < 0.1 and precision error < 10 ppb. We find that the annual emission estimates from these sensitivity tests to be in statistical agreement with our original emission estimate, i.e. the total emissions under varied conditions ranged from 500 – 565 Gg a⁻¹.
Section S2: Data Availability

Different data sets used in the study are available from their respective data portals.

- TROPOMI methane Scientific product: https://ftp.sron.nl/open-access-data-2/TROPOMI/tropomi/ch4/14_14_Lorenzo et al_2020_AMTD/
- TROPOMI methane Operational product: https://s5phub.copernicus.eu/dhus/#/home
- ERA5 surface and pressure level hourly meteorology dataset: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form
- EDGARv4.3.2 global emission inventory of greenhouse gases: https://edgar.jrc.ec.europa.eu/overview.php/overview.php?v=432_GHG&SECURE=123
Section S3: Details on plume rotation technique

The localization of the origin of the observed plumes is done by using the wind-rotation technique introduced by Maasakkers et al.\textsuperscript{3}. TROPOMI observations on individual days are rotated around a suggested source location based on the local GEOS-FP 10 m wind vector\textsuperscript{4} on that given day. If the suggested source location is indeed the main emission source, the downwind concentrations will always be larger than the upwind concentrations and an average of multiple days of rotated data will result in a mean ‘plume’ in the average. By repeating this exercise for a full grid of points, the resulting ‘plumes’ can be compared, the location with the largest enhancement compared to the background is estimated to be the actual emission source. Rotations for this study were performed using 2018-2019 TROPOMI methane data.\textsuperscript{5}

For the most northern plume (source 1), the rotated data points towards 2km north and 2km east of the marked location (Figure S4) at the Hail Creek Surface mine, effectively pointing at the North-East corner of the mine. While the bottom-up emission estimates for this surface mine (RBU: 6 Gg a\textsuperscript{-1}) are rather low, no other sources are apparent in the vicinity (± 3km) suggested by the rotation method as the footprint of the mine and pre-mining operations are much larger than that. The other two signals in TROPOMI appear to be caused by underground mines. For the source-2 plume, the rotation method leads us about 2km east of the Moranbah North mine (Figure S4) where multiple vents and drill-holes are visible in satellite imagery. Given the more spread out nature of the plumes observed here and the proximity of the Broadmeadow and Grosvenor mines, we are only able to analyze the aggregation of the three mines. The origin of the most southern source-3 is located 4km east of the Grasstree mine where most mining vents are visible, with a possible contribution from the Oaky North mine located to the south. Given the on-ground pixel resolution of the TROPOMI observations and the close vicinity of the coal mines for each of those two source locations, we could not further distinguish the contributions to individual mines.

In addition to the above identified mines, several surface mines are also found in the vicinity of the source 2 and 3 underground mines. The Goonyella Riverside (just above the Broadmeadow) and the Issac Plains (~13km to the east of Grosvenor) are one of the closest surface mines for source 2. Using the reconstructed bottom-up inventory\textsuperscript{6}, Goonyella Riverside contributes 13 Gg a\textsuperscript{-1} and Issac Plains 2 Gg a\textsuperscript{-1} CH\textsubscript{4} emissions annually. While Middlemount (16km to north of Grasstree), Lake Lindsay (16km to southeast of Grasstree) are the closest operating surface mines for source 3. They emit 3 Gg a\textsuperscript{-1} CH\textsubscript{4} each annually in 2018. German Creek east and Oak Park
surface mines are much closer to Grasstree, 10km to the east, but no active coal production is reported for them and hence we assume little or no emissions of relevance to the estimates here. Given the low estimates for the CH₄ emissions for these nearby surface mines, we can safely assume they do not contribute significantly to our TROPOMI emission estimates for sources 2 and 3.
Section S4: Emissions reporting from underground and surface coal mines in Australia

Underground mines in Australia are equipped with ventilation and gas drainage systems more or less for the same reason. The ventilation fans and auxiliary shafts are installed to provide sufficient air circulation so as to dilute the contaminant air within the safety limits. While gas drainage systems are installed to reduce burden on the ventilation shafts carrying higher amounts of methane released during underground mining operations and to avoid outburst for personnel safety. Effectively there are two types of gas drainage system, pre-drainage and post-drainage systems. The pre-drainage system involves extracting coal seam gas from the mine even before the mining operations have commenced. As quoted in the National Greenhouse and Energy Reporting for emission guidelines, “Pre-gas drainage occurs prior to mining in an area, primarily to avoid safety hazards from potential outbursts that could result during extraction. Where the gas concentration in the coal seam is high, the gas needs to be drained prior to mining the strata.”

While the post-drainage is performed during the mining operation that extracts not only methane but other gases from seam and surrounding strata. Collectively this is also referred to as coal mine waste gas. The gas drainage systems for underground mines at source 2, Broadmeadow, Moranbah North and Grosvenor and source 3, Grasstree and Oaky North include:

1) UIS – Underground in-seam
2) SIS – Surface to in-seam
3) Gas wells

In addition, under Carbon Credits (Carbon Farming Initiative – Coal Mine Waste Gas) Act 2011, the methane component of coal mine waste gas drawn from ventilation air and gas drainage system of underground mine is converted to carbon dioxide either by a flaring device or flameless oxidation device or electricity production devices. The combustion of coal mine waste gas reduces the impact on global warming by converting it to carbon dioxide instead of direct release of methane emissions in the atmosphere. Given below is the list of power station operated by underground mines at source 2 and 3 that uses coal mine waste gas for generating electricity.

- Moranbah North – 63.9 MW operated by EDL since 2008. (https://edlenergy.com/project/moranbah-north/)
- Grosvenor, two power station – 21 and 15 MW operated by EDL since 2016. (https://edlenergy.com/project/grosvenor/)
- Oaky North – 15 MW operated by EDL since 2016. (https://edlenergy.com/project/oaky-creek-2/)
- Grasstree – 45 MW operated by EDL since 2006. (https://edlenergy.com/project/german-creek/)

As Australia follows the highest tier-3 UNFCCC methodologies for reporting methane from underground mines, the national emissions are further classified from ventilation air (649 Gg-emitted), post-mining handling (42.5 Gg-emitted), electricity generation (1.8 Gg-emitted; 261.5 Gg-captured) and flaring (3.9 Gg-emitted; 297.9 Gg-captured) activities of underground mines\(^\text{12}\).

Similarly, for fugitive emissions from surface mines, the National Greenhouse and Energy Reporting (NGER) guidelines states, “Venting or flaring of in-situ gas can also occur from open cut coal mines. This will be from surface in seam drainage (SIS). Such gas drainage from open cut coal mines is less common than for underground coal mines. The likelihood of significant in-situ gas in place prior to coal extraction is lower where targeted coal seams are closer to the surface.” It is clear that venting (to capture methane) or flaring of fugitive methane from coal seam can be a possible methane recovery technology for surface mines, be less efficient, because of rapid diffusion to the overhead atmosphere that it is in direct contact with.
Section S5: Australia and its greenhouse gas reporting commitments

Australia is an Annex-I party to the UNFCCC, Kyoto Protocol and the Paris Agreement, under which it is obliged to report its greenhouse gas emissions each year, reduce its greenhouse gas emissions and track progress towards those commitments. Australia annually submits the National Inventory Reports to the UNFCCC. These emission estimates are compliant with UNFCCC reporting guidelines, IPCC 2006 guidelines for national greenhouse gas inventories, and supplementary reporting requirements under the Kyoto Protocol. (https://www.industry.gov.au/policies-and-initiatives/australias-climate-change-strategies/tracking-and-reporting-greenhouse-gas-emissions). Under the National Greenhouse and Energy Reporting (NGER) Scheme, entities such as facility or corporates that meet certain emission thresholds are obliged to report their emissions, energy production and energy consumption each financial year to the Clean Energy Regulator (http://www.cleanenergyregulator.gov.au/NGER/National%20greenhouse%20and%20energy%20reporting%20data/What-data-is-published-and-why). The emission threshold for a facility to report its emissions under the National Greenhouse and Energy Reporting Act 2007 is 25 ktonne or more of greenhouse gases (CO2-e), production of 100 TJ or more of energy or consumption of 100 TJ or more of energy. Similarly, the threshold for corporate group is 50 ktonne or more of greenhouse gases (CO2-e), production of 200 TJ or more of energy or consumption of 200 TJ or more of energy (http://www.cleanenergyregulator.gov.au/NGER/Reporting-cycle/Assess-your-obligations/Reporting-thresholds). The underground coal mining companies estimate methane emissions from ‘mine return ventilation’ and ‘gas drainage to surface’ activities.8 For calculating the emissions, parameters like gas flow rate, proportion of methane in the gas stream, pressure of the gas (in case of gas drainage) at STP (standard temperature and pressure) and temperature of the gas at STP is measured. Using the molecular mass of methane, these are converted into the units of mass of emissions. While tier-3 measured emissions from surface mines follow methodology developed by Saghafi13 which is also adopted by National Greenhouse and Energy Reporting (NGER). The primary data required for estimating emissions from surface mine includes parameters like in-situ gas content and the gas composition of coal. These are collected by drilling holes at multiple locations at a surface mine or a coal basin. These industry-reported emissions are compiled by the National Greenhouse Accounts department and reported as part of the national emissions to the United Nations Framework Convention on Climate Change (UNFCCC).
Figure S1. Quantification method.

Cross-sectional flux method showing the source location (black dot), upwind background area of 0.5° × 0.5° dimension (blue square), initial mask and wind direction (white dotted box), optimized wind direction over the plume (black dotted box), and the transects (grey lines).
Figure S2. Coal mines in Queensland state of Australia.

Locations of surface and underground coal mines in Queensland, Australia and their methane emissions. (a) Active surface (grey) and underground (orange) coal mine locations (b) respective methane emissions gridded on 0.1° × 0.1° resolution from Sadavarte et al.,6. Red circles denote the location of the three source locations, source 1 – Hail Creek, source 2 – Broadmeadow, Moranbah North and Grosvenor and source 3 – Grasstree and Oaky Creek.
Figure S3. Methane from bottom-up emission inventories over Queensland state.

Methane emissions from the global inventory of EDGARv4.3.2 on a 0.1° × 0.1° grid resolution for a) coal mining activities, and (b) other anthropogenic sources of energy, transport, waste water, landfills, agriculture including livestock, paddy cultivation and others except coal mines and oil and gas category and (c) Oil and gas based methane emissions estimated from production, refining, processing, transport, and storage activities over the study domain in Queensland state on a 0.1° × 0.1° grid resolution from a global inventory by Scarpelli et al.,14. The EDGARv4.3.2 methane emissions are available for year 2012, while the oil and gas methane emissions from Scarpelli et
al.,\textsuperscript{14} is available for 2016. Red circles denote the locations of the three sources, Hail Creek (top), Broadmeadow, Moranbah North and Grosvenor (centre) and Grasstree and Oaky Creek (bottom).
Figure S4. Satellite imagery of coal mines at source 1, 2 and 3.

Satellite images of (a) surface mine – Hail Creek, Source 1 (b) underground mines – Broadmeadow, Moranbah North and Grosvenor, Source 2 (c) underground mines – Grasstree and Oaky Creek, Source 3. Satellite imagery source: OpenStreetMap. Location source from the below webpage, last accessed on 21st March 2021. (https://dsdip.maps.arcgis.com/apps/webappviewer/index.html?id=77b3197acf5f415cb6f24553dd16b9de).
Figure S5. Emissions sensitivity to number of valid transects.

Total annual methane emissions quantified with varying number of valid transects are shown on left hand Y-axis and respective number of observations that were considered for the quantification are shown as scatter plot on right hand Y-axis. SRON Scientific TROPOMI XCH₄ data product with clear-sky observations (qa = 1) and enhancement calculated using background upwind of the sources were selection criteria for this estimate. Our final estimate is provided using number of valid transects >= 3 resulting in 124 observations for the three sources. The uncertainty on the total is shown by 2σ (95% confidence interval).
Figure S6. Expansion activities over Hail Creek mine.

High radiative power, flaring signals observed during the months of July, August and September of 2019 over the northeast area of the surface mine where the extension was approved\textsuperscript{15}. Satellite imagery source: OpenStreetMap.
| TROPOMI data | Quality flag and other varied conditions | Total number of valid plume observations for three source locations | Total Methane flux estimate (Gg a-1) |
|-------------|------------------------------------------|---------------------------------------------------------------|----------------------------------|
| Scientific product\(^5\) | \(q_a = 1\), enhancement estimated using upwind background region | 124 | 570 ± 98* |
| | Data filters: aerosol optical thickness < 0.10, precision error < 10 ppb | 220 | 565 ± 80 |
| | \(q_a = 1\), enhancement estimated using median XCH\(_4\) of the study domain (20°S -24°S; 146°E -150°S) as background | 124 | 550 ± 100 |
| Operational product\(^6\) | \(q_a = 1\), enhancement estimated using upwind background region | 144 | 525 ± 90 |
| | Data filters: aerosol optical thickness < 0.10, precision error < 10 ppb, | 258 | 500 ± 75 |

* baseline emission estimate.
Table S2: Annual coal production and fugitive methane emissions for coal producing states in Australia for 2018.

| Coal producing states | Coal production (ktonne) | Methane emissions (Gg) |
|-----------------------|--------------------------|------------------------|
|                       | Underground              | Surface                | Underground | Surface |
| Queensland            | 48240<sup>a</sup>        | 269119<sup>a</sup>     | 343.88<sup>e</sup>   | 196.26<sup>e</sup> |
| New South Wales       | 64288<sup>b</sup>        | 183832<sup>b</sup>     | 366.53<sup>e</sup>   | 61.06<sup>e</sup>  |
| Victoria              | 45904<sup>d</sup>        | 0.50<sup>f</sup>       |             |         |
| Tasmania              | 382<sup>d</sup>          | 0.26<sup>f</sup>       |             |         |
| Western Australia     | 6649<sup>d</sup>         | 4.50<sup>f</sup>       |             |         |
| National              | **112528<sup>c</sup>**  | **505886<sup>c</sup>** | **710.41<sup>e</sup>** | **261.58<sup>e</sup>** |

<sup>a</sup> Department of Natural Resources and Mines, Queensland, Summary of the raw and saleable coal of individual mines by financial year, [https://www.data.qld.gov.au/dataset/27febf68-dc98-4300-85b6-465f0df233a8/resource/9c3c1aaf-0afa-4e58-b67c-75c0d3574abd/download/production-by-individual-mines.xlsx](https://www.data.qld.gov.au/dataset/27febf68-dc98-4300-85b6-465f0df233a8/resource/9c3c1aaf-0afa-4e58-b67c-75c0d3574abd/download/production-by-individual-mines.xlsx).

<sup>b</sup> Raw and saleable coal production data compiled from annual review report of the respective individual coal mines for the year 2018.

<sup>c</sup> National raw coal production for year 2018, common reporting format (CRF) as reported to UNFCCC for year 2018.

<sup>d</sup> Raw coal production estimated for states of Victoria, Western Australia and Tasmania, by proportionately distributing the raw coal (calculated as difference between National and, Queensland and New South Wales) as per the saleable coal for the respective three states.

<sup>e</sup> Methane emissions reported to UNFCCC for 2018 (source: [https://ageis.climatechange.gov.au/](https://ageis.climatechange.gov.au/)).

<sup>f</sup> Estimated using bottom-up emission factors available for surface mines in the national inventory report 2018, 2020 (Table 3.32) for Victoria and Tasmania state. For Western Australia, the emission factor similar to Tasmania was used for estimating emissions.

<sup>g</sup> Sum of surface based coal mine emissions.
**Table S3:** Australia’s national greenhouse gas - methane emissions reported to United Nations Framework Convention on Climate Change (UNFCCC) for 2018.

| Sectors and sub-sectors | Methane emissions (Gg) |
|------------------------|------------------------|
| **A. Energy (combustion and fugitive)** | 1562.20 |
| Combustion | 77.92 |
| Fugitive emissions Solid fuels | 972.29 |
| Fugitive emissions Oil and natural gas | 511.98 |
| **B. Industrial processes and product use** | 3.10 |
| Chemical Industry | 0.58 |
| Metal Industry | 2.52 |
| **C. Agriculture** | 2335.52 |
| Enteric fermentation | 2066.73 |
| Manure management | 250.01 |
| Rice cultivation | 10.16 |
| Field burning of agricultural residues | 8.62 |
| **D. Land use, land use change and forestry incl. natural disturbances** | 630.73 |
| Forest land | 240.09 |
| Cropland | 0.71 |
| Grassland | 194.46 |
| Wetlands & Others\(^a\) | 194.70 |
| Settlements | 0.77 |
| **E. Waste** | 480.48 |
| Solid waste disposal | 361.80 |
| Biological treatment of solid waste | 4.46 |
| Wastewater treatment and discharge | 114.22 |
| **Total CH\(_4\) Emissions** | 5012.01 |

\(^a\)Others include CH\(_4\) from artificial water bodies.

All emissions are tabulated using common reporting format (CRF) table available at [https://unfccc.int/documents/228034](https://unfccc.int/documents/228034), last accessed on 21\(^{st}\) March 2021.
Table S4: Implied emission factors estimated as ratio of emissions to coal production compared with studies at various domain levels.

|                                | Emission year | Implied emission factors (g/kg) |
|--------------------------------|---------------|----------------------------------|
|                                |               | Underground                       | Surface |
| **Australia (National)**       |               |                                  |         |
| EDGARv4.3.2<sup>a,b</sup>     | 2012          | 10.23                            | 0.55    |
| NIR 2017 (2019)<sup>c</sup>    | 2012          | 8.38                             | 0.45    |
| NIR 2018 (2020)<sup>c</sup>    | 2012          | 8.38                             | 0.45    |
| NIR 2017 (2019)<sup>c</sup>    | 2017          | 6.05                             | 0.47    |
| NIR 2018 (2020)<sup>c</sup>    | 2017          | 6.05                             | 0.47    |
| NIR 2018 (2020)<sup>c</sup>    | 2018          | 6.31                             | 0.52    |
| **Queensland (State)**         |               |                                  |         |
| NIR (2020)<sup>c</sup>        | 2018          | 7.13                             | 0.73    |
| **Reconstructed bottom-up, Sadavarte et al., 2021** | | | |
| Source 1                       | 2018          | 8.60                             | 0.73    |
| Source 2                       |               |                                  |         |
| Source 3                       |               | 5.73                             |         |
| **IPCC default (Global)**<sup>d</sup> |           |                                  |         |
| < 200m                         |               | 7.38                             | 0.20    |
| 200-400m                       |               | 13.87                            | 0.88    |
| > 400m                         |               | 19.62                            | 1.49    |
| **Kholod et al., 2020**        |               |                                  |         |
| < 200m                         |               | 10.08                            | 2.03 - 3.38 |
| 200-400m                       |               | 12.79                            |         |
| > 400m brown coal              |               | 14.62                            |         |
| **TROPOMI (Individual source)**|               |                                  |         |
| Source 1                       |               | 34.12                            |         |
| Hail Creek                     |               |                                  |         |
| Source 2                       |               |                                  |         |
| Broadmeadow<sup>h</sup>        | 2018-2019     | 10.00                            |         |
| Moranbah North: 270-370m<sup>i</sup> | |         |
| Grosvenor: 220m<sup>i</sup>    |               |                                  |         |
| Source 3                       |               |                                  |         |
| Grasstree: 370m<sup>i</sup>    |               | 11.50                            |         |
| Oaky North: 215-300m<sup>i</sup> |           |                                  |         |

<sup>a</sup>Split EDGAR underground and surface based on 2012 ratio NIR 2017<sup>17</sup>.  
<sup>b</sup>EDGARv4.3.2 CH4 emissions for 2012 and used national raw coal production from common reporting format table for 2012.  
<sup>c</sup>Using emissions and raw coal production details from common reporting format table for respective year.
d2006 IPCC guidelines for national greenhouse gas inventories, Vol. 2. Energy, Chapter 4, Fugitive emissions\textsuperscript{18}.

eKholod et al.,\textsuperscript{19}.

fAshurst Report,\textsuperscript{9}.

\textsuperscript{9}https://www.angloamerican.com/~/media/Files/A/Anglo-American-Group/PLC/media/presentations/2019pres/metallurgical-coal-bulks-seminar-and-site-visit-brisbane.pdf, last accessed on 27\textsuperscript{th} March 2021.

\textsuperscript{10}Board of Inquiry Report, Queensland coal mining, November 2020\textsuperscript{20}.
Supporting Animation 1.
Four years (2017-2020) of Sentinel 2 satellite imagery over Hail Creek coal mine that shows the change in topography over the proposed coal mine extension area.
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