

Characterising Methane Concentration Variability at Coal Stockpiles in a Surface Coal Mine

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Abstract

The spatiotemporal variability of atmospheric methane concentration at surface coal mines remains insufficiently characterised. The impact of local meteorology and mining activities on methane emission have not yet been fully evaluated. In this study, ground observations of the methane concentration along with meteorology were carried out around coal stockpiles (CSP) in an active surface coal mine in Australia for a continuous 110 days. A network of 16 semiconductor metal oxide sensors (MOS) was deployed to characterise spatiotemporal variability of near surface atmospheric methane. The mean 15-minute maximum and average CH₄ concentrations were approximately 10.40 ppm and 6.09 ppm, respectively which were higher than the mean atmospheric background (~2 ppm). Short-duration methane plumes produced substantial spatial variability across the sensor network, with sensor-mean CH₄ average concentrations ranging from 4.40 ppm to 12.08 ppm and sensor-mean CH₄ maximum concentrations ranging from 5.50 ppm to 28.31 ppm. The maximum CH₄ concentration of 251.8 ppm was recorded during observations, indicating episodic interception of concentrated methane plumes. Clear diurnal variability in methane concentrations was observed, with peaks during the late night and early morning and lower, more consistent concentrations at midday, indicating near-surface methane accumulation. Upwind-downwind analysis showed that mean upwind CH₄ concentrations remained above the atmospheric background, suggesting contributions from sources within the broader surrounding environment. Downwind CH₄ concentrations showed a mean enhancement of 2.39 ppm above upwind levels. The observed variability reflected impact of multiple factors, including coal-handling activity and local meteorological conditions. The highest concentrations occurred when source activity coincided with conditions favouring plume retention or transport towards the sensor network. Elevated mean CH₄ concentrations were most frequently observed with 50–80% relative humidity and temperatures of 5–15 °C. These findings demonstrate that methane concentrations were highly intermittent, temporally episodic and spatially heterogeneous, with high concentrations being rare but recurrent.

Keywords: Coal mine methane; Surface coal mine; Coal stockpile; Metal oxide sensor

1. Introduction

Atmospheric methane is one of the major drivers of anthropogenic radiative forcing and, after carbon dioxide, the second-largest contributor to global warming (Etmann et al., 2016; Li et al., 2022). Methane has a global warming potential (GWP) approximately 84 times that of CO₂ over a 20-year horizon and 28

61 times that of CO₂ over a 100-year horizon the GWP-100 value forming the reporting basis under Australia's
62 National Greenhouse and Energy Reporting (NGER) scheme and the International Panel on Climate
63 Change (IPCC) with an atmospheric lifetime of approximately 10-12 years (Myhre et al., 2014 ; Li et al.,
64 2022; Prather et al., 2012): therefore, targeted reductions in anthropogenic methane emissions are
65 important for achieving near-term temperature stabilisation goals (UNEP, 2022). Anthropogenic activities
66 account for approximately two-thirds of global methane emissions and within these, the energy sector is
67 a major contributor, emitting an estimated 145 Mt of CH₄ in 2024 and representing about 35% of total
68 human-induced methane emissions (IEA, 2025). Within the energy sector, coal mining contributed
69 approximately 40 Mt in 2024, equivalent to ~27% of total energy sector methane emissions (IEA, 2025).
70 Despite regional declines in coal production, global methane emissions from this sector are expected to
71 remain substantial, underscoring the need for enhanced monitoring approaches and more effective
72 mitigation strategies (Kholod et al., 2020).

73 Both underground and surface coal mines emit methane and are referred to as coal mine methane (CMM)
74 sources. In underground coal mines, most methane emission occurred by exhausted gases through
75 ventilation shafts and referred as ventilation air methane (VAM). These emissions are relatively persistent
76 and spatially discrete release points that can often be more readily identified and quantified (Karacan et
77 al., 2025). In contrast, methane emissions from surface coal mines arise primarily from exposed coal
78 seams, active pit faces, final pit floors, highwalls, blast-induced fracture, coal haulage and stockpiles
79 creating multiple spatially distributed and temporally variable emission sources (Saghafi et al., 2012). The
80 distributed source structure may produce spatially diffuse and temporally variable methane signals,
81 making source characterisation and attribution more challenging (Chauhan and Raval, 2025; Saghafi et al.,
82 2012). Under these conditions, top-down (TD) quantification methods may suffer with large uncertainties
83 and limiting the independent verification of bottom-up (BU) inventories (Baasansuren et al., 2019;
84 Chauhan and Raval, 2025).

85 Surface coal mines contribute approximately 80% of Australia's total coal production (Geoscience
86 Australia, 2025). Under the National Greenhouse and Energy Reporting (NGER) Scheme, Method 1
87 estimates methane emissions from open-cut mines using run-of-mine (ROM) coal production and a state-
88 specific emission factor, whereas Methods 2 and 3 incorporate mine-specific coal-core gas data and
89 geological gas-distribution modelling (CER, 2026a). For FY2024–25, 27 open-cut coal mines in Australia
90 regulated under the Safeguard Mechanism reported fugitive methane emissions using Method 2, while
91 21 open-cut coal facilities reported using Method 1 (CER, 2026b). From July 2026, open-cut mines
92 regulated under the Safeguard Mechanism are required to apply either Method 2 or Method 3. In contrast,
93 methane emissions from underground mines are generally quantified using Method 4, which is based on
94 direct measurements of VAM and other forms of coal mine waste gas (CER, 2025; 2026a, b). Underground
95 coal mines feature confined and well-controlled ventilation pathways and are required to undertake in-
96 mine atmospheric monitoring for health and safety purposes. Together, these factors create favourable
97 conditions for obtaining highly accurate direct measurements of methane emissions. In contrast, open-
98 cut coal mines are exposed to the atmosphere and do not possess confined or controlled ventilation
99 pathways, increasing the complexity and uncertainty associated with direct emissions measurement. To
100 date, atmospheric measurement approaches for open-cut coal mines remain outside established IPCC and

national inventory reporting frameworks and have not been sufficiently developed or validated for routine inventory reporting purposes. Early satellite-based top-down (TD) estimates indicated substantial discrepancies between reported emissions and observation-derived emission rates. Sadavarte et al. (2021) estimated methane emissions from the Hail Creek mine to be approximately 35 times higher than the corresponding bottom-up estimate. However, the mine operator raised concerns regarding inaccurate information related to their coal production and operations used in the study (Glencore, 2022). Palmer et al. (2021) also reported substantially lower emissions, although their top-down estimates still exceeded the BU inventory by ~2.5 times. Also, satellite measurements provide spatially integrated snapshots acquired at discrete overpass times, limiting their ability to resolve short-term emission variability driven by mining activities and changing atmospheric conditions at surface coal mines (Chauhan and Raval, 2025; Karacan et al., 2011; Miller et al., 2013). Recently, aircraft-based remote-sensing methods have also been used to estimate methane emissions in Australia using short-duration observations. Neiningner et al. (2021) conducted the aircraft-based quantification of the coal seam gas (CSG) in Australian coal basin and reported a discrepancy between the BU and TD emission estimates. Borchardt et al. (2025) further used two aircrafts (in-situ and remote sensing) for methane observation and estimated the emission rates of a coal mine in Australia. The resulting annualised methane emission estimates were approximately three to eight times higher than the operator-reported annual averages (Borchardt et al., 2025). However, the mine operator raised concern regarding the discrepancy in the reported BU estimates which was not reflecting their transition from Method 1 to Method 2 (Glencore, 2025). Further, Harris et al. (2026) conducted observations based on two aircrafts (remote sensing and in situ) and estimated the emission rates for 17 coal mines. The estimates by Harris et al. (2026) also reported a difference between the reported BU and estimated TD emission rates for surface coal mines. Aircraft measurements have better spatial resolution than satellites, but they are limited in their temporal resolution and require extrapolation to derive annual emission estimates. In contrast, continuous ground-based monitoring provides high-frequency measurements capable of capturing the temporal variability and intermittency of methane emissions (Swolkień et al., 2022; Karacan et al., 2025). Carras et al. (2000) conducted a measurement of the greenhouse gas emission (both CO₂ and CH₄) using chamber methods in eleven mines in Hunter Vally and Bowen Basin and estimated the emission rates for a limited period. However, the large spatial extent and dynamic nature of surface coal mines make the deployment and maintenance of these sensors operationally and logistically challenging (Saghafi et al., 2005). The discrepancy between BU and TD estimated using satellite, aircraft or limited ground-based observation for surface coal mines, highlights the need to characterise the spatiotemporal variability of atmospheric coal mine methane. Consequently, there remains a need to develop practical observation strategies that are suitable for these complex environments, while assessing the influence of mining activities and meteorological conditions.

For ground-based observation of methane various sensing technologies are developed such as cavity ring down spectroscopy (CRDS; Berden et al., 2000), Tunable Diode Laser Absorption Spectroscopy (TDLAS; Xu et al., 2026), Fourier transform infrared (FTIR) spectroscopy (Zellweger et al., 2016), semiconductor MOS (Wang et al., 2026) and others. Each sensing technology come with own merits, limitation and operational challenges. Metal-oxide semiconductor (MOS) sensors offer a potentially suitable approach for high-frequency methane monitoring because of their compact size, low power requirements, lightweight design, and relatively low operating cost (Masson et al., 2015; Nabil Abdullah et al., 2020; Chen et al.,

2025). These sensors can be integrated with compact electronic boards and wireless communication modules to form internet-connected, distributed monitoring networks. These sensors can be integrated into a network when deployed across an area in a surface coal mine, such networked systems can provide near-real-time methane observations with improved spatial and temporal coverage compared. However, their effective application requires careful calibration and correction for environmental influences, including temperature, humidity, cross-sensitivity, baseline drift, and long-term sensor ageing (Furuta et al., 2024; Eugster and Kling, 2012). These challenges compound at operational scale because mine sites span tens of kilometres, resolving a site-level emission rate demands either a dense sensor network or repeated mobile surveys both costly and challenging to deploy and maintain, particularly in a dynamic remote mine environment.

To understand the variability of the emissions, we deployed a ground-based network of 16 sensors at CSP in an Australian surface coal mine to measure near-surface methane concentrations and associated meteorological parameters. To our knowledge, this represents the first ever deployment of a sensor array of this scale for methane monitoring at the CSP in an active surface mine. The study evaluates CSP-wide temporal variability and investigates how observed methane patterns are influenced by local meteorological conditions and mining activities. This kind of observations form the basis of source localisation and emission-rate estimation that is outside the scope of this study and will require additional analysis.

2. Site Description

The study was conducted at an active surface coal mine in Australia. This coal mine is also surrounded by a range of other underground and open-cut coal mines and is proximate to agricultural methane sources. The exact site location is withheld for confidentiality reasons. Measurements were undertaken within the coal stockpiles (CSP) area, where 16 ground-based metal-oxide semiconductor sensors (MOS1–MOS16) were deployed across approximately 0.25 km² (Figure 1).



Figure 1: Site layout of the Coal Stockpiles (CSP) showing the locations of the 16 monitoring sensors (MOS1–MOS16), marked by red pins. Blue shading denotes the conveyor belt, while the yellow pathway indicates the road around the CHPP for movement. The stockpile can be divided into the North Stockpile (NSP) and the South Stockpile (SSP), which serve as the main coal storage areas. Green shading indicates surrounding vegetated areas.

Sensor locations were selected in accordance with site-access and safety requirements while maintaining exposure to the principal operational areas. The CSP comprises two sections: the North Stockpile (NSP) and the South Stockpile (SSP). During the study period, the NSP remained operational, with continuous coal inflow and outflow movements. These two coal-movement streams were combined and represented as total CSP coal activity. The operational dataset contained the start and end times of each coal activity period and was subsequently resampled to an hourly resolution. The SSP remained inactive throughout the study period, with no recorded coal inflow or outflow. The strategically deployed sensors were able

to capture both upwind and downwind methane which helped create a useful gradient of expected methane influences across the monitoring network. The proximity of the sensors to the CSP facilitated the detection of methane concentration enhancements primarily associated with CSP operations. However, the site was also influenced by surroundings that might affected some observations and might reflected methane enhancement in upwind concentrations.

3. Data and Methods

3.1 Monitoring Network and Variables

Methane measurements were obtained using the semiconductor MOS developed by Qube Technologies Inc, a ground-based monitoring platform designed for continuous methane detection under outdoor industrial conditions. Each field unit incorporated semiconductor metal-oxide sensor for methane sensing, anemometer for wind (speed and direction) and other sensors for temperature and relative humidity (RH). Each MOS mounted at 1.5 m AGL (Figure 2).



Figure 2: Deployed MOS point sensors at the mine site for continuous methane monitoring. Each metal oxide sensor was mounted on a moonlander stand capable of withstanding wind speeds exceeding 100 km/h and secured to prevent any lateral movement. Sensors were powered by rear-mounted solar panels and internal Li-ion batteries, enabling continuous operation without external backup. An anemometer installed above each unit measured wind speed and direction. All devices were geolocated, with coordinates uploaded to the cloud upon activation.

Detection is based on the change in the sensing layer's electrical resistance in the presence of methane. MOS offers an accuracy of approximately 1 ppm over a 0–100 ppm range, extendable to higher concentrations (Qube Technologies, 2024). As MOS sensors are prone to drift from environmental conditions and ageing, each is individually calibrated with real-time temperature and humidity compensation and an automated baselining process to minimise drift. The methane, temperature, and RH sensors were housed within a weather-protected enclosure powered by a solar-assisted rechargeable battery system, while the anemometer was mounted above the enclosure. Temperature and RH were measured close to the methane-sensing element to characterise its operating environment and support environmental compensation of the raw sensor response during methane retrieval. These values were considered as ambient value for this study however there might be slight variations between the actual and considered values. The meteorological measurements were used both to interpret methane transport and dispersion and to assess potential environmental influences on sensor performance (U.S. EPA, 2026; Zhao et al., 2024; Borowski et al., 2025). The resulting methane data represented near-surface concentrations measured at each sensor location. All measurements were recorded at high temporal resolution and transmitted to a cloud-based platform for storage and processing. The present analysis covers observations collected by the MOS sensor network from 11 July to 28 October 2025.

3.2 Data Processing and Definitions

The sensor calibration and baseline correction for methane and meteorological parameters were performed by Qube Technology Inc. based on their processing framework. The two-methane metrics were considered throughout the paper: CH₄ avg and CH₄ max. CH₄ avg was the mean methane concentration at the hourly scale, and CH₄ max was the maximum methane concentration observed within the same hourly aggregation window based on the 15-minute mean values. The site-level mean and maximum concentrations were calculated across all observations from the individual sensors. Meteorological variables were analysed in the same hourly framework to permit direct comparison with methane variability across timescales. Daily values were calculated from the hourly aggregated dataset by resampling all hourly observations to daily resolution and computing the arithmetic mean for each day. All sensors operated continuously throughout the study period. We further carried out the upwind-downwind analysis of the methane concentration at CSP which provided evidence that wind direction also influenced the inter sensor methane pattern. The 360° wind fields were divided into four directional categories: Cat 1: Northerly (315–45°), Cat 2: Easterly (45–135°), Cat 3: Southerly (135–225°), and Cat 4: Westerly (225–315°). For each hourly observation, the measured wind direction determined the active category. Sensors located on the incoming airflow side relative to the prevailing wind direction were classified as upwind, whereas sensors located sequentially along the airflow path were classified as downwind. Mean CH₄ avg concentrations were then calculated separately for the upwind and downwind sensor groups within each wind-direction category.

4. Results

This section examines the temporal variability of methane concentrations and meteorological conditions, together with CSP-scale spatial variability.

4.1 Temporal Variability of CH₄ Concentration and Meteorology

The daily mean values of the methane concentration (CH₄ avg and CH₄ max) along with all meteorological parameters (temperature, RH, wind speed and pressure) as well as coal activity were analysed and compared (Figure 3).

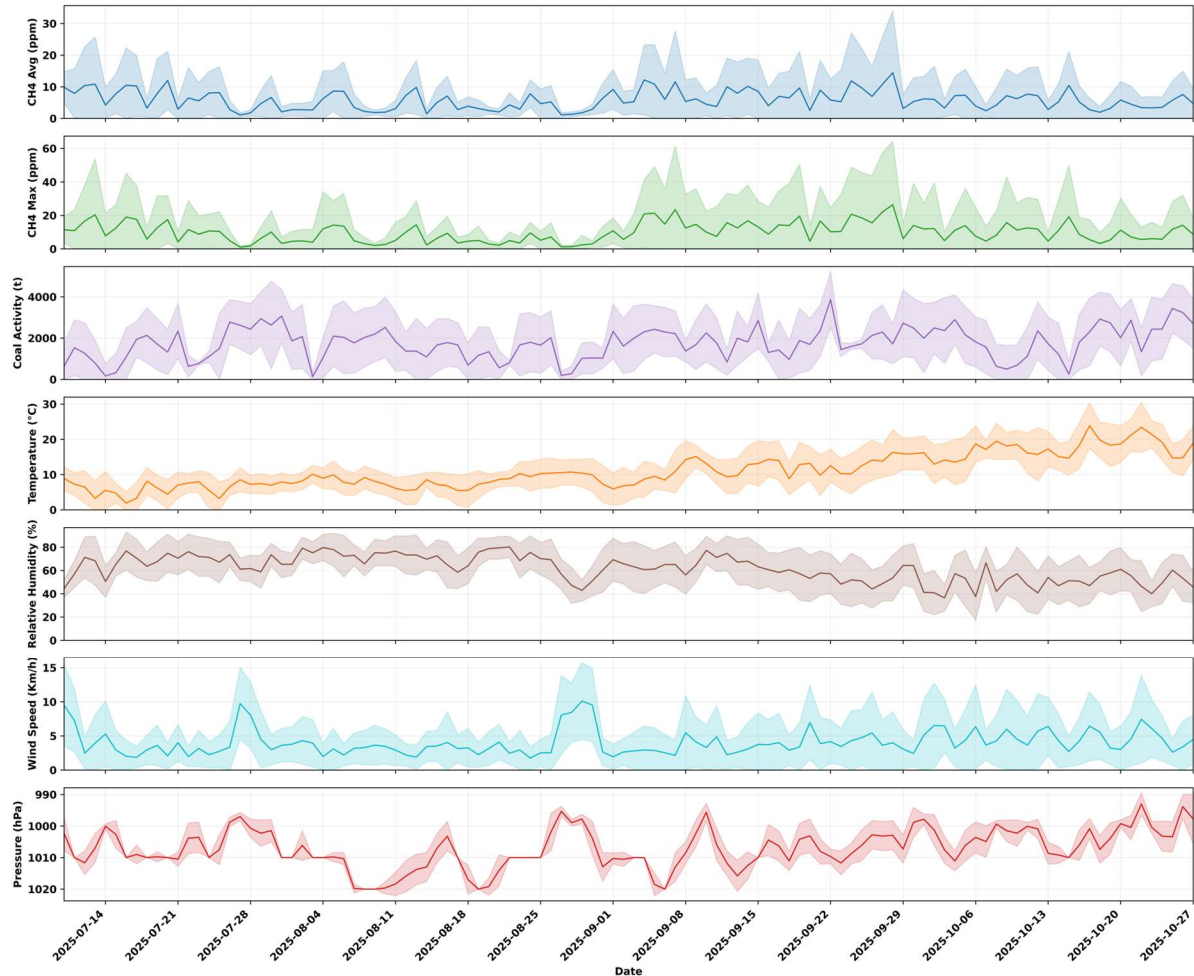


Figure 3: Variation in network-wide daily mean methane concentrations and meteorological conditions during the study period. Panels show daily mean CH₄ avg (ppm), CH₄ max (ppm), coal activity (t), temperature (°C), relative humidity (%), wind speed (km h⁻¹), and pressure (kPa), with shaded envelopes indicating Standard Deviation (SD) across observations.

Methane concentrations at the CSP showed strong temporal variability across daily scales. Across the full monitoring period from 11 July to 28 October 2025, both CH₄ avg and CH₄ max and were highly non-stationary, with short-duration enhancement events superimposed on periods of lower concentration. Daily mean CH₄ avg ranged from 1.06 to 14.45 ppm while the daily mean CH₄ max ranged from 1.06 to 26.39 ppm. The highest daily values for both metrics occurred on 28 September 2025. During July and August, elevated daily mean CH₄ (avg and max) concentrations were relatively isolated, and concentrations frequently returned to lower levels. From early September onward, both the daily mean of CH₄ avg and CH₄ max were elevated more frequently, with clusters of high-concentration events

occurring particularly in early and late September. This temporal pattern indicated that methane enrichment was episodic rather than characterised by a gradual or sustained increase throughout the campaign. Across the study period, CH₄ max exhibited larger amplitudes and wider standard-deviation envelopes than CH₄ avg, with within-day standard deviations reaching 37.96 and 19.51 ppm, respectively. These results indicated that the strongest methane enhancements occurred as short-duration concentration peaks rather than as uniformly elevated background concentrations. Further, monthly mean of the CH₄ avg and CH₄ max represented significant temporal variability (Figure 4).

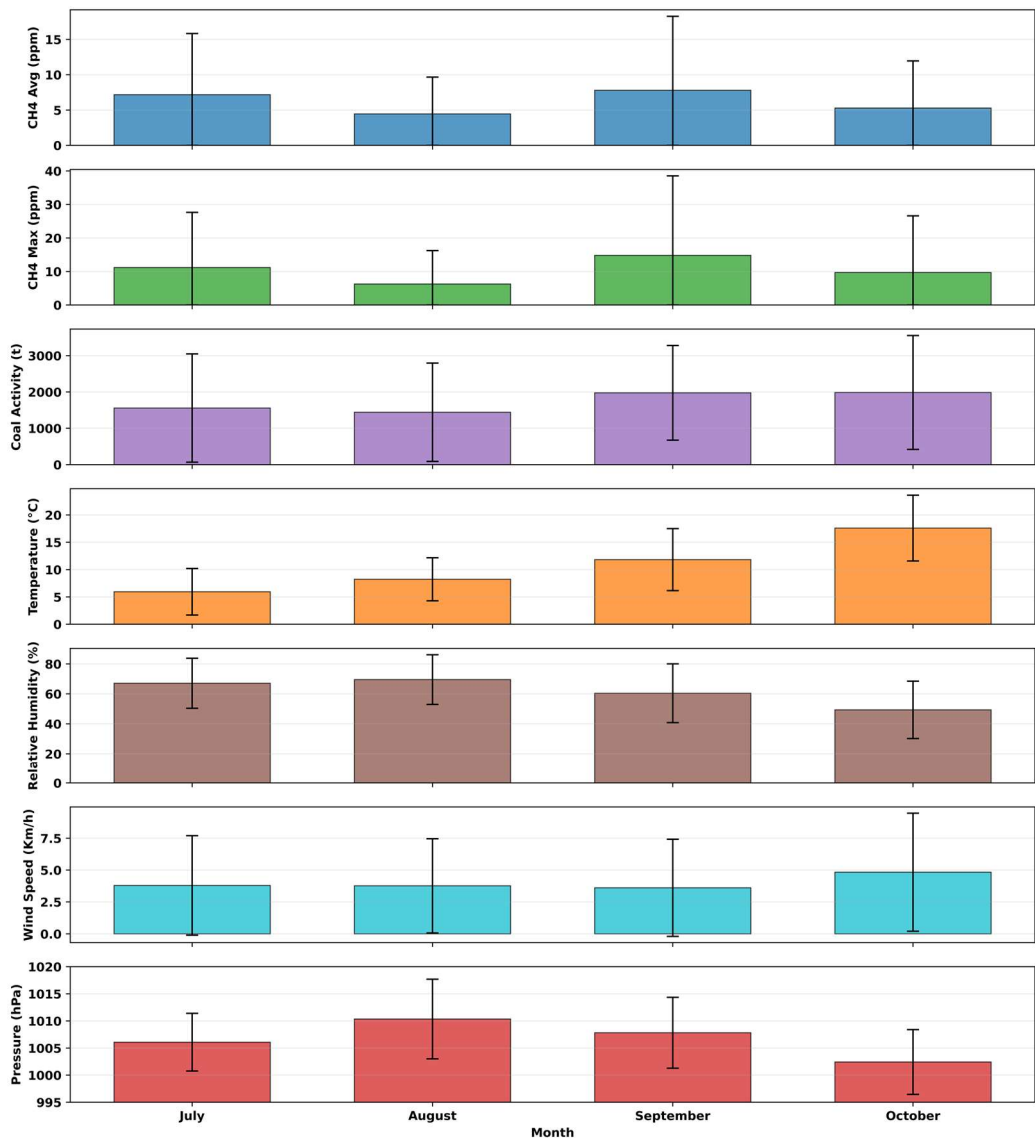


Figure 4: Monthly mean variation in CH₄ avg (ppm), CH₄ max (ppm), coal activity (t), temperature (°C), relative humidity (%), wind speed (km h⁻¹), and pressure (hPa) over the study period.

Monthly mean CH₄ avg declined from 7.18 ppm in July to 4.45 ppm in August, increasing to 7.79 ppm in September, and decreasing again to 5.28 ppm in October. Monthly mean CH₄ max followed the same

pattern and declined from approximately 11.18 ppm in July to 6.26 ppm in August, increased sharply to
 14.80 ppm in September, and then decreased to 9.68 ppm in October. Along with highest monthly
 methane concentrations, methane variability was also greatest in September, with the standard deviation
 of CH₄ max reaching approximately 23.72 ppm compared with 16.46 ppm in July, 9.99 ppm in August, and
 16.92 ppm in October. The equivalent standard deviations for CH₄ avg were lower in comparison to CH₄
 max however both parameters showed similar monthly ordering, with the highest spread in September.
 Atmospheric methane concentrations near the surface might exhibit significant diurnal variability due to
 boundary-layer dynamics and coal activity. So, we further analysed the diurnal variability of the methane
 (avg and max) for the whole observation period (Figure 5).

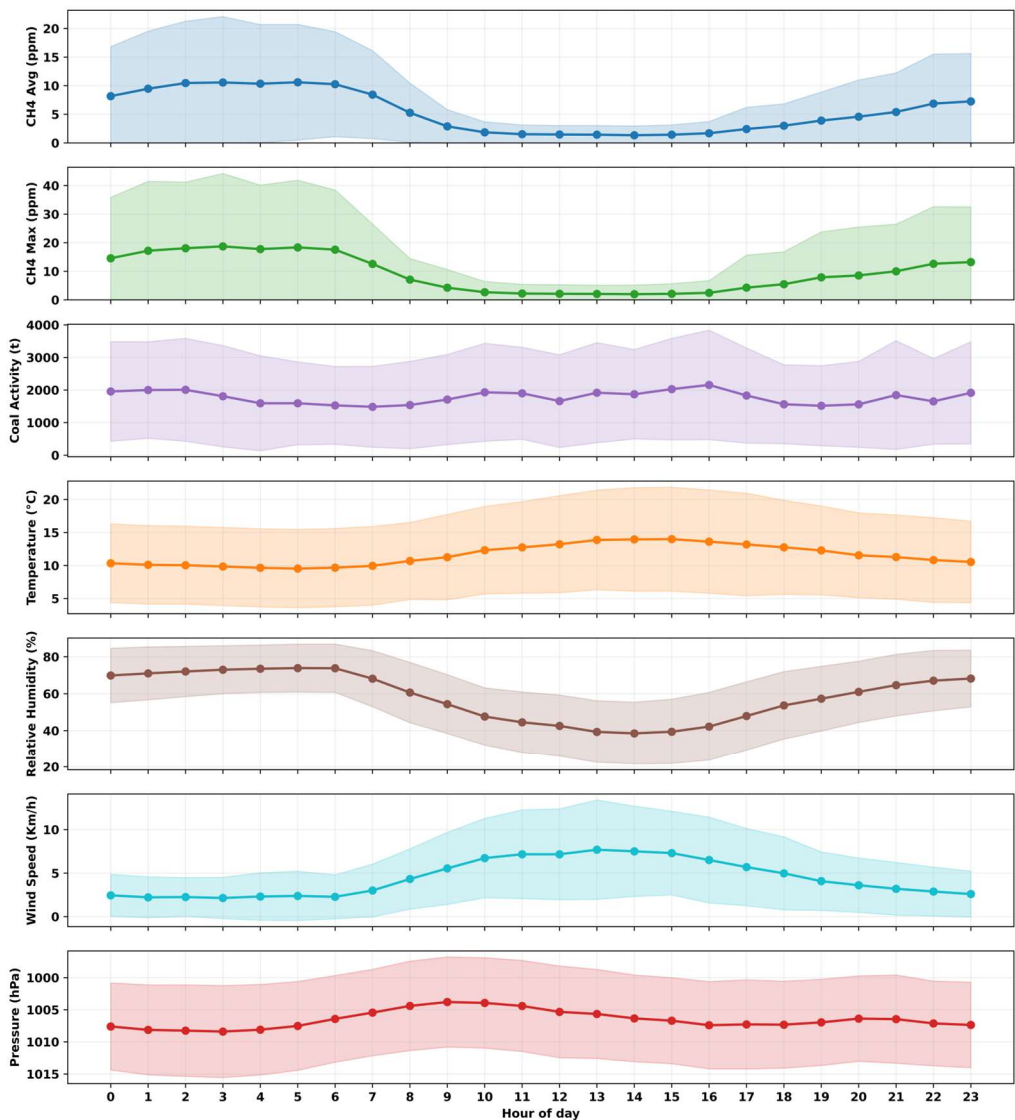


Figure 5: Diurnal Variation in CH₄ avg (ppm), CH₄ max (ppm), coal activity (t), temperature (°C), relative humidity (%),
 wind speed (km h⁻¹), and pressure (hPa) over the study period.

The highest CH₄ avg was approximately 9.47-10.57 ppm between 01:00 and 06:00, a daytime minimum of approximately 1.34-1.69 ppm from late morning to afternoon, and a gradual evening recovery. A similar pattern was also observed with CH₄ max, where it was highest during the late night and early morning, increasing from approximately 14.56 ppm at 00:00 to a broad peak of 17.20-18.71 ppm between 01:00 and 06:00. After sunrise, CH₄ max declined rapidly, reaching approximately 7.08 ppm at 08:00 and a daytime minimum of about 2.00-2.21 ppm between 11:00 and 15:00. CH₄ max then increased again during the evening, reaching 12.64-13.22 ppm by 22:00-23:00. The diurnal variability was consistent with the concentration pattern. The standard deviation of CH₄ max was largest overnight and before sunrise, reaching approximately 20.88-25.51 ppm between 00:00 and 06:00, before narrowing to approximately 3.04-4.27 ppm during the middle of the day. CH₄ avg showed the same behaviour, with larger overnight variability and much smaller midday variability. Thus, night-time and early-morning periods were characterised by both higher methane concentrations and stronger short-term fluctuations, whereas daytime periods showed lower and more stable methane concentrations.

The variability in the coal activity at CSP was further analysed. It also varied across months and provided operational context for the methane observations. Mean coal activity decreased slightly from July to August, from approximately 1557.24 to 1441.00 t, before increasing to 1975.53 t in September and remained at a similar level in October. From July to September, this pattern broadly coincided with the monthly methane pattern, with lower methane concentrations in August and higher methane concentrations in September. However, methane concentrations declined in October despite continued high coal activity, indicating that the monthly methane pattern did not follow coal activity alone. The diurnal variability in coal activity was also observed but it was not synchronous with the methane concentration. In morning hours, it reached to its first peak (2006.91 t) between 3:00 to 4:00 AM and later fell continuously and reached to its first lowest value (1484.69 t) during 7:00 to 8:00 AM. After this, activity started increasing and reached to its highest peak (2156.32 t) between 4:00 to 5:00 PM and next lowest value (156.71) between 7:00 to 8:00 PM and started to increase again. However, except early morning and nighttime highs, the afternoon peak in coal activity showed a contrasting nature with methane concentration. This highlighted that coal activity had relationship with the methane enhancement however there were other factors that also impacted the plume dynamics leading to change in the methane concentration. So, the temporal variability of the meteorology at CSP was also analysed.

Meteorological variables showed consistent temporal structure across the monitoring period. Daily wind speeds were generally low, with most daily means below 5 km h⁻¹. Monthly mean wind speed was similar from July to September, at approximately 3.61-3.79 km h⁻¹, before increasing to about 4.83 km h⁻¹ in October. At the diurnal scale, wind speed was weakest overnight and in the early morning, approximately 2.14-2.45 km h⁻¹ between 00:00 and 06:00, and strongest during late morning to early afternoon, approximately 6.73-7.69 km h⁻¹ between 10:00 and 14:00. Temperature increased seasonally from July to October and showed a clear diurnal cycle, with lower values overnight and higher values during the day. Relative humidity showed the opposite diurnal pattern, remaining highest overnight and lowest during the afternoon. Pressure varied only modestly at daily, monthly, and diurnal scales.

Overall, methane concentrations at the CSP were temporally structured rather than random. September showed the highest monthly methane concentrations and the greatest variability and the late night to early morning period showed the strongest diurnal enhancement. CH₄ max consistently displayed greater amplitude and variability than CH₄ avg, indicating that short-duration concentration peaks were a major component of the observed methane concentration. Coal activity provided important operational context, but measured methane concentrations were not proportional to coal activity at all temporal scales. The observed temporal patterns therefore provided evidence of strong episodic near-surface methane behaviour, substantial day-to-day and month-to-month variability, and a pronounced nocturnal-to-early-morning enhancements.

4.2 Inter-Sensor Variability of Methane

Methane concentrations showed clear inter-sensor variability across the monitoring network, indicating that methane was not distributed uniformly across the CSP site (Figure 6).

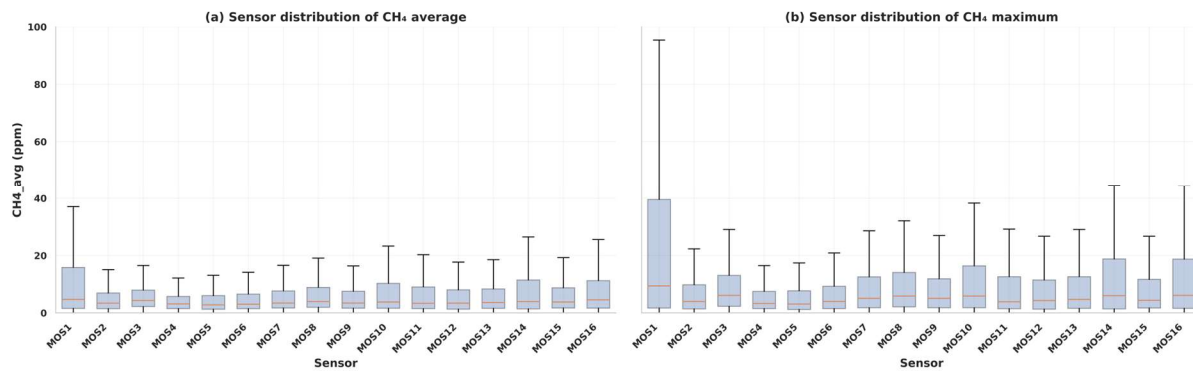


Figure 6: Inter-sensor distribution of methane concentrations shown as boxplots for (a) CH₄ avg and (b) CH₄ max across the monitoring network.

The strongest methane signal was observed at MOS1, which consistently recorded the highest concentrations and the widest spread in both CH₄ avg and CH₄ max. MOS1 recorded the highest mean and median values for CH₄ avg, with values of 12.08 ppm and 4.69 ppm, respectively. The largest variability, with a standard deviation of 17.47 ppm and a maximum recorded CH₄ avg value of 149.79 ppm was also reported at this sensor. In contrast, MOS4 and MOS5 recorded lower median of 3.15 ppm and 2.80 ppm with corresponding means of 4.40 ppm and 4.57 ppm respectively.

The contrast among sensors was stronger for CH₄ max than for CH₄ avg. MOS1 again recorded the highest values across the network, with a median CH₄ max of 9.40 ppm, a mean of 28.31 ppm, and a standard deviation of 41.77 ppm. The maximum recorded CH₄ max values at MOS1 reached 251.80 ppm. A secondary group of elevated sensors included MOS16, MOS14, MOS10, and MOS11, which recorded maximum values of 136.50 ppm, 175.20 ppm, 137.40 ppm, and 167.80 ppm. The maximum CH₄ max value at MOS1 was approximately 5.2 times higher than MOS4, 3.3 times higher than MOS5, and 3.0 times

higher than MOS6. The daily mean CH₄ heatmap further showed that this inter-sensor contrast persisted through time rather than being caused by a single isolated event (Figure 7a and 7b). The white cells in the Figure 7a and the black cells in Figure 7b indicated missing or invalid daily mean values and were excluded from the interpretation.

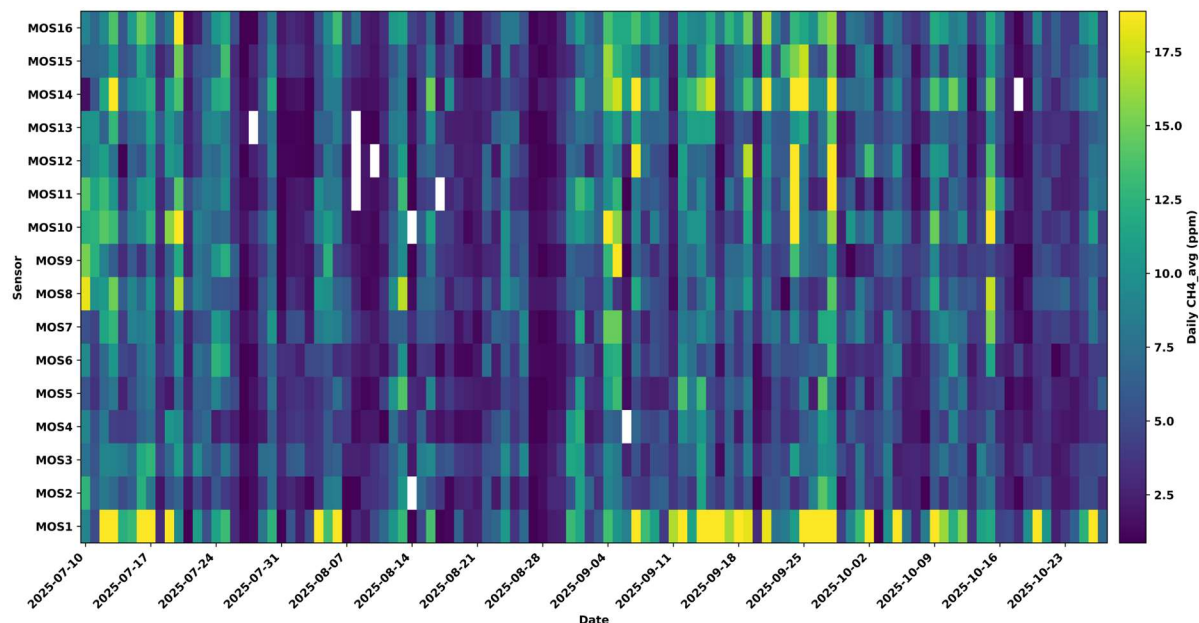


Figure 7a: Daily mean CH₄ concentration (ppm) recorded by each of the 16 sensors (MOS1–MOS16) at the CSP. White cells indicate days with no valid data or missing data for that sensor.

Each row represented one sensor, and each column represented one monitoring day, allowing both temporal and inter sensor spatial differences to be assessed simultaneously. MOS1 showed the most persistent high-concentration signal across the campaign, with repeated elevated daily mean CH₄ avg values in July, September, and October. Based on the daily mean data, MOS1 had the highest campaign-mean daily CH₄ avg concentration. MOS14, MOS16, and MOS10 formed a secondary elevated group. In contrast, MOS4, MOS5, MOS6, and MOS2 generally remained at the lower end of the daily mean distribution. The elevated methane was not spatially uniform on high-concentration days. Several days in September showed elevated daily CH₄ avg values across multiple sensors, particularly around early September and late September. However, the intensity of these events differed substantially between sensors. MOS1 frequently showed the strongest daily enhancement, whereas other sensors showed intermittent or weaker responses. MOS10, MOS11, MOS12, MOS14, and MOS16 also recorded elevated daily mean concentrations on specific days irrespective of MOS1 concentration. The daily mean anomaly analysis, presented in Figure 7b, provides a complementary view by normalising each sensor's daily mean CH₄ avg against the mean of all 16 sensors on that same day.

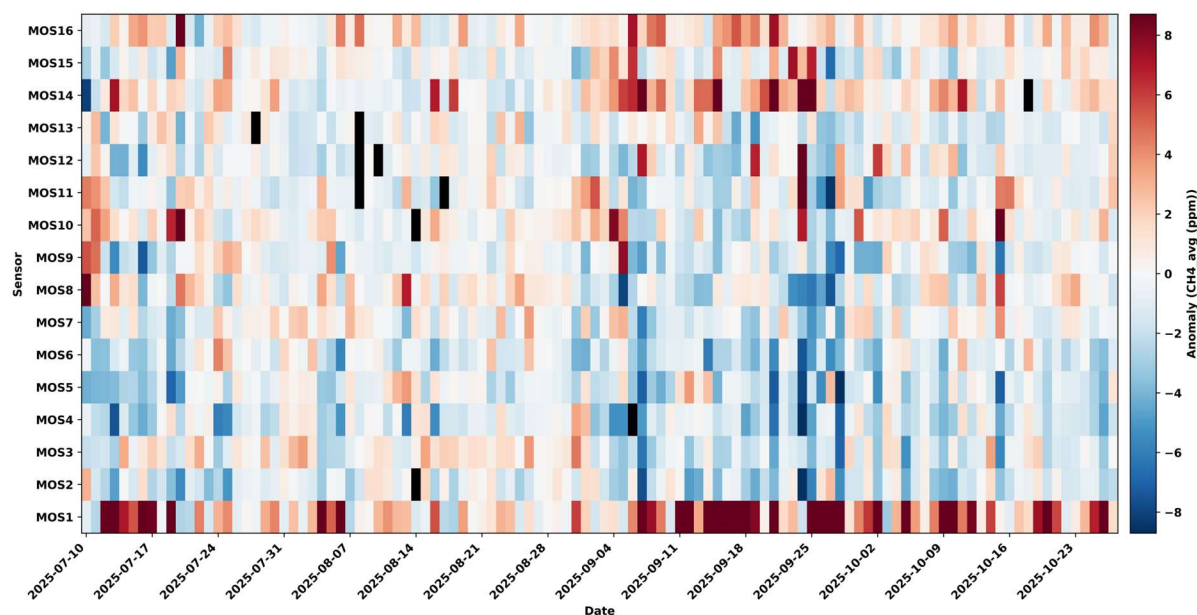


Figure 7b: Daily CH₄ avg concentration anomalies (ppm) for each of the 16 sensors at the CSP. Black cells indicate missing data.

Based on this analysis, we were able to distinguish sensors with high concentration relative to the network on the specific day by removing the influence of campaign-wide concentration fluctuations. MOS1 displayed the largest positive anomalies throughout the campaign, with a mean anomaly of +5.66 ppm for CH₄ avg. The strongest positive daily anomaly occurred at MOS1 on 28 September, when its daily mean CH₄ avg exceeded the mean by approximately 43.46 ppm. MOS1 also showed positive anomalies on 27 September (+40.26 ppm), 7 September (+29.49 ppm), and 16 July (+28.76 ppm). MOS14 and MOS16 also showed consistent positive anomalies of +1.45 ppm and +1.18 ppm respectively, and MOS14 recorded particularly strong positive anomalies during September, peaking at +12.51 ppm on 21 September. In contrast, MOS2, MOS4, MOS5, and MOS6 showed persistent negative anomalies. The largest negative anomaly was -9.46 ppm at MOS2 on 24 September. Other events were more localised, with strong positive anomalies concentrated at MOS1 or a smaller group of sensors. This pattern indicated that inter-sensor variability was not fixed through time: the same sensor network experienced persistent sensor-specific offsets alongside temporally varying concentration gradients across the deployment area.

Overall, the inter-sensor comparison showed a clear spatial gradient in methane exposure across the CSP monitoring network. MOS1 consistently emerged as the highest-concentration monitoring location, while MOS14, MOS16, MOS10, MOS11, and several other sensors formed an intermediate group with elevated but less persistent concentrations. Sensors such as MOS4, MOS5, MOS6, and MOS2 generally recorded lower concentrations and narrower variability. The stronger inter sensor contrast in CH₄ avg compared with CH₄ max indicated that differences among sensors were driven mainly by short-duration concentration peaks rather than by a uniformly elevated methane background. Figures 6 and 7 together showed that methane exposure at the CSP was heterogeneous across sensors, temporally episodic, and

concentrated at selected monitoring locations rather than evenly distributed across the sensor network. This also highlighted that methane was significantly driven by wind and required wind-based analysis.

5. Discussion

The CSP sensor network showed that near-surface CH₄ concentrations were spatially heterogeneous across sensors, temporally episodic, and strongly influenced by meteorological transport. The results revealed three linked patterns: first, methane concentrations were highest in September as well as during the night-to-early-morning period; second, MOS1 consistently recorded the strongest CH₄ concentration; and third, coal activity alone did not explain the observed concentration field. Together, these patterns indicate that CH₄ observations at the CSP require further analysis to disentangle source strength from plume transport and atmospheric mixing.

5.1 Drivers of Spatial Variability

The hotspot behaviour distinguishes source proximity from sustained source strength. A sensor located near an active source corridor can record very high CH₄ max values when a plume passes across it, even if the broader site background remains relatively low. The most persistent inter-sensor feature of the monitoring campaign was the dominance of methane at MOS1, which recorded the highest CH₄ avg and CH₄ max values, the widest distributions, and the strongest daily anomalies. The inter-sensor boxplots (Figure 6) showed this clearly, where MOS1 exhibited both a higher central tendency and a broader upper tail than the other sensors for CH₄ avg and CH₄ max. Located closest to the active North Stockpile and conveyor system, MOS1 was repeatedly exposed to methane-rich air from exhaust of the coal reclaim tunnels. However, the large difference between CH₄ avg and CH₄ max indicated that MOS1 was not continuously exposed to uniformly elevated methane; rather, its strongest signal reflected intermittent, short-duration concentration peaks superimposed on a lower background. The daily mean and anomaly heatmaps support this interpretation by showing that MOS1 was frequently elevated but also experienced periods of below-baseline concentration. Therefore, MOS1 represented the dominant methane hotspot within the network.

The other sensors, including MOS10, MOS11, MOS14, MOS15, and MOS16, further suggested that methane exposure was organised along preferred plume pathways rather than distributed evenly across the site. This could be interpreted from sensor-wise wind roses, which showed that individual monitoring locations experienced different wind-direction and wind-speed exposures during the campaign (Figure S1). These sensors did not reach the magnitude or persistence of MOS1, but they recorded repeated elevated concentrations and positive anomalies during selected periods. Although some of these sensors were positioned near the SSP area, which was operationally inactive during the monitoring period. Their elevated concentrations should therefore not be attributed directly to SSP emissions. These sensors intermittently intercepted transported methane from active operational areas, conveyor corridors, nearby mine activities, or broader CSP source zones under favourable wind directions. Further the upwind-downwind analysis suggested that across all wind-direction categories, mean downwind CH₄ concentrations were higher than upwind concentrations (Figure 8).

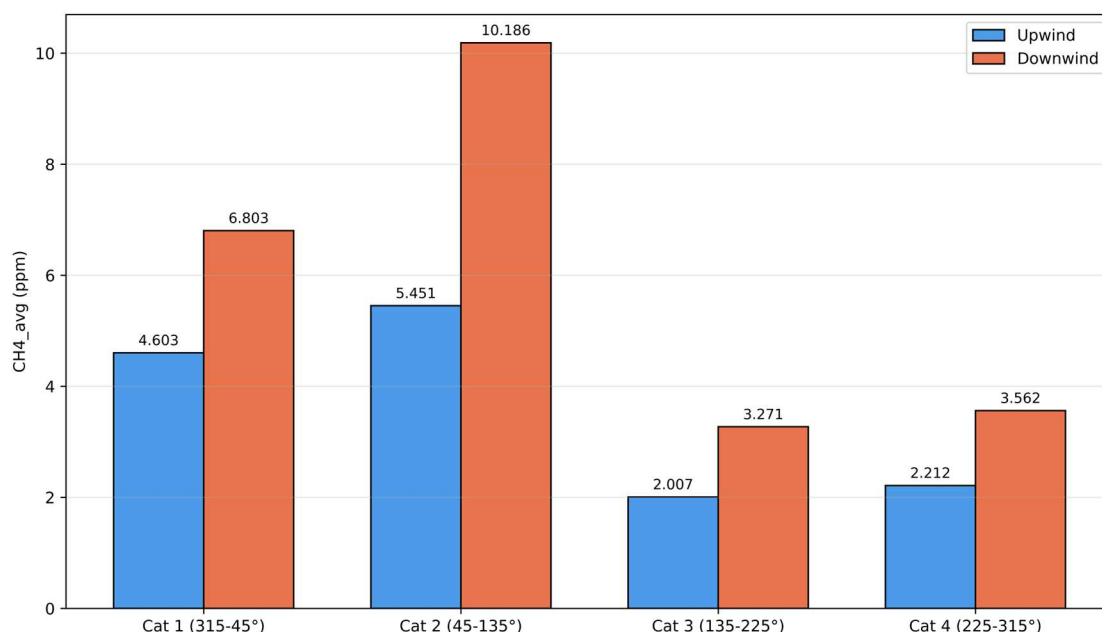


Figure 8: Mean upwind and downwind CH₄ concentrations (ppm) by wind direction category, showing consistent downwind enhancement across all sectors, with the largest difference under Cat 2 (45–135°) winds.

This wind-sector comparison therefore provided an independent check on the hotspot interpretation: the sensors that appeared elevated in the spatial plots were also part of a broader pattern in which downwind positions recorded higher CH₄ than upwind positions. The largest contrast occurred under Cat 2, where downwind mean CH₄ concentration reached approximately 10.19 ppm compared with 5.45 ppm upwind. Downwind enhancement was also observed in Cat 1, Cat 3, and Cat 4, although with smaller absolute differences. This consistent downwind increase indicated that the monitoring network captured source-influenced air masses with elevated regional background. The monthly and daily upwind-downwind comparisons support this interpretation too (Figure S2 and S3). Monthly mean CH₄ concentrations remained higher at downwind positions across all wind-direction categories, with the strongest enhancement generally occurring during the higher-methane phase of the campaign. Daily time series showed that downwind concentrations often exceeded upwind concentrations during short-lived enhancement events, especially in Cat 1 and Cat 2. However, the size of the downwind enhancement varied substantially from day to day. This variability suggested that wind direction alone did not determine methane exposure; source activity, wind speed, atmospheric stability, and plume intermittency also controlled whether a downwind sensor recorded a strong concentration response. The contribution of the Southeast to Southerly winds are least on a daily scale in comparison to other wind categories (Figure S3). The higher daily mean CH₄ avg concentrations observed at the upwind sensor likely reflect day-to-day variability in wind direction, intermittent plume recirculation, and the influence of nearby local sources, indicating that daily upwind–downwind classification did not always correspond to a fixed transport pathway. Overall, the hotspot analysis was not simply a static map of source locations. It reflected the interaction between source proximity, wind-sector alignment, plume intermittency, and local dispersion. Elevated methane was observed when sensors were aligned with transport pathways.

5.2 Drivers of Temporal Variability

The significant temporal variability in methane concentration was observed which might have a direct association with the variability in coal activity, wind transport and atmospheric stability. A single variable might not explain the observed CH₄ variability across all time scales. Instead, high concentrations occurred when source activity coincided with meteorological conditions that favoured plume retention or transport towards the sensor network. The hourly anomaly analysis helped explain the episodic methane event rather than gradual or random (Figure 9).

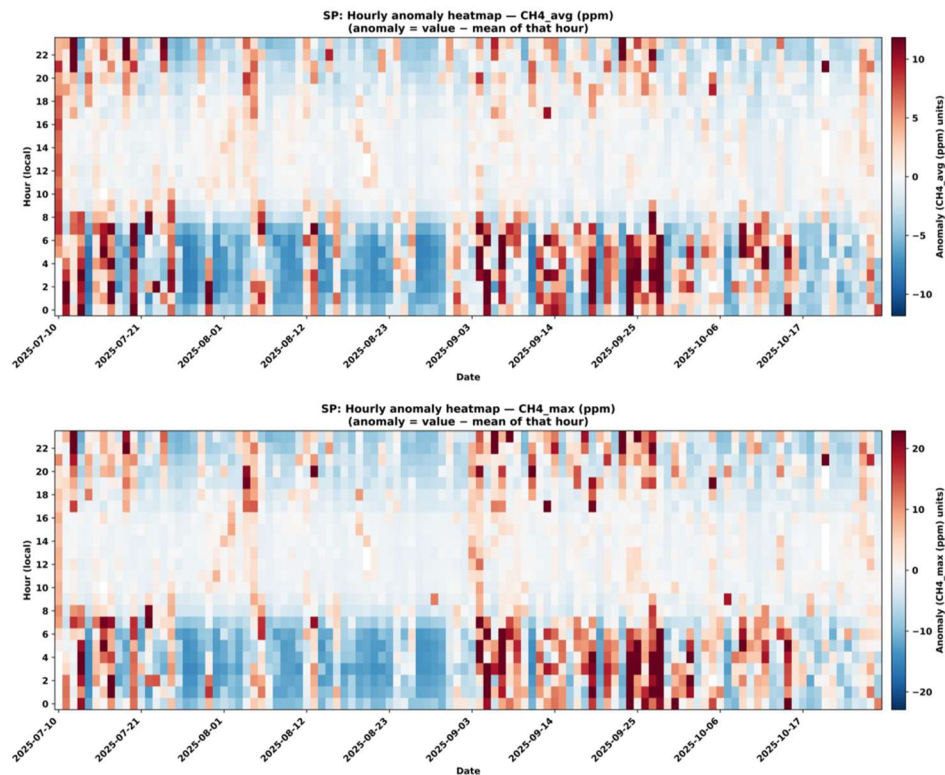


Figure 9: Hourly anomaly heatmaps of CH₄ avg (top) and CH₄ max (bottom), where anomalies were calculated relative to the mean concentration for each hour of day across the study period.

Positive CH₄ anomalies were concentrated into sustained enhancement periods, especially during the nocturnal and early-morning hours between 00:00 and 07:00, whereas daytime anomalies were generally weaker or negative. The shift from predominantly negative early-morning anomalies in late July and August to repeated positive anomalies from early September indicated a change in the conditions under which methane accumulated near the sensor network. This pattern suggested that the September enhancement was not simply a site-wide increase in background CH₄ but was also driven by more frequent and stronger short-duration plume encounters during periods when nocturnal atmospheric conditions favoured near-surface persistence. The monthly pattern showed broad agreement from July to September: coal activity decreased from July to August, when methane also declined, and then increased in September, when both CH₄ avg and CH₄ max reached their highest monthly values (Figure 4). So, the

intensified coal activity increased the potential for methane release during September. However, the methane concentration declined in October despite continued high coal activity led to further investigations. To evaluate the association of the coal activity with methane concentrations, we further analysed correlation between coal activity and methane concentrations (Figure 10).

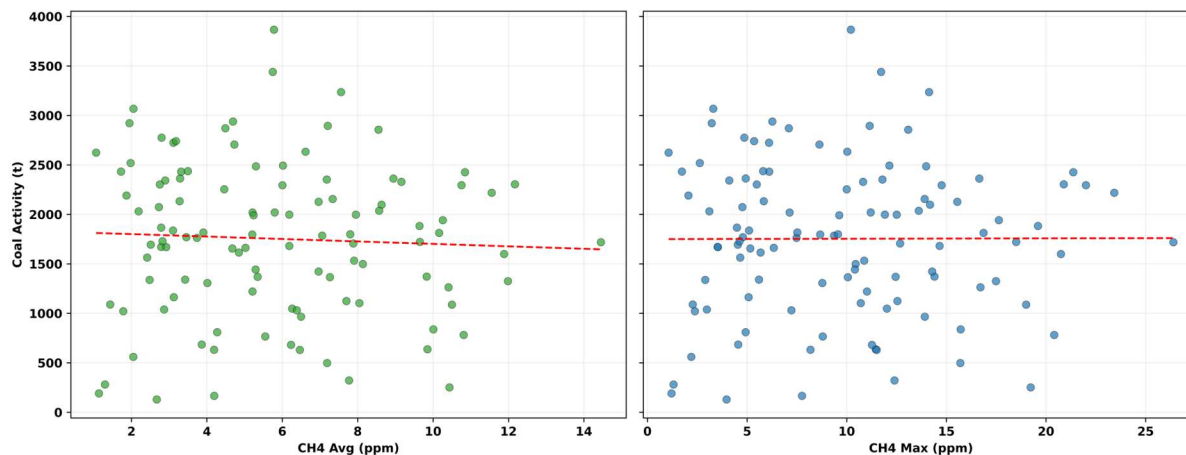


Figure 10: Daily coal activity (t) versus daily mean CH₄ concentrations at the CSP: (a) network-mean CH₄ avg concentration and (b) network-mean CH₄ max concentration. Each point represents one day; dashed red lines show ordinary least-squares fits.

These plots are important because they distinguish operational activity from the atmospheric methane response measured by the sensor network. Higher coal activity at the CSP did not consistently correspond to higher CH₄ concentrations, and elevated CH₄ levels were not confined to days with the greatest coal throughput. The fitted relationship between daily coal activity and daily mean CH₄ concentration was weak and slightly negative, whereas the relationship with the daily maximum CH₄ concentration was approximately flat. These results indicated that variations in daily coal throughput alone did not directly control the methane concentrations observed across the monitoring network. Several high-activity days were associated with moderate CH₄ concentrations, while some of the highest methane concentrations occurred on days with comparatively lower operational activity. So, coal activity is an indicator of potential source activity rather than as a direct predictor of the concentration measured at an individual sensor or across the network. Consequently, elevated CH₄ concentrations were recorded only when operationally generated emissions were transported toward the sensors under favourable dispersion and plume-alignment conditions. The methane emission from coal activity also depends on the coal seam geology and associated gassiness.

We further analysed the impact of other factors on methane concentrations. Wind speed is also one of the key parameters as it directly impacts the plume transport. The wind-speed bin plots supported this conclusion, showing higher CH₄ avg and CH₄ max values under lower wind-speed classes and lower concentrations under stronger wind conditions (Figure 11).

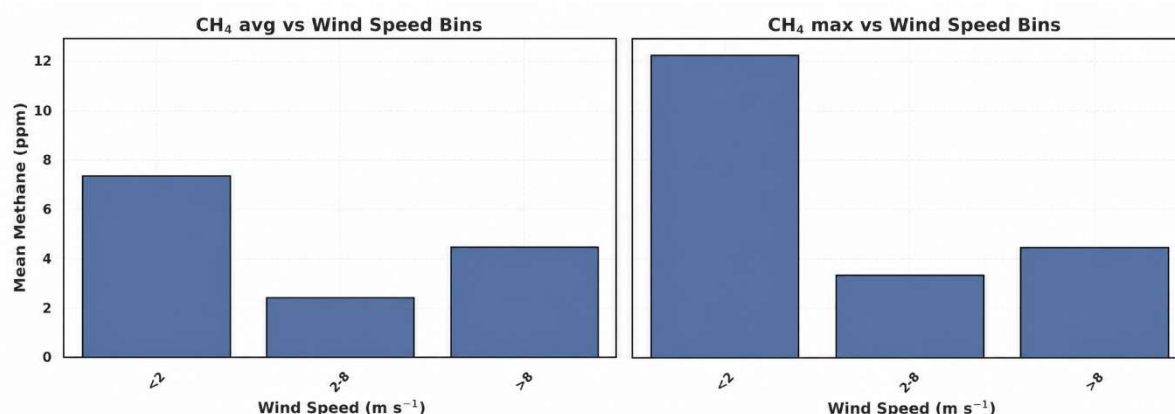


Figure 11: Mean CH₄ avg (left) and CH₄ max (right) across wind-speed classes of < 2 m s⁻¹, 2–8 m s⁻¹, and > 8 m s⁻¹.

Low wind speeds favoured near-surface accumulation and plume persistence, while stronger winds generally enhanced dilution. So, methane concentrations were highest during the night and early morning, when wind speed was weakest, and lowest, during the daytime when wind speeds were higher which translate to better atmospheric mixing. The day-night comparison (Table 1) supported this mechanism also where mean CH₄ avg increased from 4.36 ppm during the day to 8.26 ppm at night, while mean CH₄ max increased from 6.48 ppm to 14.15 ppm. Thus, night-time methane was approximately 1.9 times higher for CH₄ avg and 2.2 times higher for CH₄ max. The larger night-time standard deviations also indicated that the nocturnal enhancement was not simply a smooth background increase but involved more frequent or stronger intermittent plume events.

Table1: Summary of day- and night-time CH₄ concentrations and meteorological conditions.

Time of Day	CH4 Average (ppm)	CH4 Maximum (ppm)	Temperature	Humidity	Pressure (hPa)
Day	4.3545	6.4839	12.3609	52.6570	1005.199
Night	8.2637	14.1533	10.6713	68.0081	1006.951

Temperature and RH further modified this day-night behaviour (Figure S4 and S5). Night-time conditions were cooler and more humid, with mean temperature decreasing from 12.36 °C during the day to 10.67 °C at night, and mean RH increasing from 52.66% to 68.01%. These conditions were consistent with a lower boundary layers, weaker vertical mixing, and greater potential for methane to persist near the surface close to the sensor height. In contrast, daytime heating likely increased boundary-layer mixing and atmospheric ventilation, suppressing both CH₄ avg and CH₄ max even when coal activity remained high. No For further analysis of the integrated impact of temperature, RH and pressure, we plotted them in one frame using polar bubble plot (Figure 12).

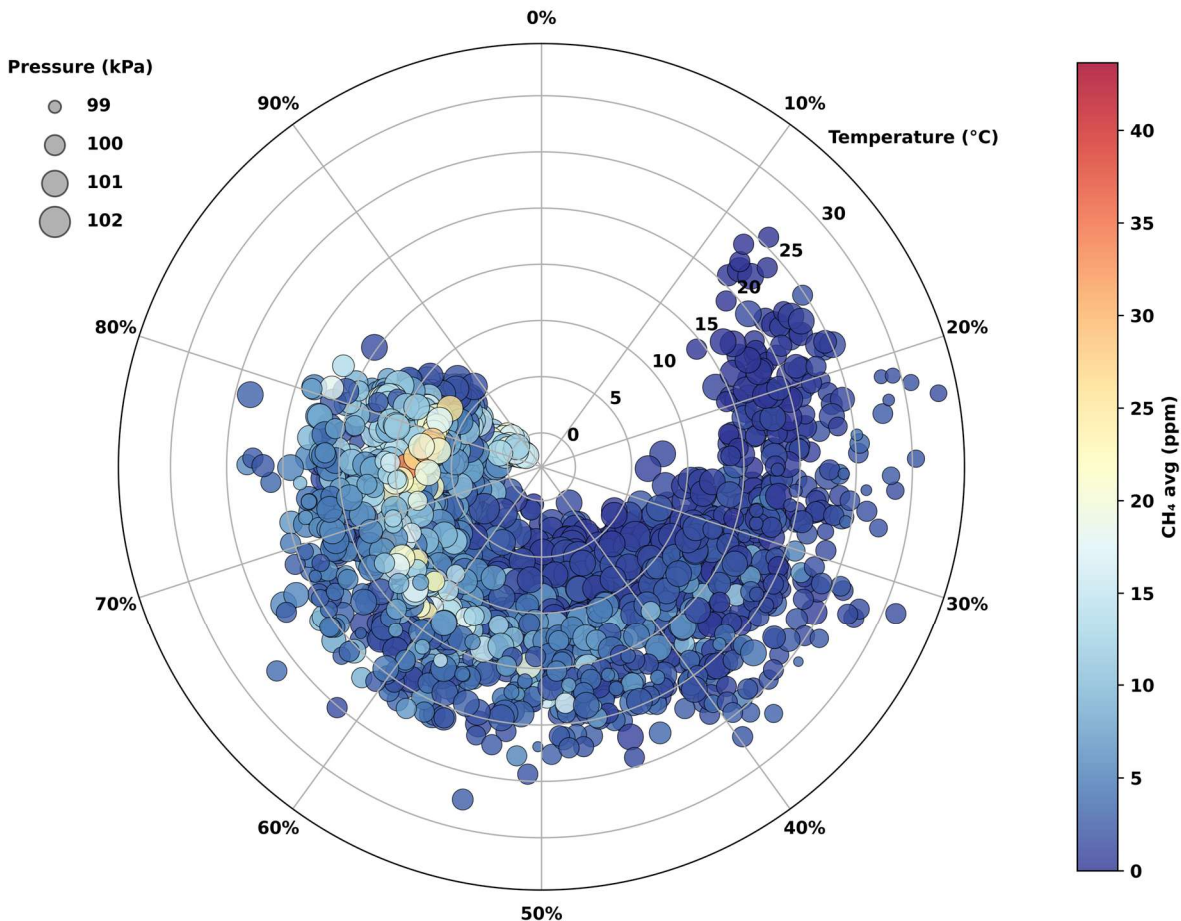


Figure 12: Polar bubble plot of hourly mean CH₄ avg concentration as a function of meteorological conditions at the CSP. Angular position denotes relative humidity (0–100%, clockwise from north), radial distance denotes ambient temperature (°C), marker color denotes hourly mean CH₄ avg concentration (ppm), and marker size denotes pressure (kPa).

Elevated CH₄ concentrations were concentrated mainly under moderate-to-high (43.7–74.5%) RH and lower-to-moderate (7.5–15.3 °C) temperature conditions, whereas lower CH₄ values were more common under warmer and drier conditions. Marker size, representing pressure, did not show a clear separation between high- and low-CH₄ conditions. This supports the interpretation that humidity and temperature were important modifiers of methane persistence, while pressure played a weaker role. The concentration-class analysis further showed that methane variability at the CSP was episodic rather than continuously extreme (Figure 13).

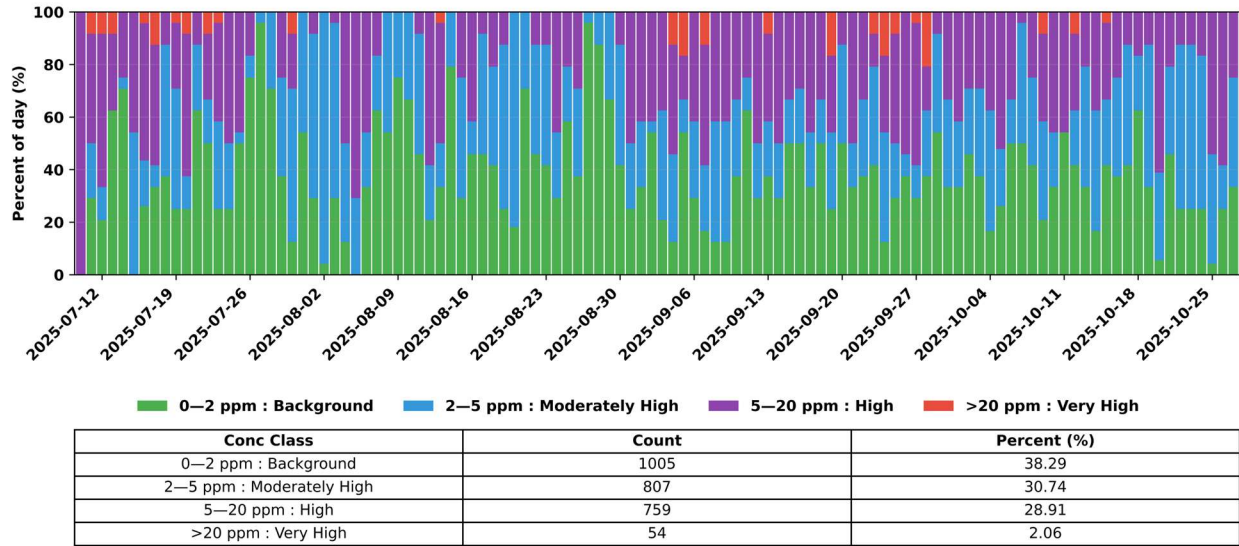


Figure 13: Daily proportion of hourly mean CH₄ avg classes at the CSP. Each stacked bar represents one day, partitioned by the percentage of hourly intervals falling within four concentration classes: background (0–2 ppm), moderately high (2–5 ppm), high (5–20 ppm), and very high (>20 ppm). CH₄ avg values are hourly means across the 16 MOS sensors. The accompanying table summarizes the total count and overall percentage of intervals in each class across the full campaign.

Across the campaign, 38.29% of hourly averaged observations fell within the 0-2 ppm background class, 30.74% fell within the 2-5 ppm moderately high class, 28.91% fell within the 5-20 ppm high class, and only 2.06% exceeded 20 ppm. This distribution is important because it showed that very high methane was rare but recurrent. Most of the monitoring record consisted of background to moderately elevated conditions, while a smaller number of high-concentration intervals contributed disproportionately to the observed variability. This pattern was consistent with intermittent plume interception rather than a persistently elevated site-wide methane concentration.

5.3 Implications for CSP Methane Monitoring

These findings have important implications for interpreting fixed near-surface CH₄ observations at CSP. First, high CH₄ concentration at a sensor did not necessarily mean that the closest source had the highest emission rate. It indicated that the sensor was exposed to methane-rich air under transport conditions. Second, coal activity was necessary for interpreting source potential, but it couldn't be used alone to explain measured concentration. The weak daily relationship between coal activity and methane concentration showed that dispersion and plume routing strongly filter the observed signal. Third, CH₄ max was especially useful for identifying intermittent plume impacts, whereas CH₄ avg better represented sustained exposure. The stronger inter sensor contrast in CH₄ max indicated that short-duration plume events were a major component of site variability.

The ground-based sensor network captured the emission from the CSP with the consistent downwind enhancement across all wind categories. However, the variable magnitude of downwind enhancement

also showed that source attribution remains challenging without more detailed dispersion modelling, background correction, and high-resolution operational activity data. The higher upwind concentrations also highlighted the impact of the surrounding sources and potential methane transport under suitable wind conditions.

Overall, the CSP methane field was shaped by the coupling of operational source activity with meteorological transport. Site-wide methane variability was strongest with weak winds, cooler and more humid conditions, and favourable wind-direction alignment. Conversely, high coal activity produced lower measured concentrations when atmospheric ventilation was stronger. Therefore, fixed near-surface CH₄ measurements at CSPs should be interpreted as concentration responses shaped by source proximity, plume pathways, operational timing, and meteorology, not as direct estimates of emission strength. Future work should combine these observations with background correction, wind-field characterisation, and dispersion or inverse-dispersion modelling to move from hotspot detection towards quantitative source attribution.

6. Limitations

There are a few limitations associated with this work. First, this study reports CH₄ concentration variability, not methane emission rates. The RH, Temperature and Pressure values are not the direct observed ambient values and need careful discussions. Third, the study was conducted over a single monitoring period at CSP, so the results may not capture seasonal or operational variability across a full annual cycle. Fourth, coal activity was used as an operational indicator, but it did not fully resolve source type, exact source location, timing of material movement, or variable methane content of handled coal. These limitations restrict direct source attribution.

7. Conclusion

This study demonstrates that near-surface CH₄ concentrations at the CSP were highly variable in both time and space. Across the July-October monitoring period, methane did not behave as a uniform site-wide background signal. Instead, concentrations were characterised by episodic enhancements, strong nocturnal and early-morning peaks, clear month-to-month variability, and substantial spatial variability across the site. September represented the strongest methane phase of the campaign, while August showed the lowest concentrations. At the diurnal scale, CH₄ concentrations were consistently higher at night and in the early morning than during the daytime, indicating that atmospheric conditions strongly influenced near-surface methane accumulation.

The sensor network also revealed substantial inter sensor heterogeneity. The sensor in close proximity of NSP (MOS1) consistently recorded the highest CH₄ avg and CH₄ max values, the widest variability, and the strongest daily anomalies, identifying it as the dominant methane-exposure location within the monitoring network, driven by its proximity to the primary emission source (NSP). Other sensors also recorded elevated concentrations during specific periods, but methane enhancement was not evenly distributed across the site. The stronger inter sensor contrast in CH₄ max compared with CH₄ avg indicates that short-duration plume encounters were a major component of the observed methane signal.

The combined analysis of coal activity, meteorology, and upwind-downwind concentration differences show that measured CH₄ at the CSP should be interpreted as a source-transport-receptor response. Coal activity provided important source context, but it did not directly or consistently predict measured CH₄ concentration. Some high-activity periods produced only moderate methane levels, while some high-methane periods occurred under lower activity. This indicates that coal-related source potential was filtered by wind direction, wind speed, atmospheric stability, humidity, and plume alignment with individual sensors. Downwind concentrations were generally higher than upwind concentrations across wind-direction categories, supporting the influence of local or nearby methane sources, but the magnitude of enhancement varied through time. Temperature and humidity emerged as key meteorological factors influencing methane persistence, whereas atmospheric pressure appeared to have a comparatively weaker effect. So, the methane concentration at CSP is a coupling of coal activity and the local meteorology.

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