Environmental Science & Technology LETTERS

pubs.acs.org/journal/estlcu

Letter

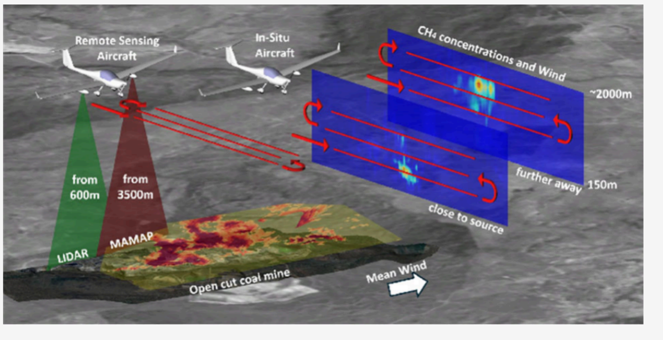
Insights into Elevated Methane Emissions from an Australian Open-Cut Coal Mine Using Two Independent Airborne Techniques

Jakob Borchardt,* Stephen J. Harris, Jorg M. Hacker, Mark Lunt, Sven Krautwurst, Mei Bai, Hartmut Bösch, Heinrich Bovensmann, John P. Burrows, Shakti Chakravarty, Robert A. Field, Konstantin Gerilowski, Oke Huhs, Wolfgang Junkermann, Bryce F. J. Kelly, Martin Kumm, Wolfgang Lieff, Andrew McGrath, Adrian Murphy, Josua Schindewolf, and Jakob Thoböll

Cite This: https://doi.org/10.1021/acs.estlett.4c01063

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information



ABSTRACT: Governments and industries worldwide are seeking methods to accurately estimate their methane inventories, particularly in the open-cut coal mining sector, where quantifying facility-level emissions remains challenging and robust verification methods are not yet widespread. Here, we compare methane emission rates estimated from two aircraft-based measurement platforms with operator-reported emissions from an open-cut coal mine in the Bowen Basin (Queensland, Australia). Coarse-resolution satellite-based data identified the mine as a significant emitter, making it ideal for case studies using airborne in situ and remote sensing platforms that provide high-resolution measurements to isolate mine-scale emissions. Using airborne in situ measurements, we estimated methane emission rates of 14.0 ± 3.3 (±2σ) t h^{-1} during May and June 2022. In September 2023, airborne in situ and remote sensing measurements yielded consistent emission rate estimates of 9.6 ± 1.9 (±2σ) t h^{-1} and 11.3 ± 5.3 (±2σ) t h^{-1}, respectively. If sustained, these rates would equate to annual emissions of 1.5−4.2 Mt of CO_2 equivalents (CO_2-e) $year^{-1}$, 3−8 times higher than operator-reported annual Scope 1 emissions (0.53−0.54 Mt of CO_2-e $year^{-1}$). Beyond highlighting the potential for under-reporting of emissions at this mine, our results indicate that aircraft-based technologies are valuable tools for supporting accurate reporting of facility-scale methane emissions from open-cut coal mines.

KEYWORDS: *coal mine methane, greenhouse gases, climate change, emission inventory, airborne remote sensing, airborne in situ, top-down, airborne atmospheric measurements*

INTRODUCTION

Top-down atmospheric measurement technologies are being used worldwide to verify methane emission inventories.[1−4] There is also a growing emphasis on quantifying methane emissions from individual sites to accelerate mitigation efforts.[5−10]

Coal mine methane emissions, which account for approximately one-third of anthropogenic fossil fuel methane emissions,[11] are a key focus for top-down methane emissions verification and mitigation efforts.[4,12−16] However, the literature on verification of methane emissions from a subset of this sector, open-cut coal mines, remains sparse[17,18] despite the potentially significant contribution to national emissions and its expected increase in the future relative to underground mining.[19]

In Australia, for example, fugitive methane emissions from open-cut coal mines comprise roughly one-fifth of the nation's total fugitive emissions.[20] However, bottom-up reporting methods developed under the National Greenhouse and Energy Reporting (NGER) Scheme—Methods 1−3, based on Tier 2 and Tier 3 IPCC methodologies[21−23]—have yet to be validated using atmospheric observations, raising concerns about their accuracy. For instance, methane emissions at the Hail Creek open-cut coal mine in Queensland's Bowen Basin, derived from the TROPOspheric Monitoring Instrument (TROPOMI), exceeded operator-reported Scope 1 emissions (including both carbon dioxide and methane) by more than 12 times.[18,24] While the prevalence of such discrepancies is unclear, this underscores the urgent need for independent verification of methane emissions from individual open-cut coal mines across Australia.

Received: December 9, 2024
Revised: March 7, 2025
Accepted: March 7, 2025

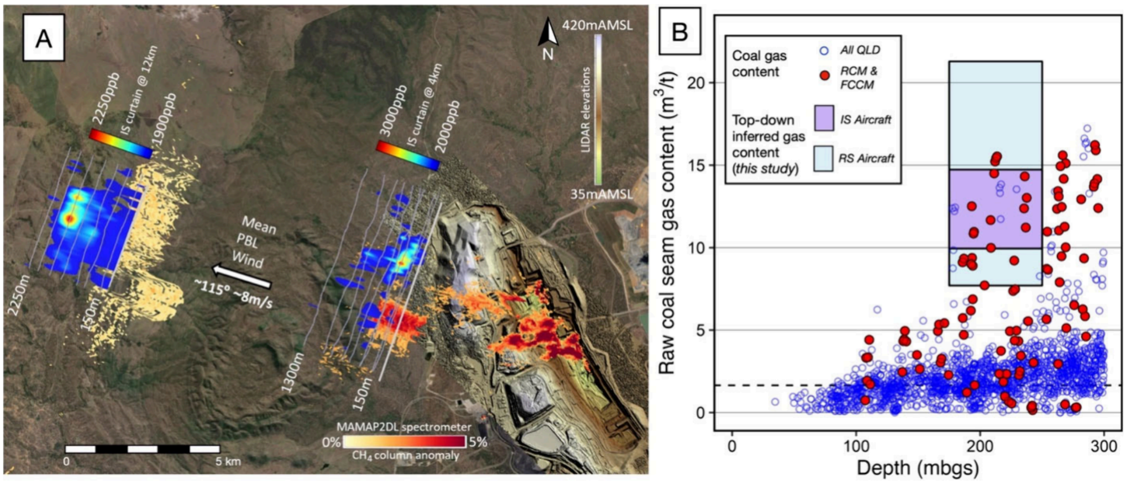


Figure 1. (A) Hail Creek open-cut coal mine methane plume on September 28, 2023. The two image insets to the west and downwind of the mine depict the two curtains flown by the in situ aircraft, with atmospheric methane concentrations (in parts per billion) interpolated between different transect heights on a blue-to-red color scale. The first curtain was flown ∼4 km downwind of the mine, the second at ∼12 km. The methane plume imaged by the MAMAP2DL spectrometer onboard the remote sensing aircraft is shown with the yellow-to-red color scale. MAMAP2DL images were acquired ∼2 h after the first in situ curtain; thus, minor differences in the spatial location of the plume due to shifts in wind direction are to be expected. The LIDAR-derived topography of the Hail Creek mine is also shown in terrain colors. (B) Plots of raw coal seam gas content (in m^3 t^{-1}) vs depth for all boreholes in the Bowen Basin, as recorded in the Queensland Petroleum Exploration database,[49] are shown to depths of 300 m below the ground surface (blue). Superimposed in red are coal gas contents from the Rangal Coal Measures (RCM) and Fort Cooper Coal Measures (FCCM). The dashed line represents the basin-wide mean in situ coal methane gas content of 1.65 m^3 t^{-1} for the Bowen Basin.[50] The boxes represent the inferred coal methane content derived from our top-down emission rate quantifications for FY2023 (see the text and Supporting Information for details). Map data in Figure 1A, modified from Google Earth, Image 2025 Airbus.

While area flux mapping satellites like TROPOMI can quantify coal mine emissions at regional scales,[18,25] their limited spatial resolution reduces their effectiveness for verifying annual inventory reported emissions at the scale of individual mines.[26] Furthermore, the ability of point-source imaging satellites to quantify emissions from individual open-cut coal mines is unproven. These mines may emit methane diffusely over large areas, including exposed coal seams and from beneath the pit floor due to fractioning and reduced pressure in the seams, waste piles, and water management ponds, areas which may lack localized plumes associated with emissions. The absence of well-constrained, mine-scale studies for open-cut coal mines remains a barrier to verifying emission estimates and refining estimation methods for Australian open-cut coal mining facilities.

Given the challenges with satellite resolution and the potentially diffuse nature of methane emissions from open-cut mines, aircraft-based techniques provide a promising alternative for high-resolution measurements. Airborne measurement platforms have been used extensively to quantify emissions at the facility scale from fossil fuel,[27−33] waste,[34−36] and agricultural[37−39] sectors, relying on either remote sensing or in situ measurements. These platforms have the potential to measure both methane point sources[40] and diffuse sources,[34] offering a pathway for verifying methane emissions from open-cut coal mines based on approved IPCC methodologies. These approaches record gas concentration and meteorological data at the tens-of-meters scale with high precision, allowing for more accurate methane quantification at individual mines. This is due to improved separation between mines, detection of smaller sources,[41,42] and better spatial resolution of plumes compared to TROPOMI observations and inverse modeling.

Here, we present methane emission rates estimated from two aircraft-based in situ and remote sensing measurement platforms for a single mine in the Bowen Basin, Australia (the Hail Creek coal mine). This mine was previously identified by coarse-resolution satellite-based measurements as a high methane emitter per unit of coal production,[18,25] making it an ideal case study for applying higher-precision top-down measurement approaches to reduce uncertainty. By comparing our measurements with methane emissions estimates derived through NGER methodologies and operator-reported Scope 1 emissions, we provide the first high-resolution empirical top-down verification of NGER methodologies for an open-cut coal mine in Australia.

METHODS AND MATERIALS

Measurement Approaches. From May to June 2022, a Diamond Aircraft HK36TTC-ECO Dimona motorglider was deployed to sample methane plumes downwind of the Hail Creek coal mine. This aircraft, termed the "in situ" aircraft, provided direct measurements of methane and carbon dioxide concentrations, as well as meteorological parameters (such as wind, temperature, and pressure) directly at the aircraft's location during flight.[1,43]

In September 2023, a second ECO-Dimona "remote sensing" aircraft was deployed alongside the in situ aircraft. It was equipped with the Methane Airborne Mapper 2D-Light (MAMAP2DL) instrument[44] to map atmospheric methane and carbon dioxide concentration gradients at a spatial resolution of 50 m × 50 m, as well as a LIDAR system to scan and determine the current mine pit topography.

The in situ aircraft flew stacks of horizontal transects through the downwind methane plume ranging from low altitudes (∼130 m above ground level) to the top of the planetary boundary layer, forming downwind "curtains". The curtains consisted of 2−10 transects with spacing ranging from 10 to 1020 m (Table S5). The remote sensing aircraft flew at higher altitudes (∼3200 m above ground level), imaging

https://doi.org/10.1021/acs.estlett.4c01063
Environ. Sci. Technol. Lett. XXXX, XXX, XXX−XXX

Table 1. Comparison of Top-Down Emission Rate Estimates with Bottom-Up Reporting from the Hail Creek Coal Mine[a]

top-down approach	financial year	estimated top-down methane emission rate (t h^{-1}) (±2σ)	estimated top-down methane emission rate (Mt of CO_2-e $year^{-1}$) (±2σ)	bottom-up NGER Method 1 fugitive methane emission rate[c] (Mt of CO_2-e $year^{-1}$)	reported bottom-up Safeguard Scope 1 emissions[d] (Mt of CO_2-e $year^{-1}$)	ref
in situ aircraft	2022	14.0 ± 3.3	3.42 ± 0.80	0.33	0.54	this study
	2024	9.6 ± 1.9	2.36 ± 0.46	0.31[b]	0.53[b]	this study
remote sensing aircraft	2024	11.3 ± 5.3	2.77 ± 1.30	0.31[b]	0.53[b]	this study
TROPOMI	2018–2019	26.3 ± 5.7	6.44 ± 1.40	0.24–0.32	0.50–0.55	18
	2018–2019	4.9 ± 2.4	1.20 ± 0.60	0.24–0.32	0.50–0.55	25
	2018–2023	25.0 ± 12.6	6.10 ± 3.09	0.24–0.33	0.50–0.55	this study

[a]All data are converted to CO_2 equivalents (CO_2-e) using a GWP of 28 from AR5. The methane emission rates were calculated from two quantifications on two days for the in situ aircraft in 2022, from seven quantifications on three days for the in situ aircraft in 2023, and from six quantifications on one day for the remote sensing aircraft in 2024. For the calculation of the TROPOMI average from 2018 to 2023, quantifications of 272 days were averaged. All values are compared to fugitive methane bottom-up estimations using Method 1 and operator-reported bottom-up Scope 1 emissions. [b]Data for FY2024 were unavailable at the time of writing; here, we report data from FY2023. [c]Derived from Queensland Government.[52] [d]Department of Climate Change, Energy, the Environment and Water.[51]

methane column anomalies (percent change of the methane column relative to the background) flying above the boundary layer. On September 28, 2023, clear skies and consistent, strong winds (~8–10 m s^{-1}) allowed for the coordination of both in situ and remote sensing flights to simultaneously measure the methane plume downwind of the mine.

Methane Flux Estimation. For the in situ aircraft data, we applied a mass balance approach to quantify methane emission rates.[5,8,13,45] In this approach, the methane flux quantified for each transect was linearly interpolated using a trapezoidal method (also termed the layer method).[8,45]

The methane flux from the MAMAP2DL remote sensing data was estimated in two steps. Methane column anomaly maps were derived from measured spectra using the Weighting Function-Modified Differential Optical Absorption Spectroscopy (WFM-DOAS) retrieval method.[44,46] Methane emission rates were estimated from these anomaly maps using the cross-sectional flux method.[44,46,47] Importantly, our approach relies solely on flight legs acquired downwind of the mining pit to estimate fluxes, as the mean wind speed and direction within the pit are poorly defined due to topographic effects.

Detailed descriptions of the in situ and remote sensing measurement platforms, the flux estimations, and the associated uncertainties are provided in the Supporting Information.

RESULTS

The in situ aircraft acquired two curtains on May 31 and June 3, 2022, yielding a mean methane emission rate of 14.0 ± 3.3 (±2σ) t h^{-1}. In 2023, the in situ aircraft acquired seven curtains on September 15, 28, and 29. The remote sensing aircraft acquired imagery of the methane plume on September 15 and 28; however, the methane emission rate on September 15 was not quantified due to partial cloud cover above the methane plume. Based on in situ and remote sensing measurements in 2023, we estimated mean methane emission rates of 9.6 ± 1.9 and 11.3 ± 5.3 t h^{-1}, respectively.

During the coordinated flight on September 28, 2023, the in situ aircraft flew two curtains at the position of two flight tracks flown by the remote sensing aircraft (Figure 1A). Both platforms identified a consistent methane plume location, with MAMAP2DL imagery indicating that most emissions originated from the eastern highwall of the Main Western Pit,[48] where coal was being excavated during both 2022 and 2023 campaigns. On this measurement day, the mean emission rate measured by the in situ aircraft (8.9 ± 1.6 t h^{-1}) was consistent with the rate measured by the remote sensing aircraft (11.3 ± 5.3 t h^{-1}). Subsequent topographic LIDAR imagery recorded on October 2 (Figure 1A) revealed that the coal being mined was located 180–200 m below the ground surface, with the pit floor approximately 220–250 m below the ground surface.

DISCUSSION

Comparison of Bottom-Up and Top-Down Estimates. Under Australia's NGER Scheme, open-cut coal mine operators report methane emissions using one of three methods (Methods 1–3). Method 1 is a Tier 2 IPCC methodology that relies on emission factors derived from average basin-wide coal core gas contents. Methods 2 and 3 are Tier 3 IPCC methodologies based on mine-specific coal core gas distribution models.[21–23]

In Table 1, we compare all top-down methane emission rate estimates available for the Hail Creek coal mine with the two corresponding bottom-up estimates:

1. fugitive methane emissions calculated using NGER Method 1, applied to the run-of-mine coal extracted
2. methane and carbon dioxide emissions from both fugitive and nonfugitive sources (Scope 1 emissions) reported under Australia's Safeguard Mechanism[51].

These comparisons are based on data for the equivalent or most recently available financial year from the mine.[51,52] The NGER method used by the mine operators has not been publicly disclosed and is, therefore, unknown. Irrespective of the reporting method, fugitive methane emissions are lower than the reported Scope 1 emissions, encompassing both carbon dioxide and methane emissions.

To compare our point-in-time measurements with the reported annual total bottom-up emissions estimates in Table 1, we converted our results to annualized emission rates, assuming that the measurements reflect average operational conditions over the entire financial year. While we recognize that further research is needed to validate this

https://doi.org/10.1021/acs.estlett.4c01063
Environ. Sci. Technol. Lett. XXXX, XXX, XXX−XXX

assumption, it is important to note that no blasts were observed during the sampling period. This likely rules out the possibility of elevated methane emissions from blast-related plumes, leading to overestimated yearly average emissions from our measurements. Since emissions from open-cut coal mines in Australia are reported on an annualized basis, our comparisons are inherently limited by this assumption.

The mean emission rate derived from the in situ approach in 2022 is approximately 10 ± 2 times higher than the average annual emission rate estimated using NGER Method 1. Similarly, it is about 6 ± 1 times higher than the average annual Scope 1 emission rate reported under the Safeguard Mechanism for FY2023. At this emission rate, the reported Scope 1 emissions would be exceeded within roughly 2−3 months.

In 2023, the mean in situ and remote sensing emission rate estimates are 8 ± 1 to 9 ± 4 times higher than the average annual emission rate estimated using NGER Method 1 and 4 ± 1 to 5 ± 2 times higher than the average annual Scope 1 emission rate reported for FY2023. Similarly, at these rates, the reported Scope 1 emissions would be exceeded within approximately 2−5 months.

Previous TROPOMI estimates from 2018 to 2019 provide a valuable point of comparison.[18,25] On average, our aircraft-based estimates are approximately 2−3 times those reported by Palmer et al.[25] yet more than half of those estimated by Sadavarte et al.[18] However, direct comparisons with these publications are challenging as the measurements were conducted 3−4 years apart. To address this temporal gap, we report a mean quantification of emissions between 2018 and 2023 derived from inverted TROPOMI observations[53] using an automated method[54,55] in Table 1 (see the Supporting Information). Although less precise than aircraft-based measurements, the mean TROPOMI-derived emissions over this extended period [25.0 ± 12.6 (±2σ) t h^{-1} (Table 1)] align closely with those reported by Sadavarte et al.[18] and suggest long time frame-averaged emission rates were sustained outside the period of our sampling campaigns. However, they are notably higher than those of Palmer et al.[25] and the aircraft-based estimates from our study.

Although a more granular comparison of our aircraft-based estimates to TROPOMI estimates would be informative, we note that no sufficiently cloud-free TROPOMI measurements are available for emission estimation on the individual days flown during our campaign. Additionally, emission estimates from single-day TROPOMI measurements are highly uncertain, and a reliable uncertainty range can be achieved only by averaging estimates over longer time frames.

The discrepancy between satellite- and aircraft-based measurements may stem from several factors. Interference from nearby mines and their plumes, which can affect the downwind portion of the cross-sectional flux method partly due to TROPOMI's lower spatial resolution, along with inadequate accounting for methane accumulation within the mining pit during low-altitude atmospheric inversions, could contribute to overestimations in the TROPOMI mass balance calculations. Furthermore, the source-pixel estimation method used by Palmer et al.[25] carries large uncertainties and may be prone to low bias.[56] Nevertheless, all available atmospheric data-based estimates qualitatively indicate higher average emission rates compared to both NGER Method 1 and Scope 1 estimates.

Assessment of Current Bottom-Up Methods. To the best of our knowledge, the mine operator has not reported any premining methane drainage, which could reduce the in situ coal gas content at the mine. Although the reporting method used at the mine has not been disclosed, publicly available coal core gas content and production data allow us to derive insights and assess the suitability of various bottom-up methods for estimating emissions.

NGER Method 1. Method 1 uses an emission factor based on the basin-wide mean in situ coal methane gas content of 1.65 m^3 t^{-1} for the Bowen Basin.[50] Mining at Hail Creek specifically targets coal seams within the Rangal Coal Measures and the upper parts of the Fort Cooper Coal Measures.[48] Within the upper 250 m below ground surface (representing the maximum pit depth measured by our LIDAR), these seams have mean gas contents of 6.6 and 5.6 m^3 t^{-1}, respectively, based on data from the Queensland Petroleum Exploration Database[49] (Figure 1B). Since the average methane contents of the coal seams mined at Hail Creek are approximately 4 times higher than the basin-wide average, applying Method 1 at the mine could lead to an underestimation of methane emissions.

Furthermore, if all of the methane measured during our in situ and remote sensing flights originated from the gas within the in situ coal, we estimate that the required in situ coal gas contents to match our 2023 aircraft-based emission rates would be 12 ± 2 and 14 ± 7 m^3 of CH_4 t^{-1}, respectively. These estimates were derived by calculating the average hourly rate of coal extraction from annual run-of-mine production figures for FY2023 at Hail Creek and determining the gas contents necessary to produce the measured emission rates during our flights (Supporting Information). Although we cannot confirm that the average annual run-of-mine production rate was maintained during our measurements, this approximation provides a meaningful comparison. Notably, the coal gas contents inferred by our aircraft-based emission rates fall within the range of those measured for the Rangal Coal Measures and Fort Cooper Coal Measures at the depths currently mined at Hail Creek [0.2−15.5 m^3 t^{-1} (Figure 1B)]. These findings suggest that bottom-up methods at Hail Creek are better suited to using emission factors based on the coal gas contents of the seams being directly extracted rather than relying on the basin-wide average used in Method 1.

NGER Methods 2 and 3. Without knowledge of which method is applied, and in the absence of a publicly disclosed mine-specific coal core gas distribution model for the Hail Creek coal mine (if one is used), we are unable to verify the methods applied under Methods 2 and 3 (note that Method 3 is identical to Method 2, with the addition of adhering to an appropriate gas sampling standard[57]). As shown in the previous section, our aircraft-based data indicate a substantial alignment with the in situ gas contents reported for coal seams mined at Hail Creek.[49] However, additional methane sources not accounted for by current Methods 2 and 3 could further contribute to the discrepancies between our aircraft-based estimates and bottom-up estimates, especially if Method 2 or 3 were applied at the mine.

During both underground and open-cut coal mining, gas is emitted not only from the mined coal seam but also from adjacent and underlying seams and gas-bearing strata. This occurs due to preexisting fractures, the fracturing of seams during mining, and the removal of overburden and adjacent earth, which reduces the pressure on the coal seams. For instance, underground coal mines in Australia[58] demonstrated that measured emissions can be up to 4 times greater than in situ coal seam methane contents. However, current Method 2 and 3 guidelines for open-cut mines do not require accounting for emissions from strata below a depth of 20 m beneath the pit floor, despite evidence that contributions from deeper underburden vary across mines due to differences in geo-mechanical properties and mining intensity.[21,59−63]

Additionally, Methods 2 and 3 do not consider lateral gas migration via exposed highwalls, a well-documented process in underground coal mines.[64] While lateral gas inflow into open-cut mines has not been characterized in the Bowen Basin, early research on Methods 2 and 3 recognized its relevance for open-cut operations.[63] Processes enabling the formation of biologically derived methane in Bowen Basin coals suggest locally high hydraulic conductivity and extensive lateral connectivity, which could facilitate such migration.[65] Regional and local geological features, such as faults and volcanic intrusions, may also influence the in situ gas content depending on their exposure within the highwall. These structures have been extensively mapped within the Main Western Pit at the Hail Creek mine.[48]

Finally, in addition to within-pit methane sources, in situ biological methane production within water management ponds, disturbed soils, and exposed coal stockpiles may also contribute to the Hail Creek methane emissions budget. However, they are not accounted for under Methods 2 and 3. While MAMAP2DL imaging data did not suggest that these sources significantly contribute to the total emissions, further research is needed to quantify their annual proportional contribution.

IMPLICATIONS

Our study is the first to successfully use aircraft-based measurement platforms to verify NGER methodologies at an open-cut coal mine in Australia. While this study focuses on a single high-emitting mine, aircraft-based approaches should be applicable to most open-cut coal mines across the country and can play an increasingly important role in verifying methane emissions in Australia's National Inventory. For instance, Queensland coal mines reported a combined total of 258 kt of methane emissions across 54 operating mines in 2022,[66,67] suggesting average methane emission rates of approximately 0.5 t h^{-1}. Although a quantification limit for this specific in situ instrumentation has not yet been established, similar aircraft-based platforms have successfully quantified methane emission rates below 0.01 t h^{-1} during controlled-release studies.[41,68] Furthermore, emissions from open-cut coal mines with rates exceeding 0.4−0.7 t h^{-1} are anticipated to be quantifiable using MAMAP2DL (see the Supporting Information).

The discrepancy between operator-reported emissions and our two aircraft-based estimates underscores the need for a comprehensive review of the bottom-up reporting methods currently applied at Hail Creek. While our results reveal significant disagreement between bottom-up and top-down estimates for this mine, Figure 1B shows that the coal seams mined at Hail Creek are among the gasiest in the Bowen Basin. Consequently, it remains unclear whether these discrepancies are representative of other mines in the region. Further measurements are needed to better understand these differences and assess their applicability to other Australian open-cut mines. Additionally, our findings highlight the need for extensive measurements to evaluate and quantify temporal variations in methane emissions from open-cut coal mines.

ASSOCIATED CONTENT

Data Availability Statement

The MAMAP2D-Light column anomaly data used in this publication are accessible via Zenodo at 10.5281/zenodo.14264352. The in situ and LIDAR data acquired by Airborne Research Australia used in this publication are accessible via Zenodo at https://zenodo.org/records/14286295.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.4c01063.

Additional information about the aircraft instrumentation, MAMAP2D-Light retrieval, emissions estimate and uncertainties, in situ aircraft measurements, emissions estimates and uncertainties, TROPOMI emissions estimate, and calculation of the coal core gas content from emissions estimates (PDF)

AUTHOR INFORMATION

Corresponding Author

Jakob Borchardt − *University of Bremen, Institute of Environmental Physics (IUP), Bremen 28359, Germany;* orcid.org/0000-0002-2380-0823; Phone: 0049 421 218-62131; Email: jakob.borchardt@iup.physik.uni-bremen.de; Fax: 0049 421 218-62070

Authors

Stephen J. Harris − *UNEP's International Methane Emissions Observatory (IMEO), Paris 75000, France; University of New South Wales, School of Biological, Earth and Environmental Sciences, Sydney, NSW 2052, Australia*

Jorg M. Hacker − *Airborne Research Australia, Parafield, SA 5106, Australia; Flinders University, College of Science and Engineering, Adelaide, SA 5001, Australia*

Mark Lunt − *Environmental Defense Fund, Perth, WA 6000, Australia*

Sven Krautwurst − *University of Bremen, Institute of Environmental Physics (IUP), Bremen 28359, Germany*

Mei Bai − *The University of Melbourne, School of Agriculture, Food and Ecosystem Sciences, Parkville, VIC 3010, Australia;* orcid.org/0000-0003-0594-2067

Hartmut Bösch − *University of Bremen, Institute of Environmental Physics (IUP), Bremen 28359, Germany*

Heinrich Bovensmann − *University of Bremen, Institute of Environmental Physics (IUP), Bremen 28359, Germany*

John P. Burrows − *University of Bremen, Institute of Environmental Physics (IUP), Bremen 28359, Germany*

Shakti Chakravarty − *Airborne Research Australia, Parafield, SA 5106, Australia*

Robert A. Field − *UNEP's International Methane Emissions Observatory (IMEO), Paris 75000, France*

Konstantin Gerilowski − *University of Bremen, Institute of Environmental Physics (IUP), Bremen 28359, Germany*

Oke Huhs − *University of Bremen, Institute of Environmental Physics (IUP), Bremen 28359, Germany*

Wolfgang Junkermann − *Airborne Research Australia, Parafield, SA 5106, Australia; Karlsruhe Institute of Technology, IMK-IFU, Garmisch-Partenkirchen 82467, Germany*

Bryce F. J. Kelly − *University of New South Wales, School of Biological, Earth and Environmental Sciences, Sydney, NSW 2052, Australia*

https://doi.org/10.1021/acs.estlett.4c01063
Environ. Sci. Technol. Lett. XXXX, XXX, XXX−XXX

Martin Kumm − *Jade University of Applied Sciences, Wilhelmshaven 26389, Germany*
Wolfgang Lieff − *Airborne Research Australia, Parafield, SA 5106, Australia*
Andrew McGrath − *Airborne Research Australia, Parafield, SA 5106, Australia; Flinders University, College of Science and Engineering, Adelaide, SA 5001, Australia*
Adrian Murphy − *Airborne Research Australia, Parafield, SA 5106, Australia*
Josua Schindewolf − *Alfred Wegener Institute - Helmholtz Centre for Polar and Marine Research, Bremerhaven 27570, Germany*
Jakob Thoböll − *University of Bremen, Institute of Environmental Physics (IUP), Bremen 28359, Germany*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.estlett.4c01063

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was funded in the framework of UNEP's International Methane Emissions Observatory (IMEO). One of the ARA research motorgliders was donated by the late Joyce Schultz of Adelaide. ARA has been substantially supported by the Hackett Foundation, Adelaide. The contributions of the IUP team were in part funded by the State and University of Bremen and the German Federal Ministry of Education and Research (BMBF) Project AIR-SPACE (Grant 01LK1701B).

■ REFERENCES

(1) Neininger, B. G.; Kelly, B. F. J.; Hacker, J. M.; LU, X.; Schwietzke, S. Coal Seam Gas Industry Methane Emissions in the Surat Basin, Australia: Comparing Airborne Measurements with Inventories. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **2021**, *379* (2210), 20200458.

(2) Johnson, M. R.; Tyner, D. R.; Conley, S.; Schwietzke, S.; Zavala-Araiza, D. Comparisons of Airborne Measurements and Inventory Estimates of Methane Emissions in the Alberta Upstream Oil and Gas Sector. *Environ. Sci. Technol.* **2017**, *51* (21), 13008−13017.

(3) Henne, S.; Brunner, D.; Oney, B.; Leuenberger, M.; Eugster, W.; Bamberger, I.; Meinhardt, F.; Steinbacher, M.; Emmenegger, L. Validation of the Swiss Methane Emission Inventory by Atmospheric Observations and Inverse Modelling. *Atmos. Chem. Phys.* **2016**, *16* (6), 3683−3710.

(4) Varon, D. J.; Jacob, D. J.; Jervis, D.; McKeever, J. Quantifying Time-Averaged Methane Emissions from Individual Coal Mine Vents with GHGSat-d Satellite Observations. *Environ. Sci. Technol.* **2020**, *54* (16), 10246−10253.

(5) Foulds, A.; Allen, G.; Shaw, J. T.; Bateson, P.; Barker, P. A.; Huang, L.; Pitt, J. R.; Lee, J. D.; Wilde, S. E.; Dominutti, P.; Purvis, R. M.; Lowry, D.; France, J. L.; Fisher, R. E.; Fiehn, A.; Pühl, M.; Bauguitte, S. J. B.; Conley, S. A.; Smith, M. L.; Lachlan-Cope, T.; et al. Quantification and Assessment of Methane Emissions from Offshore Oil and Gas Facilities on the Norwegian Continental Shelf. *Atmos. Chem. Phys.* **2022**, *22* (7), 4303−4322.

(6) Mitchell, A. L.; Tkacik, D. S.; Roscioli, J. R.; Herndon, S. C.; Yacovitch, T. I.; Martinez, D. M.; Vaughn, T. L.; Williams, L. L.; Sullivan, M. R.; Floerchinger, C.; Omara, M.; Subramanian, R.; Zimmerle, D.; Marchese, A. J.; Robinson, A. L. Measurements of Methane Emissions from Natural Gas Gathering Facilities and Processing Plants: Measurement Results. *Environ. Sci. Technol.* **2015**, *49* (5), 3219−3227.

(7) Brown, J. A.; Harrison, M. R.; Rufael, T.; Roman-White, S. A.; Ross, G. B.; George, F. C.; Zimmerle, D. Informing Methane Emissions Inventories Using Facility Aerial Measurements at Midstream Natural Gas Facilities. *Environ. Sci. Technol.* **2023**, *57* (39), 14539−14547.

(8) Pühl, M.; Roiger, A.; Fiehn, A.; Gorchov Negron, A. M.; Kort, E. A.; Schwietzke, S.; Pisso, I.; Foulds, A.; Lee, J.; France, J. L.; Jones, A. E.; Lowry, D.; Fisher, R. E.; Huang, L.; Shaw, J.; Bateson, P.; Andrews, S.; Young, S.; Dominutti, P.; Lachlan-Cope, T.; et al. Aircraft-Based Mass Balance Estimate of Methane Emissions from Offshore Gas Facilities in the Southern North Sea. *Atmos. Chem. Phys.* **2024**, *24* (2), 1005−1024.

(9) Jervis, D.; McKeever, J.; Durak, B. O. A.; Sloan, J. J.; Gains, D.; Varon, D. J.; Ramier, A.; Strupler, M.; Tarrant, E. The GHGSat-D Imaging Spectrometer. *Atmospheric Measurement Techniques* **2021**, *14* (3), 2127−2140.

(10) Chulakadabba, A.; Sargent, M.; Lauvaux, T.; Benmergui, J. S.; Franklin, J. E.; Chan Miller, C.; Wilzewski, J. S.; Roche, S.; Conway, E.; Souri, A. H.; Sun, K.; Luo, B.; Hawthrone, J.; Samra, J.; Daube, B. C.; Liu, X.; Chance, K.; Li, Y.; Gautam, R.; Omara, M.; et al. Methane Point Source Quantification Using MethaneAIR: A New Airborne Imaging Spectrometer. *Atmos. Meas. Technol.* **2023**, *16* (23), 5771−5785.

(11) Saunois, M.; Stavert, A. R.; Poulter, B.; Bousquet, P.; Canadell, J. G.; Jackson, R. B.; Raymond, P. A.; Dlugokencky, E. J.; Houweling, S.; Patra, P. K.; Ciais, P.; Arora, V. K.; Bastviken, D.; Bergamaschi, P.; Blake, D. R.; Brailsford, G.; Bruhwiler, L.; Carlson, K. M.; Carrol, M.; Castaldi, S.; et al. The Global Methane Budget 2000−2017. *Earth System Science Data* **2020**, *12* (3), 1561−1623.

(12) Barkley, Z. R.; Lauvaux, T.; Davis, K. J.; Deng, A.; Fried, A.; Weibring, P.; Richter, D.; Walega, J. G.; DiGangi, J.; Ehrman, S. H.; Ren, X.; Dickerson, R. R. Estimating Methane Emissions From Underground Coal and Natural Gas Production in Southwestern Pennsylvania. *Geophys. Res. Lett.* **2019**, *46* (8), 4531−4540.

(13) Fiehn, A.; Kostinek, J.; Eckl, M.; Klausner, T.; Gałkowski, M.; Chen, J.; Gerbig, C.; Röckmann, T.; Maazallahi, H.; Schmidt, M.; Korbeń, P.; Nęçki, J.; Jagoda, P.; Wildmann, N.; Mallaun, C.; Bun, R.; Nickl, A.-L.; Jöckel, P.; Fix, A.; Roiger, A. Estimating CH4, CO2 and CO Emissions from Coal Mining and Industrial Activities in the Upper Silesian Coal Basin Using an Aircraft-Based Mass Balance Approach. *Atmospheric Chemistry and Physics* **2020**, *20* (21), 12675−12695.

(14) Kostinek, J.; Roiger, A.; Eckl, M.; Fiehn, A.; Luther, A.; Wildmann, N.; Klausner, T.; Fix, A.; Knote, C.; Stohl, A.; Butz, A. Estimating Upper Silesian Coal Mine Methane Emissions from Airborne in Situ Observations and Dispersion Modeling. *Atmospheric Chemistry and Physics* **2021**, *21* (11), 8791−8807.

(15) Luther, A.; Kleinschek, R.; Scheidweiler, L.; Defratyka, S.; Stanisavljevic, M.; Forstmaier, A.; Dandocsi, A.; Wolff, S.; Dubravica, D.; Wildmann, N.; Kostinek, J.; Jöckel, P.; Nickl, A.-L.; Klausner, T.; Hase, F.; Frey, M.; Chen, J.; Dietrich, F.; Nęcki, J.; Swolkień, J.; Fix, A.; Roiger, A.; Butz, A. Quantifying CH4 Emissions from Hard Coal Mines Using Mobile Sun-Viewing Fourier Transform Spectrometry. *Atmos. Meas. Tech.* **2019**, *12* (10), 5217−5230.

(16) Luther, A.; Kostinek, J.; Kleinschek, R.; Defratyka, S.; Stanisavljevic, M.; Forstmaier, A.; Dandocsi, A.; Scheidweiler, L.; Dubravica, D.; Wildmann, N.; Hase, F.; Frey, M. M.; Chen, J.; Dietrich, F.; Nęcki, J.; Swolkien, J.; Knote, C.; Vardag, S. N.; Roiger, A.; Butz, A. Observational Constraints on Methane Emissions from Polish Coal Mines Using a Ground-Based Remote Sensing Network. *Atmos. Chem. Phys.* **2022**, *22* (9), 5859−5876.

(17) Karacan, C. Ö.; Field, R. A.; Olczak, M.; Kasprzak, M.; Ruiz, F. A.; Schwietzke, S. Mitigating Climate Change by Abating Coal Mine Methane: A Critical Review of Status and Opportunities. *International Journal of Coal Geology* **2024**, *295*, 104623.

(18) Sadavarte, P.; Pandey, S.; Maasakkers, J. D.; Lorente, A.; Borsdorff, T.; Denier van der Gon, H.; Houweling, S.; Aben, I. Methane Emissions from Superemitting Coal Mines in Australia

Quantified Using TROPOMI Satellite Observations. *Environ. Sci. Technol.* **2021**, *55* (24), 16573−16580.
(19) Kholod, N.; Evans, M.; Pilcher, R. C.; Roshchanka, V.; Ruiz, F.; Coté, M.; Collings, R. Global Methane Emissions from Coal Mining to Continue Growing Even with Declining Coal Production. *Journal of Cleaner Production* **2020**, *256*, 120489.
(20) 2023 Review of the National Greenhouse and Energy Reporting Legislation. Climate Change Authority: Canberra, Australia, 2023.
(21) Australian Government; Clean Energy Regulator; National Greenhouse and Energy Reporting. Estimating Emissions and Energy from Coal Mining Guideline. 2024. https://cer.gov.au/document/estimating-emissions-and-energy-coal-mining-guideline (accessed 2024-09-17).
(22) Burra, A.; Esterle, J. Guidelines for the Implementation of NGER Method 2 or 3 for Open Cut Coal Mine Fugitive GHG Emissions Reporting (C20005). 2011. https://www.acarp.com.au/abstracts.aspx?repId=C20005 (accessed 2024-09-17).
(23) Burra, A.; Esterle, J. Technical Discussion of the Implementation of NGER Method 2 or 3 for Open Cut Coal Mine Fugitive GHG Emissions Reporting (C20005A). 2011. https://www.acarp.com.au/abstracts.aspx?repId=C20005 (accessed 2024-09-17).
(24) Sadavarte, P.; Pandey, S.; Maasakkers, J. D.; Lorente, A.; Borsdorff, T.; Denier Van Der Gon, H.; Houweling, S.; Aben, I. Rebuttal to Correspondence on "Methane Emissions from Superemitting Coal Mines in Australia Quantified Using TROPOMI Satellite Observations.". *Environ. Sci. Technol.* **2024**, *58* (12), 5629−5630.
(25) Palmer, P. I.; Feng, L.; Lunt, M. F.; Parker, R. J.; Bösch, H.; Lan, X.; Lorente, A.; Borsdorff, T. The Added Value of Satellite Observations of Methane Forunderstanding the Contemporary Methane Budget. *Philos. Trans. R. Soc. A* **2021**, *379* (2210), 20210106.
(26) Sturgiss, R. Correspondence on "Methane Emissions from Superemitting Coal Mines in Australia Quantified Using TROPOMI Satellite Observations.". *Environ. Sci. Technol.* **2024**, *58* (12), 5627−5628.
(27) Krings, T.; Gerilowski, K.; Buchwitz, M.; Hartmann, J.; Sachs, T.; Erzinger, J.; Burrows, J. P.; Bovensmann, H. Quantification of Methane Emission Rates from Coal Mine Ventilation Shafts Using Airborne Remote Sensing Data. *Atmospheric Measurement Techniques* **2013**, *6* (1), 151−166.
(28) Krautwurst, S.; Gerilowski, K.; Borchardt, J.; Wildmann, N.; Gałkowski, M.; Swolkień, J.; Marshall, J.; Fiehn, A.; Roiger, A.; Ruhtz, T.; Gerbig, C.; Necki, J.; Burrows, J. P.; Fix, A.; Bovensmann, H. Quantification of CH4 Coal Mining Emissions in Upper Silesia by Passive Airborne Remote Sensing Observations with the Methane Airborne MAPper (MAMAP) Instrument during the CO2 and Methane (CoMet) Campaign. *Atmospheric Chemistry and Physics* **2021**, *21* (23), 17345−17371.
(29) Frankenberg, C.; Thorpe, A. K.; Thompson, D. R.; Hulley, G.; Kort, E. A.; Vance, N.; Borchardt, J.; Krings, T.; Gerilowski, K.; Sweeney, C.; Conley, S.; Bue, B. D.; Aubrey, A. D.; Hook, S.; Green, R. O. Airborne Methane Remote Measurements Reveal Heavy-Tail Flux Distribution in Four Corners Region. *Proc. Natl. Acad. Sci. U. S. A.* **2016**, *113* (35), 9734−9739.
(30) Borchardt, J.; Gerilowski, K.; Krautwurst, S.; Bovensmann, H.; Thorpe, A. K.; Thompson, D. R.; Frankenberg, C.; Miller, C. E.; Duren, R. M.; Burrows, J. P. Detection and Quantification of CH4 Plumes Using the WFM-DOAS Retrieval on AVIRIS-NG Hyperspectral Data. *Atmospheric Measurement Techniques* **2021**, *14* (2), 1267−1291.
(31) Cusworth, D. H.; Duren, R. M.; Thorpe, A. K.; Olson-Duvall, W.; Heckler, J.; Chapman, J. W.; Eastwood, M. L.; Helmlinger, M. C.; Green, R. O.; Asner, G. P.; Dennison, P. E.; Miller, C. E. Intermittency of Large Methane Emitters in the Permian Basin. *Environmental Science & Technology Letters* **2021**, *8* (7), 567−573.
(32) Ayasse, A. K.; Thorpe, A. K.; Cusworth, D. H.; Kort, E. A.; Negron, A. G.; Heckler, J.; Asner, G.; Duren, R. M. Methane Remote Sensing and Emission Quantification of Offshore Shallow Water Oil and Gas Platforms in the Gulf of Mexico. *Environmental Research Letters* **2022**, *17* (8), 084039.
(33) Mehrotra, S.; Faloona, I.; Suard, M.; Conley, S.; Fischer, M. L. Airborne Methane Emission Measurements for Selected Oil and Gas Facilities Across California. *Environ. Sci. Technol.* **2017**, *51* (21), 12981−12987.
(34) Krautwurst, S.; Gerilowski, K.; Jonsson, H. H.; Thompson, D. R.; Kolyer, R. W.; Iraci, L. T.; Thorpe, A. K.; Horstjann, M.; Eastwood, M.; Leifer, I.; Vigil, S. A.; Krings, T.; Borchardt, J.; Buchwitz, M.; Fladeland, M. M.; Burrows, J. P.; Bovensmann, H. Methane Emissions from a Californian Landfill, Determined from Airborne Remote Sensing and in Situ Measurements. *Atmospheric Measurement Techniques* **2017**, *10* (9), 3429−3452.
(35) Cusworth, D. H.; Duren, R. M.; Thorpe, A. K.; Tseng, E.; Thompson, D.; Guha, A.; Newman, S.; Foster, K. T.; Miller, C. E. Using Remote Sensing to Detect, Validate, and Quantify Methane Emissions from California Solid Waste Operations. *Environmental Research Letters* **2020**, *15* (5), 054012.
(36) Cusworth, D. H.; Duren, R. M.; Ayasse, A. K.; Jiorle, R.; Howell, K.; Aubrey, A.; Green, R. O.; Eastwood, M. L.; Chapman, J. W.; Thorpe, A. K.; Heckler, J.; Asner, G. P.; Smith, M. L.; Thoma, E.; Krause, M. J.; Heins, D.; Thorneloe, S. Quantifying Methane Emissions from United States Landfills. *Science* **2024**, *383* (6690), 1499−1504.
(37) Amini, S.; Kuwayama, T.; Gong, L.; Falk, M.; Chen, Y.; Mitloehner, Q.; Weller, S.; Mitloehner, F. M.; Patteson, D.; Conley, S. A.; Scheehle, E.; FitzGibbon, M. Evaluating California Dairy Methane Emission Factors Using Short-Term Ground-Level and Airborne Measurements. *Atmospheric Environment: X* **2022**, *14*, 100171.
(38) Yu, X.; Millet, D. B.; Wells, K. C.; Henze, D. K.; Cao, H.; Griffis, T. J.; Kort, E. A.; Plant, G.; Deventer, M. J.; Kolka, R. K.; Roman, D. T.; Davis, K. J.; Desai, A. R.; Baier, B. C.; McKain, K.; Czarnetzki, A. C.; Bloom, A. A. Aircraft-Based Inversions Quantify the Importance of Wetlands and Livestock for Upper Midwest Methane Emissions. *Atmos. Chem. Phys.* **2021**, *21* (2), 951−971.
(39) Pollack, I. B.; McCabe, M. E.; Caulton, D. R.; Fischer, E. V. Enhancements in Ammonia and Methane from Agricultural Sources in the Northeastern Colorado Front Range Using Observations from a Small Research Aircraft. *Environ. Sci. Technol.* **2022**, *56* (4), 2236−2247.
(40) Krings, T.; Neininger, B.; Gerilowski, K.; Krautwurst, S.; Buchwitz, M.; Burrows, J. P.; Lindemann, C.; Ruhtz, T.; Schüttemeyer, D.; Bovensmann, H. Airborne Remote Sensing and in Situ Measurements of Atmospheric CO_2 to Quantify Point Source Emissions. *Atmospheric Measurement Techniques* **2018**, *11* (2), 721−739.
(41) El Abbadi, S. H.; Chen, Z.; Burdeau, P. M.; Rutherford, J. S.; Chen, Y.; Zhang, Z.; Sherwin, E. D.; Brandt, A. R. Technological Maturity of Aircraft-Based Methane Sensing for Greenhouse Gas Mitigation. *Environ. Sci. Technol.* **2024**, *58* (22), 9591−9600.
(42) Sherwin, E. D.; El Abbadi, S. H.; Burdeau, P. M.; Zhang, Z.; Chen, Z.; Rutherford, J. S.; Chen, Y.; Brandt, A. R. Single-Blind Test of Nine Methane-Sensing Satellite Systems from Three Continents. *Atmos. Meas. Technol.* **2024**, *17* (2), 765−782.
(43) Hacker, J. M.; Chen, D.; Bai, M.; Ewenz, C.; Junkermann, W.; Lieff, W.; McManus, B.; Neininger, B.; Sun, J.; Coates, T.; Denmead, T.; Flesch, T.; McGinn, S.; Hill, J. Using Airborne Technology to Quantify and Apportion Emissions of CH4 and NH3 from Feedlots. *Anim. Prod. Sci.* **2016**, *56* (3), 190.
(44) Krautwurst, S.; Fruck, C.; Wolff, C.; Borchardt, J.; Huhs, O.; Gerilowski, K.; Galkowski, M.; Kiemle, C.; Quatrevalet, M.; Wirth, M.; Burrows, J. P.; Gerbig, C.; Fix, A.; Bösch, H.; Bovensmann, H. Identification and Quantification of CH_4 Emissions from Madrid Landfills Using Airborne Imaging Spectrometry and Greenhouse Gas Lidar. October 29, 2024. DOI: 10.5194/egusphere-2024-3182
(45) Erland, B. M.; Adams, C.; Darlington, A.; Smith, M. L.; Thorpe, A. K.; Wentworth, G. R.; Conley, S.; Liggio, J.; Li, S.-M.; Miller, C. E.; Gamon, J. A. Comparing Airborne Algorithms for Greenhouse Gas

Flux Measurements over the Alberta Oil Sands. *Atmospheric Measurement Techniques* **2022**, *15* (19), 5841−5859.

(46) Krings, T.; Gerilowski, K.; Buchwitz, M.; Reuter, M.; Tretner, A.; Erzinger, J.; Heinze, D.; Pflüger, U.; Burrows, J. P.; Bovensmann, H. MAMAP − a New Spectrometer System for Column-Averaged Methane and Carbon Dioxide Observations from Aircraft: Retrieval Algorithm and First Inversions for Point Source Emission Rates. *Atmospheric Measurement Techniques* **2011**, *4* (9), 1735−1758.

(47) Varon, D. J.; Jacob, D. J.; McKeever, J.; Jervis, D.; Durak, B. O. A.; Xia, Y.; Huang, Y. Quantifying Methane Point Sources from Fine-Scale (GHGSat) Satellite Observations of Atmospheric Methane Plumes. *Atmos. Meas. Tech.* **2018**, *11*, 5673.

(48) SLR Consulting Australia Pty Ltd. Environment Assessment Report Hail Creek Eastern Margin Extension Project. 2024. https://environment.desi.qld.gov.au/__data/assets/pdf_file/0034/336859/a-ea-amd-100576264-enviornmental-assessment-report.pdf (accessed 2024-09-17).

(49) Geological Survey of Queensland. Queensland Petroleum Exploration Data-QPED. 2017. https://geoscience.data.qld.gov.au/data/dataset/ds000005 (accessed 2024-01-07).

(50) National Inventory Report 2022. Volume I; Department of Climate Change, Energy, the Environment and Water. 2024.https://www.dcceew.gov.au/climate-change/publications/national-inventory-report-2022 (accessed 2024-09-17).

(51) Department of Climate Change, Energy, the Environment and Water. A. G. National Greenhouse and Energy Reporting (Safeguard Mechanism). 2024. https://www.legislation.gov.au/F2015L01637/latest/details.

(52) Queensland Government. Coal Production Data by Mine, Coal Type and Financial Year. https://www.data.qld.gov.au/dataset/coal-industry-review-statistical-tables/resource/bab54159-f38b-4e6f-8652-4b04bca29139 (accessed 2024-01-10).

(53) Schneising, O.; Buchwitz, M.; Hachmeister, J.; Vanselow, S.; Reuter, M.; Buschmann, M.; Bovensmann, H.; Burrows, J. P. Advances in Retrieving XCH_4 and XCO from Sentinel-5 Precursor: Improvements in the Scientific TROPOMI/WFMD Algorithm. *Atmos. Meas. Technol.* **2023**, *16* (3), 669−694.

(54) Schneider, A.; Borsdorff, T.; aan de Brugh, J.; Aemisegger, F.; Feist, D. G.; Kivi, R.; Hase, F.; Schneider, M.; Landgraf, J. First Data Set of H2O/HDO Columns from the Tropospheric Monitoring Instrument (TROPOMI). *Atmospheric Measurement Techniques* **2020**, *13* (1), 85−100.

(55) Schneising, O.; Buchwitz, M.; Reuter, M.; Weimer, M.; Bovensmann, H.; Burrows, J. P.; Bösch, H. Towards a Sector-Specific CO/CO_2 Emission Ratio: Satellite-Based Observations of CO Release from Steel Production in Germany. *Atmos. Chem. Phys.* **2024**, *24* (13), 7609−7621.

(56) Varon, D. J.; Jacob, D. J.; McKeever, J.; Jervis, D.; Durak, B. O. A.; Xia, Y.; Huang, Y. Quantifying Methane Point Sources from Fine-Scale Satellite Observations of Atmospheric Methane Plumes. *Atmospheric Measurement Techniques* **2018**, *11* (10), 5673−5686.

(57) Clean Energy Regulator. Safeguard Facility Reported Emissions Data. 2024. https://cer.gov.au/markets/reports-and-data/safeguard-facility-reported-emissions-data (accessed 2024-09-17).

(58) Saghafi, A.; Williams, D. J.; Lama, R. D. Worldwide Methane Emissions from Underground Coal Mining. In *Proceedings of the 6th International Mine Ventilation Congress*; Ramani, R. V., Ed.; Society for Mining, Metallurgy, and Exploration, Inc.: Pittsburgh, PA, 1997; pp 441−445.

(59) Saghafi, A. A Tier 3 Method to Estimate Fugitive Gas Emissions from Surface Coal Mining. *International Journal of Coal Geology* **2012**, *100*, 14−25.

(60) Saghafi, A. Estimating Greenhouse Gas Emissions from Open-Cut Coal Mining: Application to the Sydney Basin. *Australian Journal of Earth Sciences* **2014**, *61* (3), 453−462.

(61) Saghafi, A.; Day, S.; Williams, D.; Roberts, D.; Quintanar, A.; Carras, J. Toward the Development of an Improved Methodology For Estimating Fugitive Seam Gas Emissions From Open Cut Mining (ACARP Project C9063). ACARP Publications, 2003. https://www.acarp.com.au/abstracts.aspx?repId=C9063.

(62) Saghafi, A.; Day, S.; Carras, J. Gas Properties of Shallow Bowen Basin Coal Seams and Gas Leaks to the Atmosphere. In *Bowen Basin Symposium 2005, The Future for Coal, Fuel for Thought*; Beeston, J. W., Ed.; GSA Coal Geology Group: Yeppoon, Queensland, Australia, 2005; pp 267−271.

(63) Saghafi, A.; Day, S. J.; Fry, R.; Quintanar, A.; Roberts, D.; Williams, D. J.; Carras, J. N. Development of an Improved Methodology for Estimation of Fugitive Seam Gas Emissions from Open Cut Mining (ACARP Project C12072). ACARP Publication; CSIRO Investigation Report ET/IR 742005. https://www.osti.gov/etdeweb/biblio/20674478.

(64) Qu, Q.; Balusu, R.; Belle, B. Specific Gas Emissions in Bowen Basin Longwall Mines, Australia. *International Journal of Coal Geology* **2022**, *261*, 104076.

(65) Boreham, C. J.; Golding, S. D.; Glikson, M. Factors Controlling the Origin of Gas in Australian Bowen Basin Coals. *Org. Geochem.* **1998**, *29* (1−3), 347−362.

(66) Australian Government. Australia's National Greenhouse Accounts. https://www.greenhouseaccounts.climatechange.gov.au (accessed 2024-11-29).

(67) Queensland Government. Bowen Basin Population Report, 2023. 2024. https://www.qgso.qld.gov.au/issues/3366/bowen-basin-population-report-2023.pdf (accessed 2024-11-29).

(68) Conley, S.; Faloona, I.; Mehrotra, S.; Suard, M.; Lenschow, D. H.; Sweeney, C.; Herndon, S.; Schwietzke, S.; Pétron, G.; Pifer, J.; Kort, E. A.; Schnell, R. Application of Gausss Theorem to Quantify Localized Surface Emissions from Airborne Measurements of Wind and Trace Gases. *Atmospheric Measurement Techniques* **2017**, *10* (9), 3345−3358.