Report prepared on behalf of Unisearch Expert Opinion Services
A business of the University of New South Wales

MEASUREMENTS OF THE ATMOSPHERIC CONCENTRATION OF METHANE, CARBON DIOXIDE, AND CARBON MONOXIDE: EASTERN CREEK, HORSLEY PARK, MINCHINBURY, AND ARNDELL PARK

for

NSW Environment Protection Authority
EPA Reference SF23/55358

by

Bryce F.J. Kelly and Hannah Beaton
School of Biological, Earth and Environmental Sciences
The University of New South Wales

and

Peter Mumford
School of Aviation, The University of New South Wales

Date of Issue: 10 Aug 2023
Unisearch Reference: UN198596

Measurements of the Atmospheric Concentration of Methane, Carbon Dioxide, and Carbon Monoxide: Eastern Creek, Horsley Park, Minchinbury, and Arndell Park

Bryce F.J. Kelly[1], Hannah Beaton[1], and Peter Mumford[2]

[1] School of Biological, Earth and Environmental Sciences, The University of New South Wales
[2] School of Aviation, The University of New South Wales

August 2023

Unisearch Contact - UN198596
for
NSW Environment Protection Authority

Summary

The State Government of New South Wales (NSW) has set a goal to have net zero greenhouse gas emissions by 2050. To achieve this goal all major sources of greenhouse gases need to be either reduced or offset. Currently there are many sources of methane (CH_4), carbon dioxide (CO_2) and carbon monoxide (CO) that can be better characterised and mitigation strategies developed. The industrial and agricultural greenhouse gas emissions in the western Sydney suburbs of Eastern Creek, Horsley Park, Minchinbury, and Arndell Park are of interest to the NSW Environment Protection Authority (EPA) as there are many CH_4 sources in these suburbs that need to be better quantified to plan mitigation strategies.

On the evenings of 13 and 14 June 2023 car-based surveys were undertaken to measure the concentrations of CH_4, CO_2 and CO along all accessible roads around the facilities of interest (Environment Protection Licences (EPLs): 13426, 5272, 20339, 3511, 7119, 546a, 546b, 546c, 123 and 6152) for the NSW EPA. The primary greenhouse gas of interest for this study was CH_4, but because the analyser also measured CO_2 and CO these data have been included in the report.

Survey results were compared with the Cape Grim average values for May 2023, which were 1.868 ppm for CH_4 and 416 ppm for $C0_2$. The Cape Grim December 2021 flask reading for CO was 0.054 ppm. These values for CH_4, CO_2 and C0 are used as background (fresh air) for this discussion. The local background values will be slightly different for Sydney, but the Cape Grim values are adequate for the goals of this study. Throughout most of the regions surveyed concentrations of both CO_2 and CO were higher than would be expected for background air. The average concentration of CO_2 measured on the evening of 13 June 2023 was 447 ppm, 31 ppm above the Cape Grim reference value. The average concentration of CO measured on 13 June 2023 was 0.29 ppm, 0.24 ppm above the Cape Grim reference value. These enhancements in the concentrations of CO_2 or CO throughout Sydney are expected due to the extensive use of fossil fuels in vehicles, the use of wood fires for heating, industrial emissions, and other lesser anthropogenic and natural sources. Throughout the greater Sydney region, the cumulative impact of these CO_2 and CO emissions exceeds the impact of the EPL sites investigated in this study. Repeated car-based surveys throughout Sydney could be used to verify the inventory reported emissions from vehicles. More importantly, as electric vehicle use increases and households and industry lower their carbon footprints, repeated CO_2 or CO car-based surveys could be used to track the spatial distributions of these gases. This would provide social, economic, and environmental insights as NSW transitions to a low carbon society.

No CH_4, CO_2 or CO emissions of concern were recorded at the time of surveying downwind of **EPL 7119 - NSW Electrical Network – Transgrid, EPL 546 - Austral Bricks** (three sites: 546a, 546b, and 546c), **EPL 123 - PGH Bricks and Pavers**, or **EPL 6152 - Toll Chemical Logistics.** On-site measurements of CH_4, CO_2, and CO for these facilities would not be a priority.

Downwind of **EPL 3511 - George Borg Piggery**, 13 June 2023, the peak CH_4 concentration recorded in the plume was only 2.8 ppm. Although low in concentration, the plume had a cross section that extended for approximately 1 km along Burley Rd and was detected at 500 m from the piggery; the CH_4 emissions are therefore significant. A CO_2 plume was also mapped downwind of the piggery; it had a peak concentration of 484 ppm and extended 1 km south to Horsley Rd. The CO_2 plume corresponded to the region where there was a strong piggery odour. Characterising the rates of emissions from this facility would help with refining the National Greenhouse Gas Inventory emission factors for piggeries. However, this is ranked as a low priority compared to waste facilities discussed next.

On Tuesday 13 June 2023 a CH_4 plume extended downwind for approximately 2 km south-east from **EPL 13426 - Dial a Dump - Bingo Eastern Creek Landfill.** This plume had a peak CH_4 concentration of 11.5 ppm. On the same evening, a plume with a strong waste odour was also intersected at the junction of Lenore Dr, Old Wallgrove Rd, and Telopea Pl. This plume had a peak CH_4 concentration of 4.8 ppm. To reduce CH_4 emissions, permanent flaring has been in operation at this Bingo facility since 2022. The size of the plume measured around this facility suggests that either all CH_4 is not being captured at the facility or that the flaring is not efficient. On-site inspections would be required to determine the source of the CH_4 coming from **EPL 13426 - Dial a Dump - Bingo Eastern Creek Landfill.** Without knowing the precise source of the CH_4, it is not possible to recommend the best method to apply to determine the rate of CH_4 emissions coming from this facility.

Between Wallgrove Rd and Prospect Reservoir there is a cluster of closed landfills, energy production and waste recovery facilities. The facilities of interest are **5272 Waste Assets Management - Eastern Creek Waste Management Centre and the 20339 Veolia - Horsley Park Resource Recovery Facility.** These facilities are discussed together, because from the car-based measurements of the atmospheric concentration of CH_4, CO_2 and CO along the M4 Western Motorway (northern side), Ferrers Rd (eastern side), Chandos Rd (southern side) and Wallgrove Rd (western side) it is not possible to locate with confidence the source of the CH_4 detected.

On Tuesday 13 June 2023, there was a CH_4 plume adjacent to **EPL 5272 - Waste Assets Management - Eastern Creek Waste Management Centre.** The peak CH_4 concentration of this plume along Ferrers Rd was 10.6 ppm. At the time of surveying at this point the wind was from the north. To the immediate north there is no CH_4 source visible in Google Earth. However, dispersion of a plume originating from the north-east landfill cell cannot be excluded. It is recommended that a back-trajectory model be run to determine the likely source of this plume. A CH_4 plume was intersected on the southern side of **EPL 20339 - Veolia - Horsley Park Resource Recovery Facility**. This plume was intersected along Chandos Rd and had a peak CH_4 concentration of 7.9 ppm. This plume could result from any waste management or energy production facility, or an old landfill cell, between Chandos Rd and the M4 Western Motorway. A plume with a peak concentration of 6.9 ppm was also intersected along Wallgrove Rd, near the Eastern Creek Waste Management Centre entrance. On Wednesday 14 June 2023, when the wind was blowing from the west-north-west at 2 km/h transitioning to calm, a CH_4 plume was intersected along Ferrers Rd, which had a peak CH_4 reading of 58 ppm. This CH_4 plume likely originates from **EPL 5272 - Waste Assets Management - Eastern Creek Waste Management Centre.** The relatively high concentration of CH_4 measured around the borders of the Eastern Ck and Horsley Park districts highlights the need for on-site studies to be able to pinpoint the sources and determine the rates of CH_4 emissions. The region to be surveyed covers an area of approximately five square kilometres. The area could be subdivided, and emissions assessed using trolley-based surveys over the landfills, drone-based in situ surveys, tracer gas studies, open-path laser, or solar absorption spectrometer systems.

On the evening of Tuesday 13 June 2023 an 800 m wide CH_4 plume was intersected along Hassall St in Wetherill Park. Immediately upwind of this plume is the Sustainable Resource Centre and a creek line with swampy vegetation either side. An on-site inspection is required to determine the source of the plume.

Summarising, on-site CH_4 surveys are recommended for:

- **EPL 13426 - Dial a Dump - Bingo Eastern Creek Landfill**
- **EPL 5272 - Waste Assets Management - Eastern Creek Waste Management Centre**
- **EPL 20339 - Veolia - Horsley Park Resource Recovery Facility**
- **Hassall St, in Wetherill Park, Sustainable Resource Centre**

Of lower priority a CH_4 and CO_2 survey is recommended for:

- **EPL 3511 - George Borg Piggery**

To assess the variability of greenhouse gas emissions in the Eastern Ck and Horsley Park regions, it is recommended that at least two permanent monitoring stations be installed. One of these could be located at the Bureau of Meteorology Horsley Park station. A wind direction study is required to optimise the location of a second station. These greenhouse gas monitoring stations could be used to track emission reduction progress in the Eastern Creek, Horsley Park, Minchinbury, and Arndell Park districts.

Table of Contents

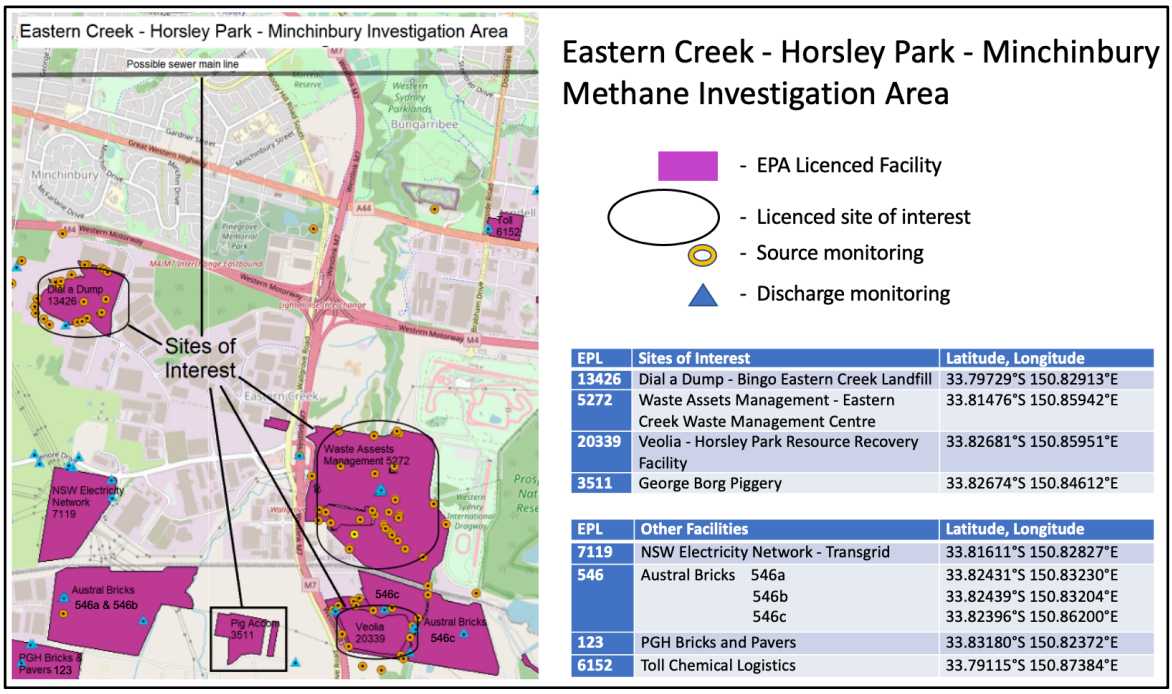
1 Scope of Work

Below is the scope of work that was undertaken for the NSW EPA as part of the surveying of greenhouse gas emissions in the Eastern Creek – Horsley Park – Minchinbury districts. Greenhouse gases (CH_4, CO_2 and CO) were measured using a Picarro 2401-m analyser. This analyser was transported in a car and the measurements georeferenced. The survey was undertaken along public access roads to determine whether there are greenhouse gases being emitted from the ten facilities listed in Figure 1 (EPLs: 13426, 5272, 20339, 3511, 7119, 546a, 546b, 546c, 123 and 6152). All measurements were converted to a Google Earth KML file format. These results will be used to guide discussions about which facilities should have on-site inspections. On-site measurements were not done as part of this project.

Tasks covered by the 4-day project included:

- Preparation of the health and safety documentation.
- The collection and setup of a car for surveying.
- An equipment calibration check.
- A car-based survey of the atmospheric concentration of CH_4, CO_2 and CO in the region shown in Figure 1. This survey was done on the evenings of 13 and 14 June 2023.
- Unpacking and returning of the car.
- Conversion of Picarro and GPS files into KML files, to enable the concentration of CH_4, CO_2 and CO to be displayed in Google Earth.
- Preparation of CSV files for CH_4, CO_2 and CO (date, latitude, longitude, coordinated universal times (UTC), and gas concentration).
- The writing of a report that includes details of the survey paths, prevailing weather conditions, materials and methods used, and recommendations with respect to further studies at EPLs 13426, 5272, 20339, 3511, 7119, 546a, 546b, 546c, 123 and 6152 (Figure 1).
- A presentation of the results to the NSW EPA.

It is important to note that the aim of the project was to identify facilities where follow-up detailed measurements would be recommended. It was not the aim of this project to undertake a detailed analysis of the plumes encountered during the surveys. The study only measures the concentrations of CH_4, CO_2 and CO in the atmosphere and this report only discusses some preliminary insights. Further studies are required to determine the rates of emissions from individual facilities.



EPL	Sites of Interest	Latitude, Longitude
13426	Dial a Dump - Bingo Eastern Creek Landfill	33.79729°S 150.82913°E
5272	Waste Assets Management - Eastern Creek Waste Management Centre	33.81476°S 150.85942°E
20339	Veolia - Horsley Park Resource Recovery Facility	33.82681°S 150.85951°E
3511	George Borg Piggery	33.82674°S 150.84612°E

EPL	Other Facilities	Latitude, Longitude
7119	NSW Electricity Network - Transgrid	33.81611°S 150.82827°E
546	Austral Bricks 546a 546b 546c	33.82431°S 150.83230°E 33.82439°S 150.83204°E 33.82396°S 150.86200°E
123	PGH Bricks and Pavers	33.83180°S 150.82372°E
6152	Toll Chemical Logistics	33.79115°S 150.87384°E

Figure 1. *A map of the facilities studied as part of the car-based street survey that measured the concentrations of CH_4, CO_2 and CO in the ground level atmosphere using a Picarro 2401-m CH_4, CO_2, and CO analyser. Where access allowed, both up- and down-wind surveys were done adjacent to the EPA licenced facilities (Image supplied by the NSW EPA).*

2 Introduction

NSW has a carbon dioxide equivalent (CO_2-e) goal of net zero by 2050 (NSW Government, 2020). To achieve this goal, it is important to identify mitigation opportunities and to verify the amount of greenhouse gas emissions reported under the National Greenhouse and Energy Reporting Act (Australian Government, 2007).

This report documents the results of a car-based survey that measured the concentrations of methane (CH_4), carbon dioxide (CO_2) and carbon monoxide (CO) in the atmosphere using a Picarro 2401-m analyser. The main suburbs for the survey were Eastern Creek, Minchinbury, Arndell Park, and the industrial/agricultural portions of Horsley Park. Portions of Prospect, Pemulwuy and Wetherill Park were also surveyed. These suburbs were surveyed on two evenings. The first survey was done on Tuesday 13 June 2023, between 073000 UTC (5:30 pm) and 130000 UTC (11:00 pm), and the second survey was undertaken on Wednesday 14 June 2023, between 073000 UTC (5:30 pm) and 120000 UTC (10:00 pm). The rationale for the evening surveys is that during daylight hours the warming of the Earth's surface often results in rapidly rising plumes, which are then not detected by car-based surveys. During the early evening plumes rise and mix more slowly, and there are usually light winds at this time of day that result in the plumes extending smoothly away from facilities. These plumes are then interested by car-based surveys. The contrast between daytime and evening surveys is shown in Lu et al. (2021).

The aim of the survey was to identify facilities that are significant sources of CH_4, CO_2, or CO. The primary compound of interest is CH_4, because CH_4 is a potent greenhouse gas and sources of CH_4 can often be reduced or eliminated (Nisbet et al., 2020). Major facilities of interest are listed in Table 1.

The measured concentration of CH_4, CO_2 or CO does not provide an estimate of the rate of emissions. The closer you survey to a source of CH_4, CO_2, or CO the higher the concentration. To assign a rate of emissions to a facility further study is required using different measurement and modelling techniques. The survey results presented in this report aim to highlight where further studies are required to quantify the rates of emissions of CH_4, CO_2, or CO.

Table 1. *Sites of interest for emissions of CH_4, CO_2, or CO.*

EPL	Sites of Interest	Latitude (south)	Longitude (east)
13426	Dial a Dump - Bingo Eastern Creek Landfill	-33.79729	150.82913
5272	Waste Assets Management - Eastern Creek Waste Management Centre	-33.81476	150.85942
20339	Veolia - Horsley Park Resource Recovery Facility	-33.82681	150.85951
3511	George Borg Piggery	-33.82674	150.84612
7110	NSW Electricity Network - Transgrid	-33.81611	150.82827
546a	Austral Bricks - Site A	-33.82431	150.83230
546b	Austral Bricks - Site B	-33.82439	150.83204
546c	Austral Bricks - Site C	-33.82396	150.86200
123	PGH Bricks and Pavers	-33.8318	150.82372
6152	Toll Chemical Logistics	-3379115	150.87384

3 Methods

A Picarro 2401-m analyser was used to measure the concentrations of CH_4, CO_2 and CO in the atmosphere above the vehicle as we drove along the road. The manufacturer's specification sheet is included in the supplementary information. The Picarro 2401-m analyser was only recently purchased by UNSW and calibration and drift testing are ongoing. The analyser is being calibrated using Southern Ocean air standards supplied by CSIRO Aspendale. This air is referenced to NOAA standards and has been independently measured by CSIRO Aspendale, Royal Holloway University of London, and Utrecht University (Lu et al. 2021). Based on ten standard air tests the Picarro 2401-m is reading 2 ppm too low for CO_2, 0.008 ppm too high for CO, and 0.003 ppm too low for CH_4. Because the calibration testing is preliminary, and the offsets are small compared to other errors associated with mobile measurements, no adjustments were made to the data presented below. These small offsets from the standard air have no ramifications for the aims of this project. It is important to note that the operating ranges for the Picarro 2401-m are: CH_4: 0–20 ppm, CO_2: 0–1000 ppm, and CO_2: 0–5 ppm. Where values are reported beyond these ranges, they are not reliable.

All the greenhouse gas monitoring equipment was transported in a Mitsubishi 2.4L Outlander Wagon. This vehicle used E10 fuel. Along main roads the surveys were done close to the speed limit. Along streets where there was little or no traffic the surveys were done at 10 to 30 km/h. The air intake was mounted approximately 30 cm above the vehicle roof, above the left side rear window (Figure 2). The height of the intake was set based on past testing, which determined that when the inlet is mounted in this position there is no input from the car exhaust or exhaled air by the passengers. Using 10 spike air sample tests it was determined that there was a 10 second lag between the air intake and the recorded timestamped measurement. The survey data are corrected for this lag. GPS readings were recorded every second, using a Septentrio GNSS, which is a multi-constellation, triple frequency receiver that uses the new SouthPAN GBAS correction service to achieve robust one-to-two-meter level accuracy in the context of a mobile gas survey where there is a lag adjustment. The Picarro 2401-m averages readings over a ~3.5 second interval and records the results every five seconds. All data presented below use this five second timestep. All gas data and GPS readings were recorded in coordinated universal times (UTC). Most of the discussion below uses UTC time to enable quick searching in the data files.

The gas surveys were done between 073000 to 130000 UTC (5:30pm to 11:00pm) Tuesday 13 June 2023 and 073000 to 120000 UTC (5:30pm to 10:00pm) Wednesday 14 June 2023. Wind direction data were obtained from the Bureau of Meteorology (BOM), Horsley Park monitoring station. The BOM latest observation data are included in the supplementary information, Tables SI-1 and SI-2.

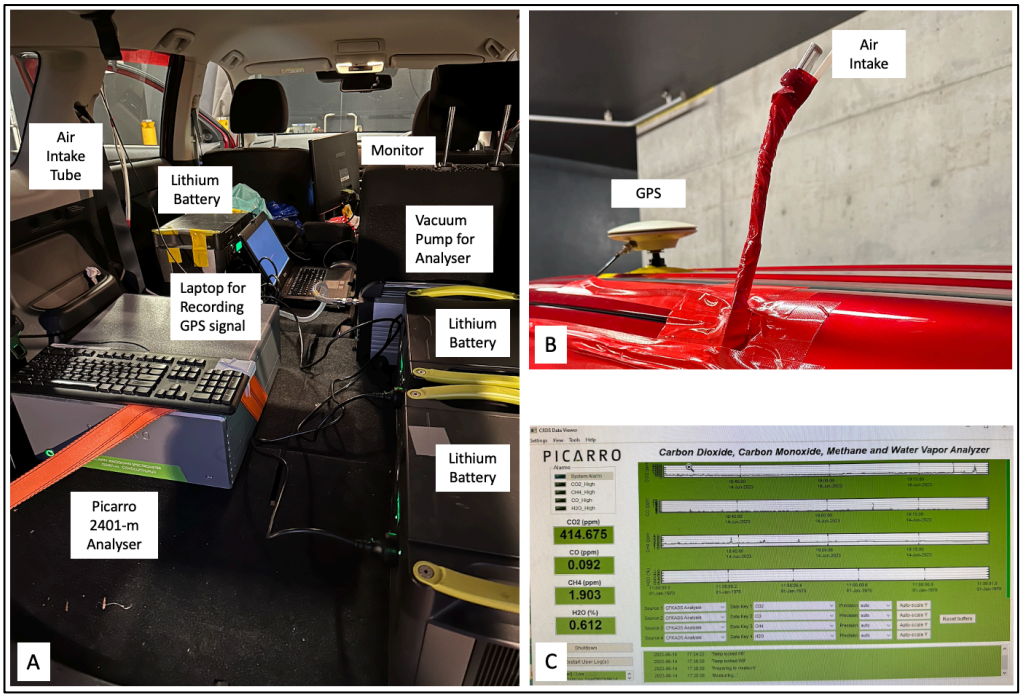


Figure 2. *Monitoring equipment setup in a Mitsubishi 2.4L Outlander Wagon. A) The Picarro 2401-m analyser, pump, monitor, GPS laptop and batteries. B) Roof mounted air intake and GPS receiver. C) Picarro 2401-m monitoring screen, which displays top-to-bottom continuous readings for CO_2, CO, CH_4 and H_2O.*

4 Results and Discussions

CO_2 and CH_4 are the primary and secondary greenhouse gases of concern with respect to their cumulative impact on global warming. Reducing the emissions of these gases is a priority for NSW net zero targets (NSW Government, 2020). On a 100-year timeline the fifth assessment IPCC global warming potential (GWP) for CH_4 is 28 (Myhre, 2013) but recently the GWP of CH_4 has been estimated to be 32 on a 100-year timeline (Etminan et al., 2016). Because of the short atmospheric lifespan of CH_4 (approximately 10 years) and its high GWP, there are immediate net zero cost effective benefits associated with reducing CH_4 emissions (United Nations Environment Programme and Climate and Clean Air Coalition, 2021).

CO is a low direct contributing gas to global warming, but it is an important indirect greenhouse gas because it reduces the amount of the hydroxide ($^{\bullet}OH$) radical in the atmosphere, which then results in a decrease in the rate of CH_4 conversion, which in turn leads to enhanced concentrations of CH_4 in the global atmosphere (Lu and Khalil, 1993). The GWP of CO ranges from 1 to 3 on a 100-year timeline (Forster et al. 2007).

Cape Grim is primarily a fresh air monitoring site and is a useful reference point for baseline values of greenhouse gases (CSIRO, 2023). For the month of May 2023, the average CO_2 concentration was 415.7 ppm and average CH_4 concentration was 1.8675 ppm. The most recently available flask data for Cape Grim is December 2021. The monthly average value for CO concentration was 0.054 ppm.

Below some preliminary insights from the car-based surveys of the concentrations of CH_4, CO_2, and CO measured in the atmosphere on the evenings of the 13 and 14 June 2023 are presented and discussed. Portions of the data could be modelled using an atmospheric puff model, but ideally on-site measurements are needed to determine the rates of emissions for the facilities discussed below.

4.1 Methane Survey Results and Discussion

All CH_4 readings for 13 and 14 June 2023 are summarised by latitude and longitude in Figure 3 and displayed in Google Earth in Figure 4. No major CH_4 plumes were intersected in the east of Sydney. The waste facilities of interest are listed in Table 1, and large CH_4 plumes intersected downwind of these facilities are discussed in more detail below.

The average CH_4 reading on 13 June 2023 was 2.272, which is 0.405 ppm above the reference concentration at Cape Grim. This enhancement above background throughout Sydney is expected due to numerous gas leaks throughout the gas network distribution system and the numerous domestic and industrial point sources.

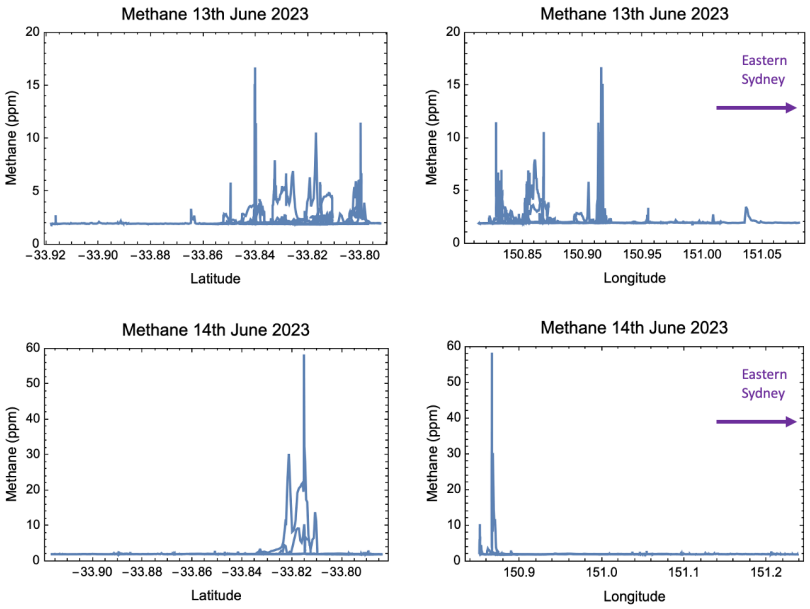


Figure 3. *CH_4 atmospheric concentration summary graphs for the car-based surveys on 13 and 14 June 2023. Note: CH_4 values reported above 20 ppm are not precise and beyond the recommended operational range of the Picarro 2401-m analyser.*

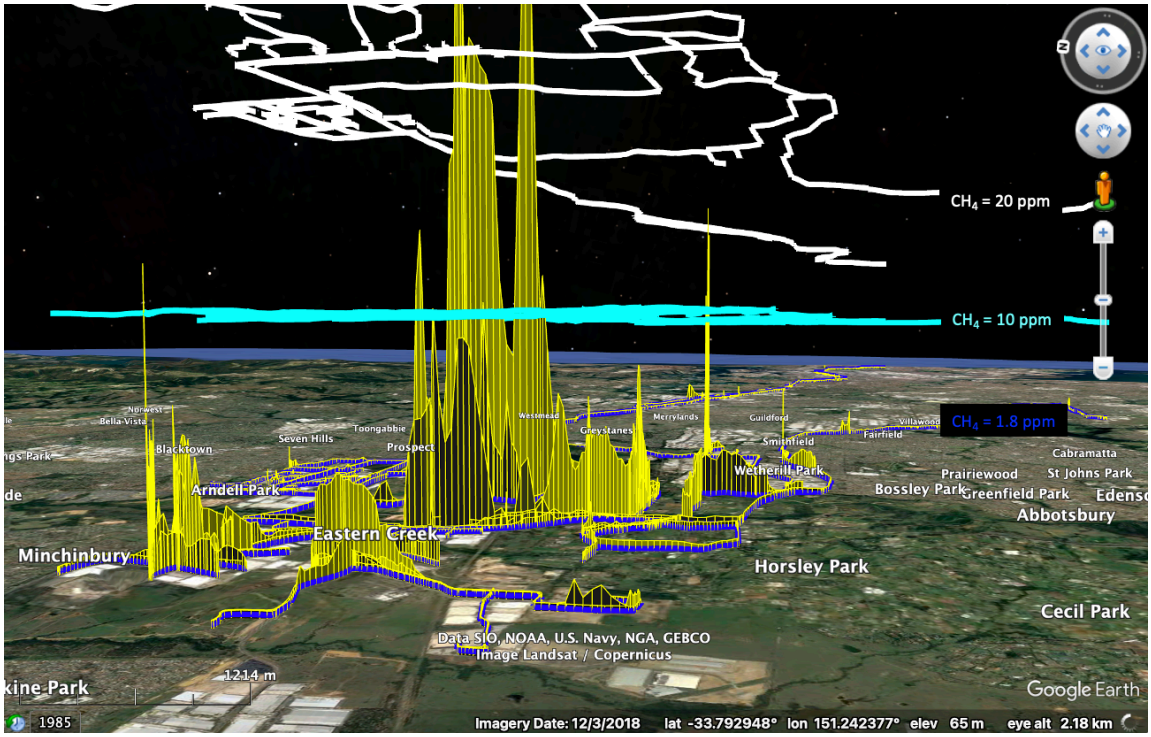


Figure 4. *CH_4 survey 13 and 14 June 2023, looking east. The height of the yellow curtain is proportional to the concentration of CH_4 in the atmosphere. The dark blue line = 1.8 ppm CH_4, the cyan line = 10 ppm CH_4, and the white line = 20 ppm CH_4. In the suburbs of Minchinbury, Eastern Creek, Horsley Park, and Wetherill Park many CH_4 plumes were intersected. Note: CH_4 values reported above 20 ppm are not precise and beyond the recommended operational range of the Picarro 2401-m analyser.*

4.1.1 EPL 13426 - Dial a Dump - Bingo Eastern Creek Landfill

On Tuesday 13 June 2023 a CH_4 plume extended ~2 km south-east from EPL 13426 - Dial a Dump - Bingo Eastern Creek Landfill (Figure 5). The peak concentration recorded was 11.5 ppm (latitude 33.799954, longitude 150.82775, at 104505 UTC; prevailing wind directions were 103000 UTC north-west at 4 km/h to 110000 UTC north-north-west at 2 km/h). A plume was also intersected at the junction of Lenore Dr, Old Wallgrove Rd, and Telopea Pl (latitude -33.812812°, longitude 150.832929°) on the evening of Tuesday 13 June 2023 this plume had a strong waste odour. It is difficult to tell from the survey alone, but this plume may also originate from EPL 13426 - Dial a Dump - Bingo Eastern Creek Landfill.

Since 2022 there has been permanent flaring at Bingo's Eastern Ck facility (Bingo 2022a; Bingo 2022b; NSW Government, 2022). The results of this study indicate that either all CH_4 is not being captured at the facility or that the flaring is not burning all CH_4. Inefficient flaring is a known issue at waste management facilities (Wang et al. 2023).

On-site inspections would be required to determine the source of the CH_4 coming from EPL 13426 - Dial a Dump - Bingo Eastern Creek Landfill. It can be observed in Figure 5 that this plume has a classic Gaussian dispersion shape. This fact in combination with the high density of data would enable the rate of emissions for this plume to be determined using advanced puff modelling applications.

4.1.2 EPL 7110 - NSW Electricity Network – Transgrid

A plume was intersected on the upwind side of EPL 7110 - NSW Electricity Network – Transgrid. This plume had a peak reading of 4.8 ppm, at the southern end of Telopea Pl (latitude -33.812131, longitude 150.833055, at 095750 UTC with wind from the north-north-west at ~7 km/h) (Figure 6). The source of this plume could not be located, but given the strong waste odours in this plume, it could be an extension of a plume from EPL 13426 - Dial a Dump – Bingo Eastern Ck Landfill. In the south-east corner of EPL 7110 - NSW Electricity Network – Transgrid and extending southwards along Old Wallgrove Rd, no enhanced CH_4 readings were recorded. This suggests that at the time of surveying there is no significant CH_4 being emitted from EPL 7110 - NSW Electricity Network – Transgrid.

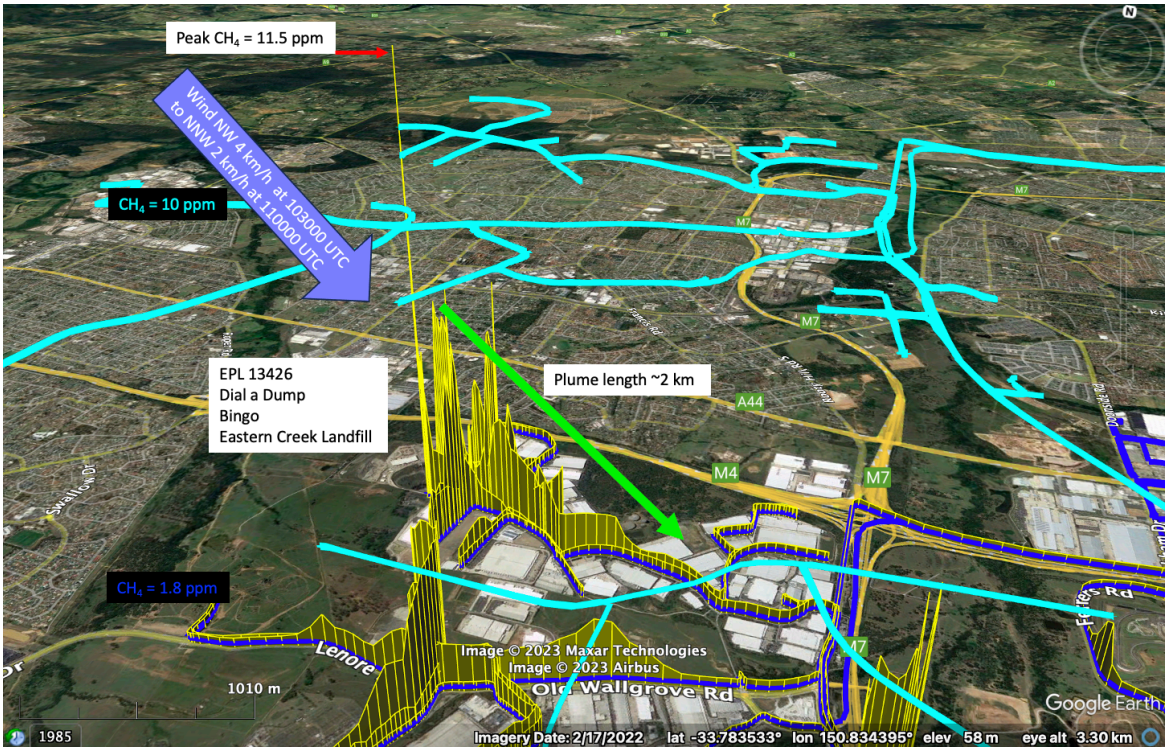


Figure 5. *CH_4 measurements near EPL 13426 - Dial a Dump - Bingo Eastern Creek Landfill, evening Tuesday 13 June 2023, looking north. The height of the yellow curtain is proportional to the concentration of CH_4 in the atmosphere. The CH_4 scale is dark blue line = 1.8 ppm, and the cyan line = 10 ppm.*

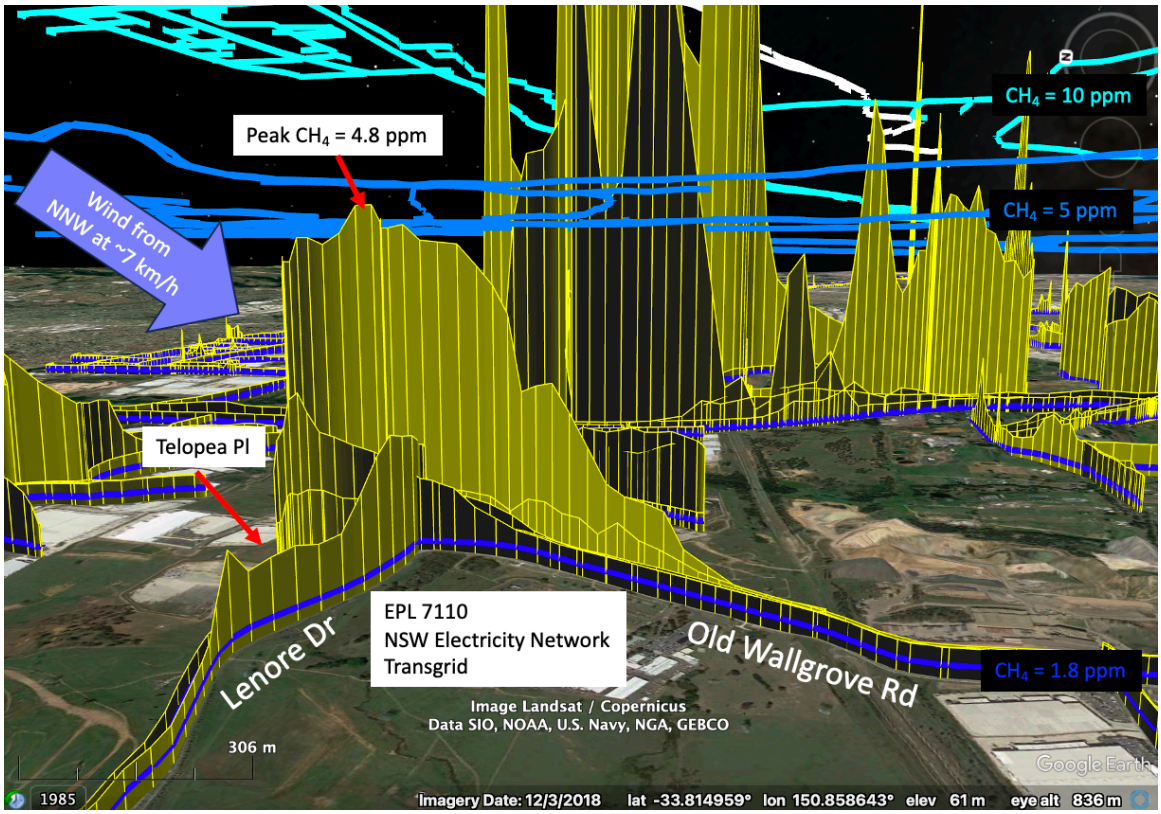


Figure 6. *CH_4 measurements near EPL 7110 - NSW Electricity Network – Transgrid, evening Tuesday 13 June 2023, looking east. The height of the yellow curtain is proportional to the concentration of CH_4 in the atmosphere. The CH_4 scale is dark blue line = 1.8 ppm, mid blue = 5 ppm, and the cyan line = 10 ppm.*

4.1.3 EPL 5272 - Waste Assets Management - Eastern Creek Waste Management Centre, EPL 20339 - Veolia - Horsley Park Resource Recovery Facility, and EPL 546c - Austral Bricks

The region bordered by the M4 Motorway (northern side), Ferrers Rd (eastern side), Chandos Rd (southern side), and Wallgrove Rd (western side) has many potential sources of CH_4 from closed landfills, active processing and recycling and the production of energy from landfill gas (Figure 7). The three EPL sites in this area are discussed collectively, because it is not possible from the survey to assign a specific source to the plumes in this region. All sides of the collective facilities were surveyed on both the 13 and 14 June 2023. On both occasions relatively high concentration CH_4 plumes were intersected along Ferrers Rd, Chandos Rd, and Wallgrove Rd.

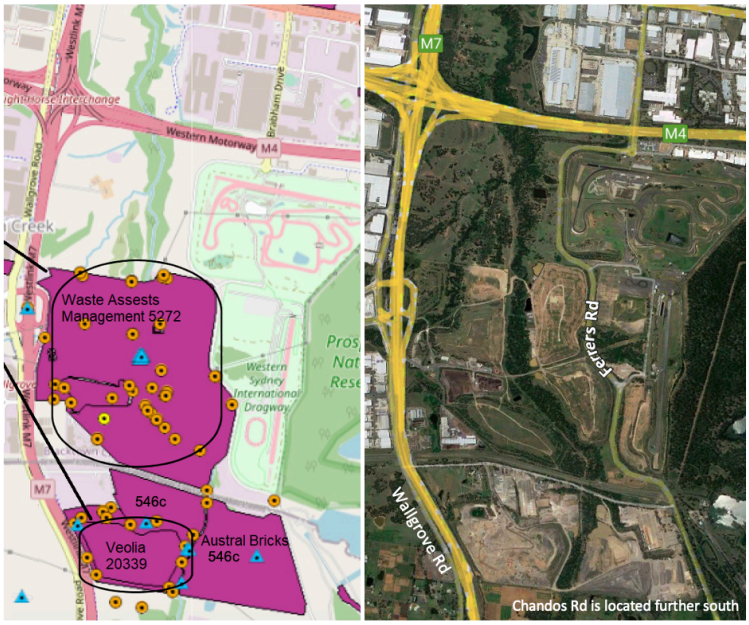


Figure 7. *Facilities EPL 5272, EPL 20339 and EPL 546c that could be the source of methane plumes intersected along Ferrers Rd, Chandos Rd, and Wallgrove Rd (image © Google Earth).*

On Tuesday 13 June 2023, when the plumes were detected near EPL 5272 and EPL 20339 the wind was from the north at 4 km/h (Figure 8). A CH_4 plume was intersected on the eastern side of EPL 5272 - Waste Assets Management - Eastern Creek Waste Management Centre along Ferrers Rd. This plume had a peak concentration of 10.6 ppm (latitude -33.816978, longitude 150.86759, at 113045 UTC). Upwind to the immediate north there is no visible source in Google Earth. However, dispersion of a plume originating from the north-east landfill cell cannot be excluded. This is consistent with the fact that at 110000 UTC the wind was from the north-north-west at 2 km/h. It is recommended that a back-trajectory model be run to determine likely sources. In the south-east corner of the subregion there was no plume near EPL 546c - Austral Bricks (Figure 8). Further to the west there was a CH_4 plume adjacent to EPL 20339 - Veolia - Horsley Park Resource Recovery Facility (Figure 8). The peak concentration of the CH_4 plume along Chandos Rd was 7.9 ppm (latitude - 33.832693, longitude 150.860037, at 112445 UTC). This plume could be from one or multiple facilities to the north as shown in Figure 7. It is recommended that a detailed on-site survey be undertaken in the Eastern Creek / Horsley complex. On the western side of the Eastern Creek / Horsley complex a CH_4 plume with a peak concentration of 6.9 ppm was intersected when driving along Wallgrove Rd at 112040 UTC (latitude -33.8258, longitude 150.855). At this time the wind was transitioning from the north-north-west at 2 km/h, 110000 UTC, to north at 4 km/h, 113000 UTC. Several facilities to the north of this point could be the source of the plume. No plume was detected along Wallgrove Rd at 083100 UTC (2.2 ppm, wind west-south-west at 11 km/h) or at 123715 UTC (2.2 ppm, calm conditions). On 13 June 2023, all CH_4 plumes detected around the Eastern Creek / Horsley complex had corresponding CO_2 plumes, but these were mostly less than 500 ppm.

On 14 June 2023 a CH_4 plume was intersected along Ferrers Rd, which had a peak CH_4 reading of 58 ppm (latitude - 33.815331, longitude 150.866153, 103640 UTC, and winds from the west-north-west at 2 km/h transitioning to calm) (Figure 9). This CH_4 plume likely originates from EPL 5272 - Waste Assets Management - Eastern Creek Waste Management Centre. There were correlated CH_4 and CO_2 plumes along Ferrers Rd. The CO_2 plume had a peak concentration of 530 ppm (latitude -33.821917, longitude 150.867698, at 103835 UTC). Further study is required to understand the correlation between the CH_4 and CO_2 plumes at these locations.

On 14 June 2023 along Chandos Rd a CH_4 plume with a peak concentration of 3.5 ppm was intercepted at 104200 UTC (latitude -33.832889, and longitude 150.861183). This plume is smaller in extent and of lower concentration than when the wind was from the north, suggesting that EPL 5272 - Waste Assets Management is the major source of CH_4, not EPL 20339 - Veolia - Horsley Park Resource Recovery Facility at the Eastern Creek / Horsley complex. This can only be validated with on-site measurements. On the western side of the complex a CH_4 plume with a peak reading of 10.4 ppm was intercepted at 104555 UTC (latitude -33.815215, and longitude 150.851437) (Figure 9). At this time, the wind was transitioning from west-north-west to calm. It is not possible from the resolution of the wind direction data to say if the CH_4 plume is from facilities to the west of the sample point or due to plume dispersion from EPL 5272 - Waste Assets Management under calm conditions.

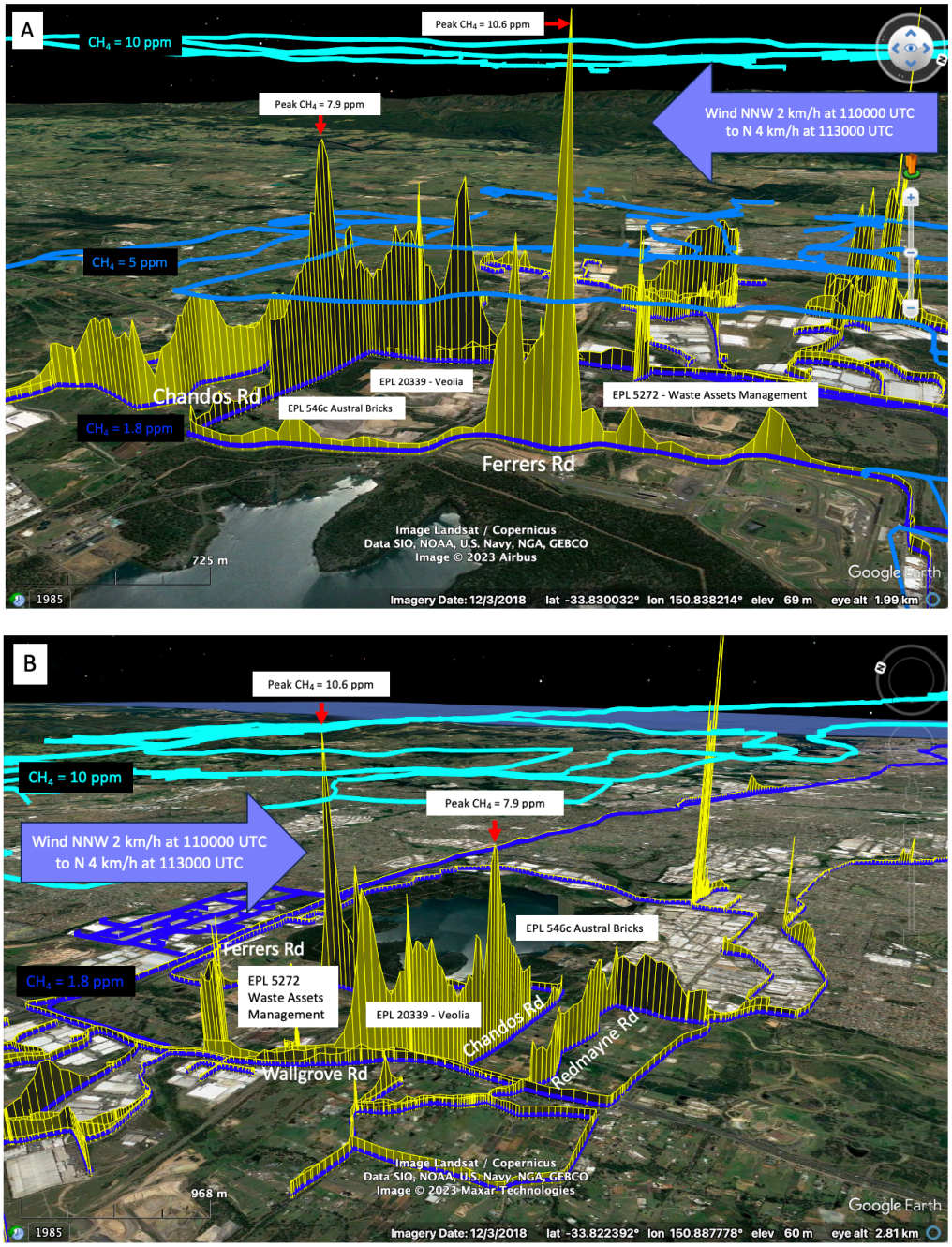


Figure 8. *CH_4 measurements near EPL 5272 - Waste Assets Management - Eastern Creek Waste Management Centre, EPL 20339 - Veolia - Horsley Park Resource Recovery Facility and EPL 546c - Austral Bricks. A) Evening Tuesday 13 June 2023, looking south-west. B) Evening Tuesday 13 June 2023, looking north-east. The height of the yellow curtain is proportional to the concentration of CH_4 in the atmosphere. The CH_4 scale is dark blue line = 1.8 ppm, and the cyan line = 10 ppm.*

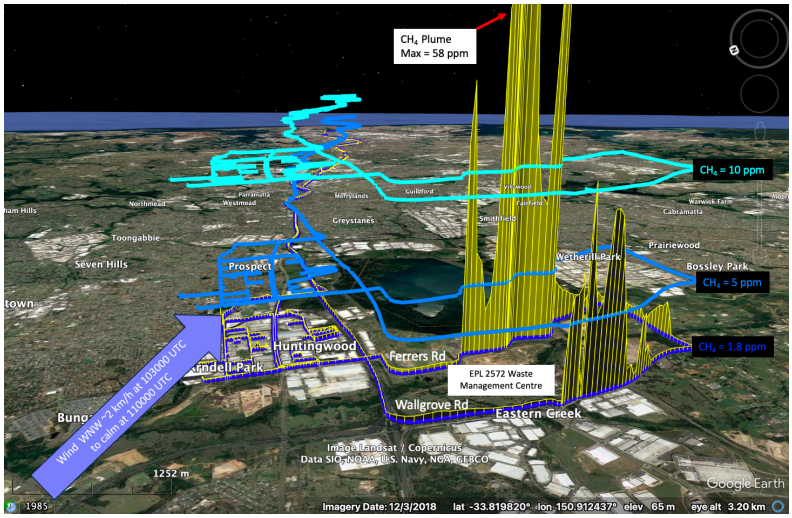


Figure 9. *CH_4 measurements near EPL 5272 - Waste Assets Management - Eastern Creek Waste Management Centre, EPL 20339 - Veolia - Horsley Park Resource Recovery Facility and EPL 546c - Austral Bricks, evening Wednesday 14 June 2023. The height of the yellow curtain is proportional to the concentration of CH_4 in the atmosphere. The CH_4 scale is dark blue line = 1.8 ppm, mid blue = 5 ppm, and the cyan line = 10 ppm. Note: CH_4 values reported above 20 ppm are not precise and beyond the recommended operation range of the Picarro 2401-m analysers.*

4.1.4 EPL 3511 - George Borg Piggery

A survey along Burley Rd, which was downwind of EPL 3511 - George Borg Piggery, was done on 13 June 2023 (Figure 10). At the time of surveying the wind was blowing from the north at 4 km/h to calm. This plume had split peaks. The peak CH_4 reading at the eastern end of Burley Rd was 2.8 ppm (latitude -33.8289, longitude 150.850353, at 121940 UTC), and the peak CH_4 reading at the northern end of Walworth Rd, was 2.8 ppm (latitude -33.828549, longitude 150.846873, at 122130 UTC). There is also a co-located CO_2 plume which correlated with the areas that had the strongest piggery odour. The CO_2 plume had a peak reading of 484 ppm (latitude -33.833515, longitude 150.84294, at 122515 UTC) and extended 1 km south to Horsley Rd. Piggery emission estimates for Australia are based on only a few historical studies (Australian Government, 2023; Skerman, et al. 2018) and the uncertainty associated with the estimate is poorly characterised. Follow-up studies at the piggery would assist in characterising the emission factor uncertainty for piggeries. However, in 2021 for NSW it is estimated that piggery emissions contributed 0.029 Mt CO_2-e enteric and 0.31 Mt waste emissions, thus piggery (swine) emissions contribute only 1.8% towards NSW's agricultural emissions, which are estimated to be 19.3 Mt (https://www.greenhouseaccounts.climatechange.gov.au/). With respect to greenhouse gas emissions, compared to the waste facilities, follow-up studies on the greenhouse gas emissions from the piggery would rank lower compared to the need for further studies at the waste facilities.

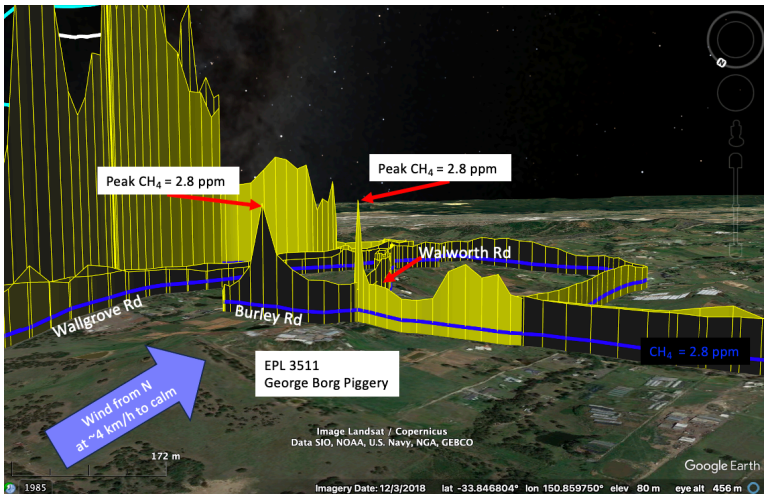


Figure 10. *CH_4 measurements near EPL 3511 - George Borg Piggery, evening Tuesday 13 June 2023, looking south-east. The height of the yellow curtain is proportional to the concentration of CH_4 in the atmosphere. There was limited CH_4 enhancement above background at this location, thus only the dark blue 1.8 ppm line is shown, and the peak concentration recorded (2.8 ppm).*

4.1.5 EPL 546a and 546b - Austral Bricks

Austral Bricks adjacent sites (latitude, longitude; -33.82439 150.83204; -33.82431, 150.83230) were surveyed on the western side along Old Wallgrove Rd at 100000 UTC (wind from the north-north-west, at ~7 km/h), and in the south-east corner along the accessible portion of Burley Rd at 122340 UTC (calm wind conditions) (Figure 11). The concentration of CH_4 along both sides surveyed ranged from 1.9 to 2 ppm. At the time of surveying, there were no significant CH_4 emissions from the Austral Brick facilities.

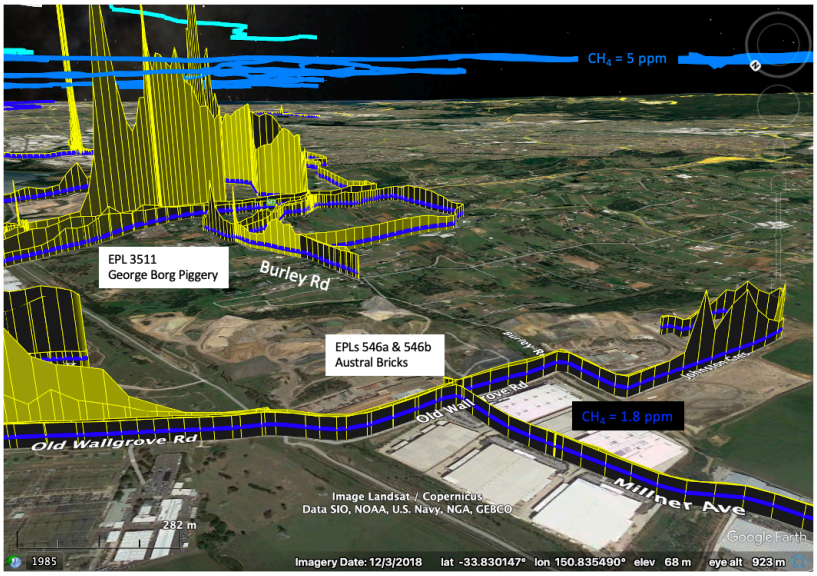


Figure 11. *CH_4 measurements near EPLs 546a and 546b - Austral Bricks adjacent sites (-33.82439 150.83204; -33.82431, 150.83230), evening Tuesday 13 June 2023, looking south-east. The height of the yellow curtain is proportional to the concentration of CH_4 in the atmosphere. The CH_4 scale is dark blue line = 1.8 ppm, and mid blue line = 5 ppm.*

4.1.6 EPL 123 - PGH Bricks and Pavers

The survey around EPL 123 - PGH Bricks and Pavers was done on the evening of Tuesday 13 June 2023 between 100130 and 100645 UTC (Figure 12). Via Johnstone Cres it was possible to survey all sides of the facility. At the time of surveying the wind was from the north-north-west at ~7 km/h. The maximum concentration of CH_4 detected near the facility was only 2.6 ppm. At the time of surveying there were no major CH_4 emissions of concern.

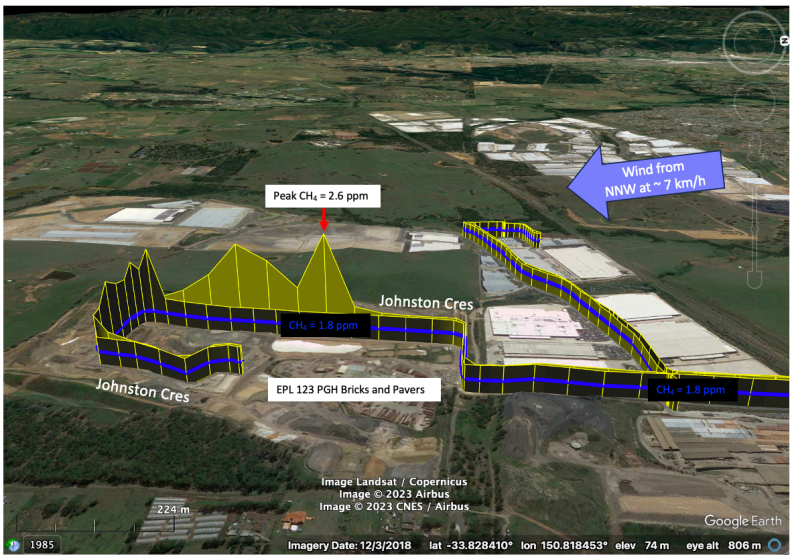


Figure 12. *CH_4 measurements near EPL 123 - PGH Bricks and Pavers. The height of the yellow curtain is proportional to the concentration of CH_4 in the atmosphere. There was limited CH_4 enhancement above background at this location, thus only the dark blue 1.8 ppm line is shown, and the peak concentration recorded (2.6 ppm).*

4.1.7 EPL 6152 - Toll Chemical Logistics

Surveying around EPL 6152 - Toll Chemical Logistics was undertaken on the evening of Wednesday 14 June 2023 (Figure 13). Throughout the suburbs of Huntingwood and Arndell Park minor plumes were detected along Lidco St and at the shopping complex corner of Holbeche Rd and Walters Rd. These types of plumes are commonly associated with gas distribution network leaks and the use of gas appliances in food outlets. No CH_4 plume was intersected near EPL 6152 - Toll Chemical Logistics.

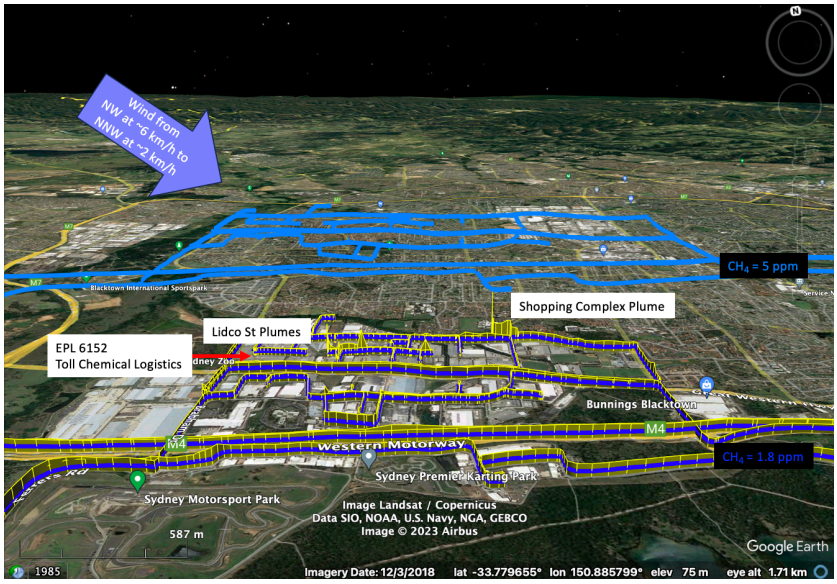


Figure 13. *CH_4 measurements near PL 6152 - Toll Chemical Logistics, evening Wednesday 14 June 2023, looking north. The height of the yellow curtain is proportional to the concentration of CH_4 in the atmosphere. The CH_4 scale is dark blue line 1.8 ppm, and mid blue 5 ppm.*

4.1.8 Hassall St, Wetherill Park

On 13 June 2023, when looping around Prospect Reservoir an 800 m wide CH_4 plume was intersected along Hassall St, Wetherill Park (Figure 14). The peak CH_4 reading in the plume was 16.7 ppm (-33.840232 latitude, 150.915522 longitude, at 115125 UTC). At this time the wind was from the north at approximately 4 km/h. To the north of Hassall St is the Sustainable Resource Centre and a creek line with swampy conditions; either of these could be the source of the CH_4. An on-site inspection would be needed to determine the source of the plume.

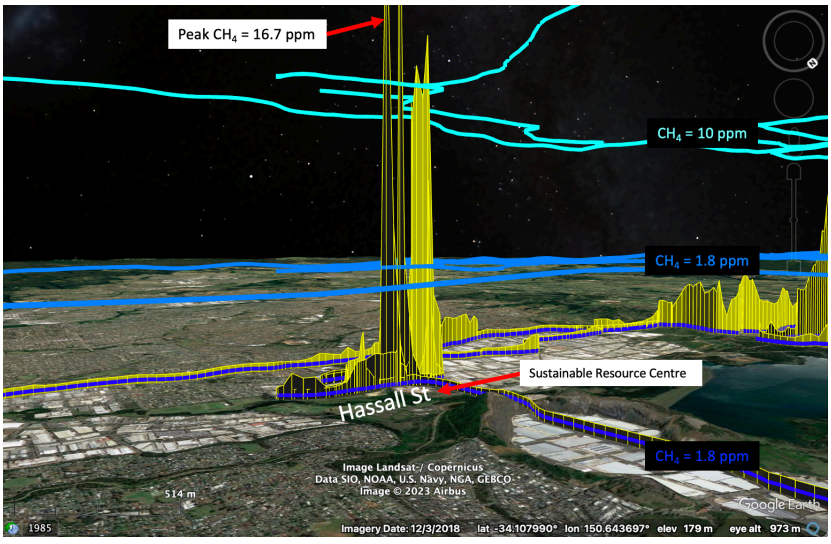


Figure 14. *CH_4 measurements along Hassall St, Wetherill Park, evening Tuesday 13 June 2023, looking south-west. The height of the yellow curtain is proportional to the concentration of CH_4 in the atmosphere. The CH_4 scale is dark blue line = 1.8 ppm, mid blue line = 5 ppm, and cyan line = 10 ppm.*

4.2 Carbon Dioxide Survey Results and Discussion

Globally CO_2 is the primary greenhouse gas of concern. In the urban areas surveyed the dominant anthropogenic source of CO_2 comes from the use of fossil fuel in vehicles, but there are many other sources. All CO_2 readings for 13 and 14 June 2023 are summarised by latitude and longitude in Figure 15 and displayed in Google Earth in Figures 16 and 17.

In Figures 15, 16 and 17 most of the CO_2 readings were below 500 ppm, but above the Cape Grim May 2023 averaged value of 415.7 ppm. The average concentration of CO_2 measured on the evening of 13 June 2023 was 447 ppm. This is expected in urban areas like Sydney due to the high density of traffic. Throughout most of the surveying only isolated spikes of CO_2 were detected. Many of the CO_2 readings above 500 ppm are associated with intersections (due to stationary traffic in one direction), or isolated truck emissions (Figure 16). The maximum concentration of CO_2 recorded on 13 June 2023 was 3495 ppm (latitude -33.81544, longitude 150.849683, at 084240 UTC), Clay Place, Eastern Creek. The maximum concentration of CO_2 recorded on 14 June 2023 was 2759 ppm (latitude -33.795129, longitude 150.889448, at 092050 UTC), at the corner of Walters Rd and the Great Western Highway, Arndell Park.

CO_2 plumes should be interpreted with caution, as trucks can produce plumes along the survey lines. From the preliminary inspection of the CO_2 concentration data in Google Earth, there are CO_2 plumes associated with the CH_4 plumes at EPL 5272 - Waste Assets Management - Eastern Creek Waste Management Centre, EPL 20339 Veolia - Horsley Park Resource Recovery Facility, and 3511 George Borg Piggery. These correlated plumes were discussed above in the CH_4 section of the report. Where on-site studies are undertaken, it is recommended that CO_2 concentrations be measured as part of those studies.

The data in Figures 15, 16 and 17 highlight that the average CO_2 readings were higher in Eastern Sydney compared to Eastern Ck region. This is due to the density of traffic in the east and inner west of Sydney. Annually repeating car-based atmospheric CO_2 surveys throughout Sydney would enable the tracking of net zero progress as electric vehicles replace fossil fuel vehicles, and these surveys could be used to verify UNFCCC reporting trends.

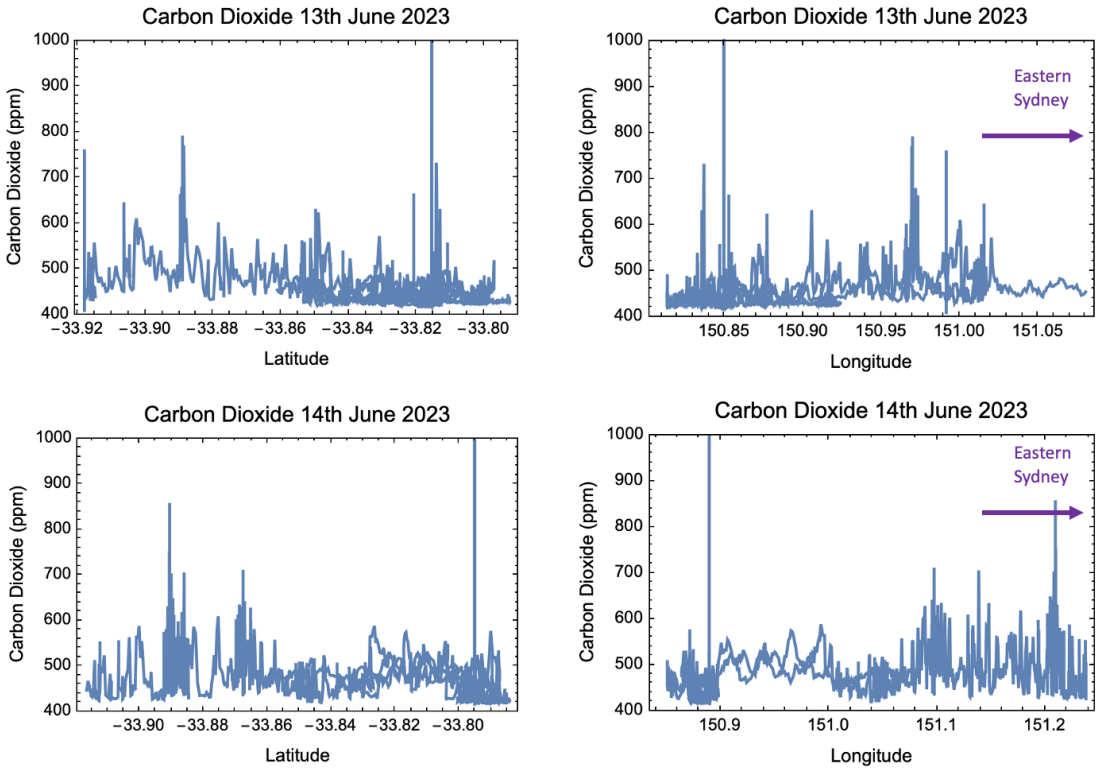


Figure 15. *CO_2 atmospheric concentration summary graphs for the car-based surveys on the 13 and 14 June 2023. Note: CO_2 values reported above 1000 ppm are not precise and are beyond the recommended operational range of the Picarro 2401-m analysers.*

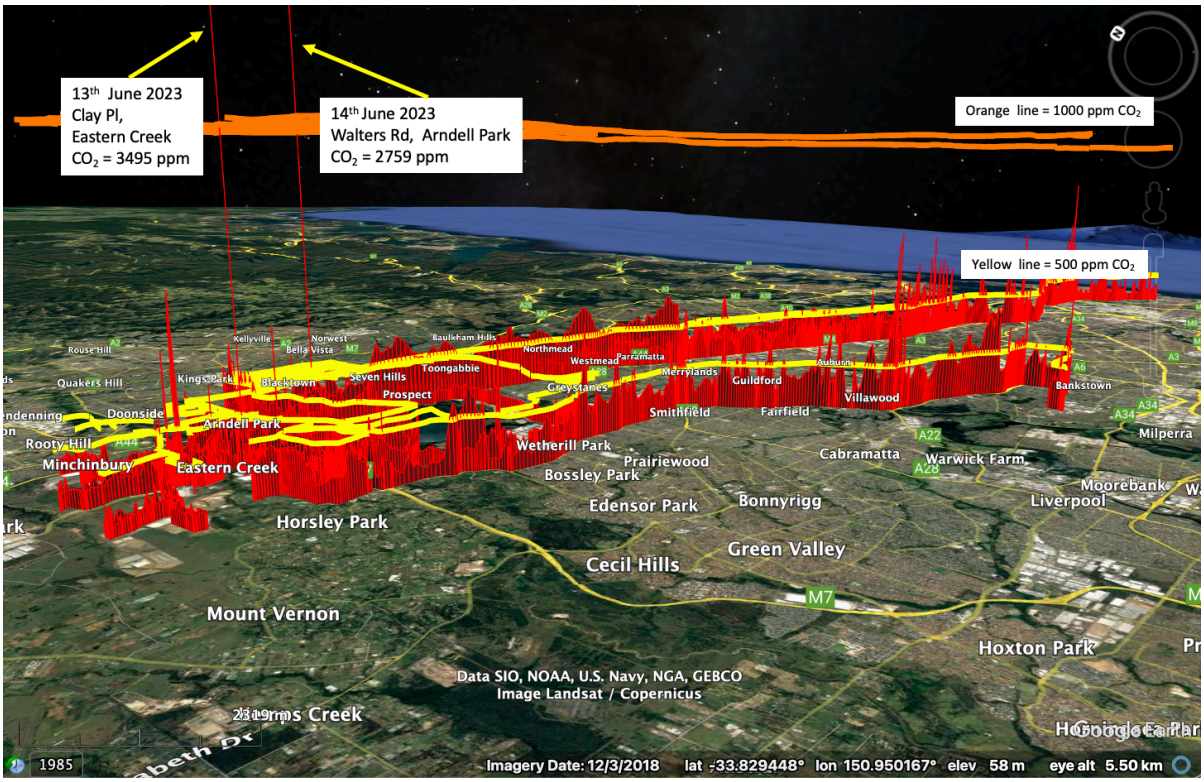


Figure 16. *CO_2 survey 13 and 14 June 2023, looking north-east. The height of the red curtain is proportional to the concentration of CO_2 in the atmosphere. The yellow line indicates 500 ppm CO_2 and the orange line 1000 ppm CO_2. Note: CO_2 values reported above 1000 ppm are not precise and are beyond the recommended operation range of the Picarro 2401-m analysers.*

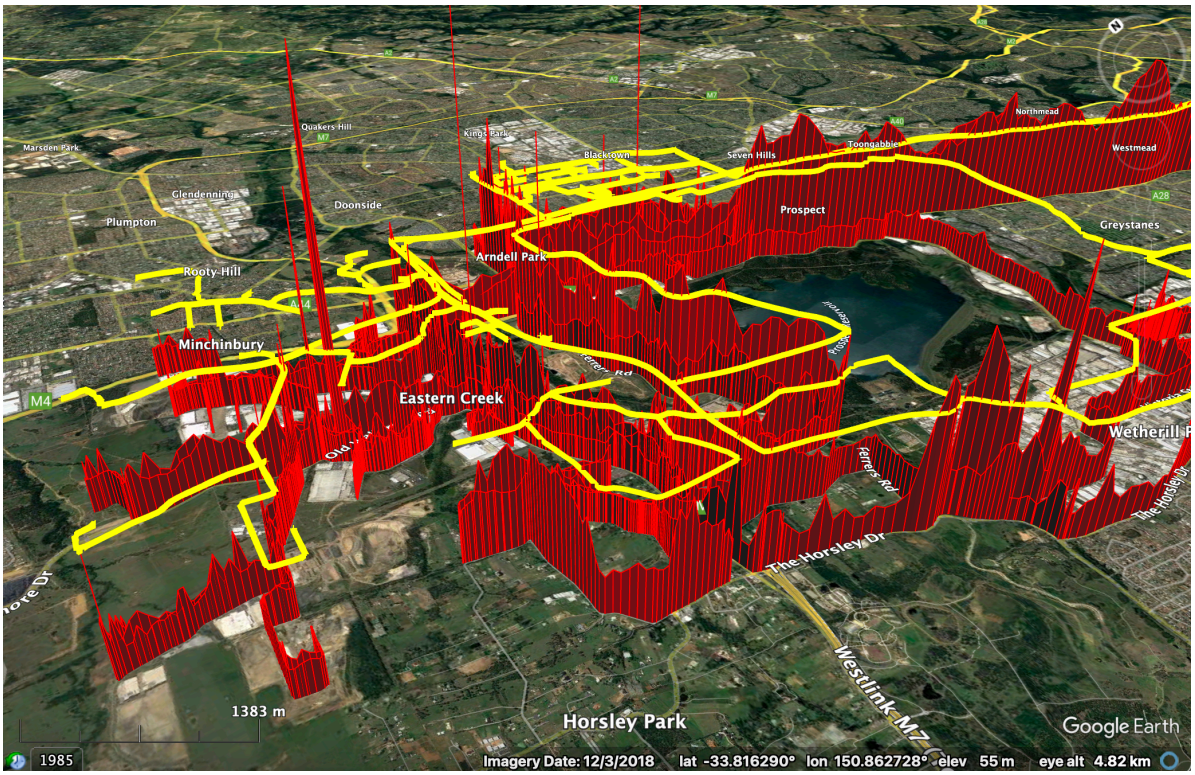


Figure 17. *CO_2 survey 13 and 14 June 2023, looking north-east. The height of the red curtain is proportional to the concentration of CO_2 in the atmosphere. The yellow line indicates 500 ppm CO_2. Note: CO_2 values reported above 1000 ppm are not precise and are beyond the recommended operation range of the Picarro 2401-m analysers.*

4.3 Carbon Monoxide Survey Results and Discussion

CO is a useful tracer gas for identifying sources of burned fossil fuel. CO is a known health hazard. The target atmospheric concentration of CO for NSW on a rolling 8-hour average is less than 9 ppm, and in 2021 there were no days over this threshold (NSW Government, 2021). All CO readings for 13 and 14 June 2023 are summarised by latitude and longitude in Figure 18 and displayed in Google Earth in Figures 19 and 20. The maximum recorded value on 13 June 2023 was 6.5 ppm (latitude -33.797015, longitude 150.853708, at 124115 UTC) at the junction of the M4 and M7 freeways (Figure 20). The relatively high readings at this junction are most likely due to the density of vehicles. On 14 June 2023 the maximum CO reading recorded was 11.4 ppm (latitude -33.810897, longitude 150.939835, at 090735 UTC). This single point was the only reading that exceeded the NSW rolling average 8-hour threshold of 9 ppm. As it was a one-off high reading it is of little concern. The most recently available flask data for Cape Grim is December 2021. For this month average value for CO at Cape Grim was 0.054 ppm, while the average concentration of CO measured on the 13 June 2023 was 0.29 ppm. Although this reading is well below the level of any health concern, these enhanced CO emissions are contributing directly to global warming via the chemical reaction between CO and hydroxyl ($^{\bullet}OH$) radicals in the atmosphere, which reduces the number of $^{\bullet}OH$ radicals that would react with CH_4 (Lu and Khalil, 1993).

The utility of CO measurements as part of greenhouse gas surveys is highlighted in Figure 21, in which it can be observed that in many locations there is a correlation between the CO_2 and CO readings. Where this occurs enhancements in CO_2 and CO above background can be attributed to being most likely due to the burning of fossil fuel, and in this study that would most likely be the burning of fuel in vehicles. Additional spatial and temporal studies using these two gases could help with verifying Sydney's fossil fuel inventory and would assist with isolating CO_2 plumes not related to the burning of fossil fuel.

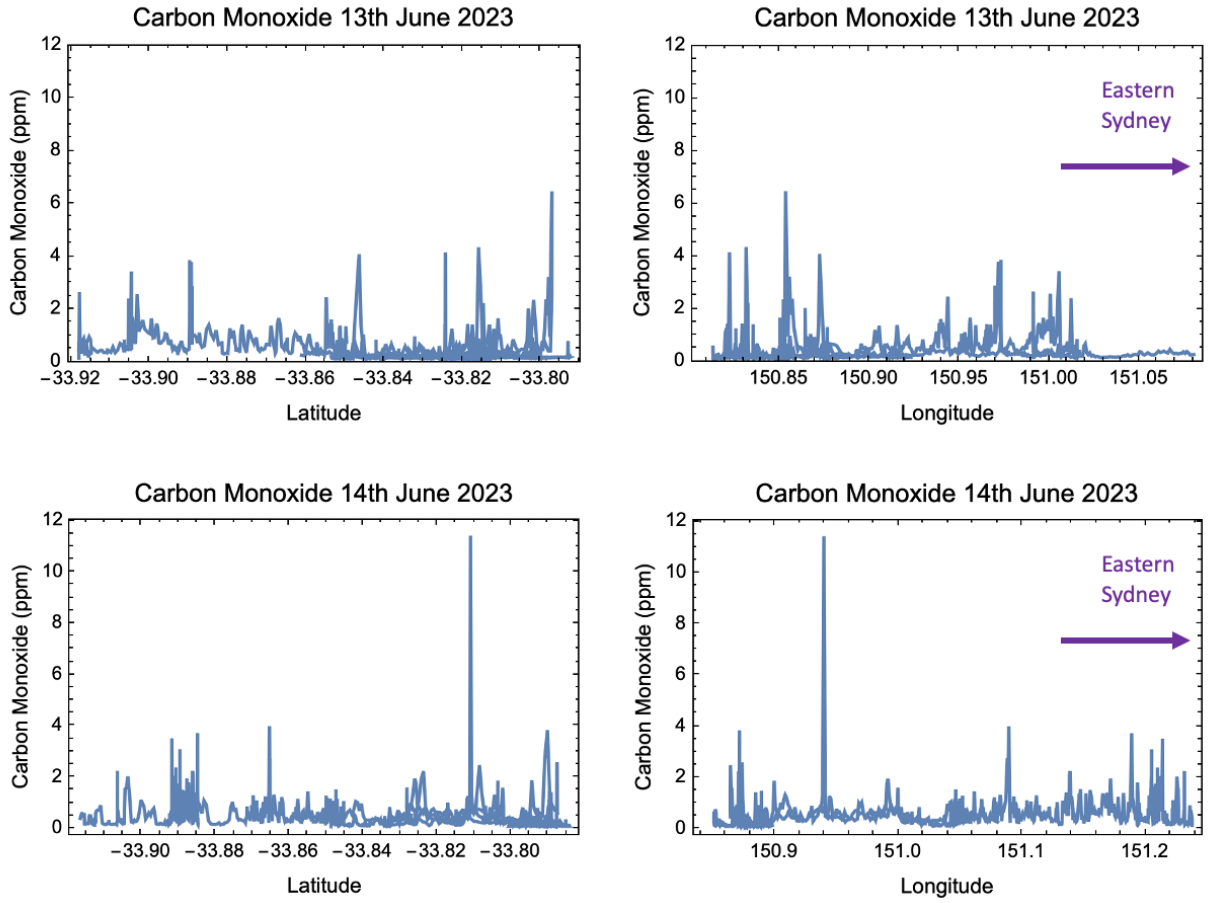


Figure 18. *CO atmospheric concentration summary graphs for the car-based surveys on 13 and 14 June 2023. Note: CO values reported above 5 ppm are not precise and are beyond the recommended operational range of the Picarro 2401-m analysers.*

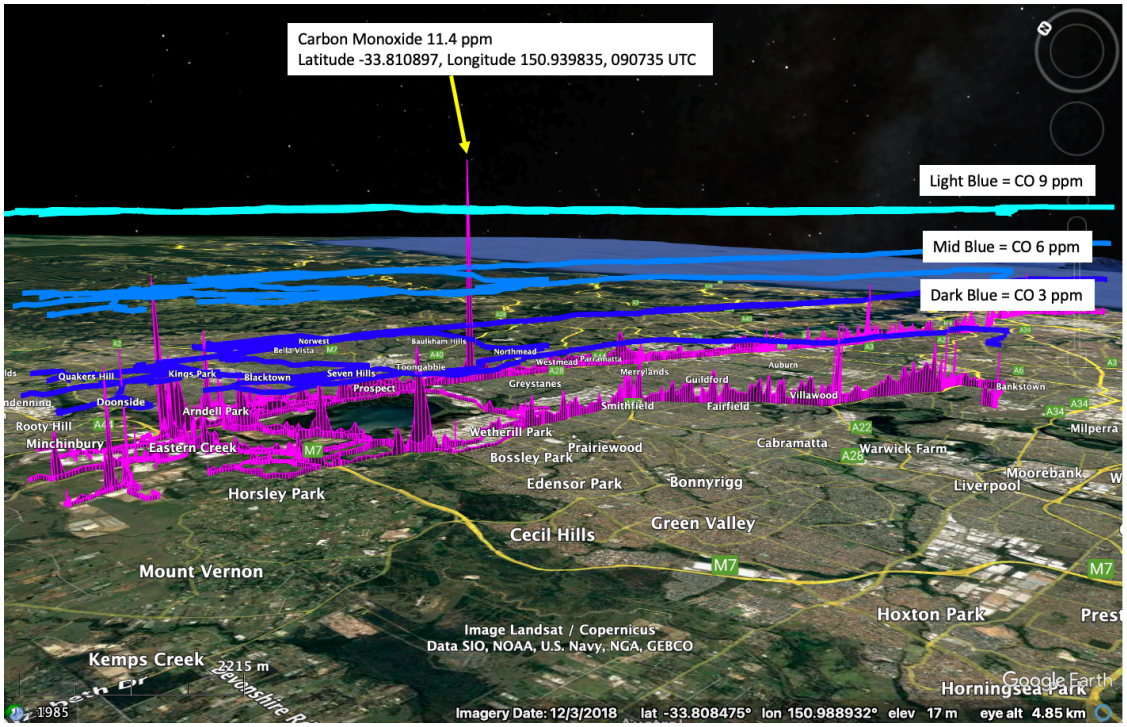


Figure 19. *CO survey 13 and 14 June 2023, looking north-east. The height of the purple curtain is proportional to the concentration of CO in the atmosphere. The colour scale is dark blue = 3 ppm, mid blue = 6 ppm, and cyan = 9 ppm. Note: CO values reported above 5 ppm are not precise and beyond the recommended operational range of the Picarro 2401-m analysers.*

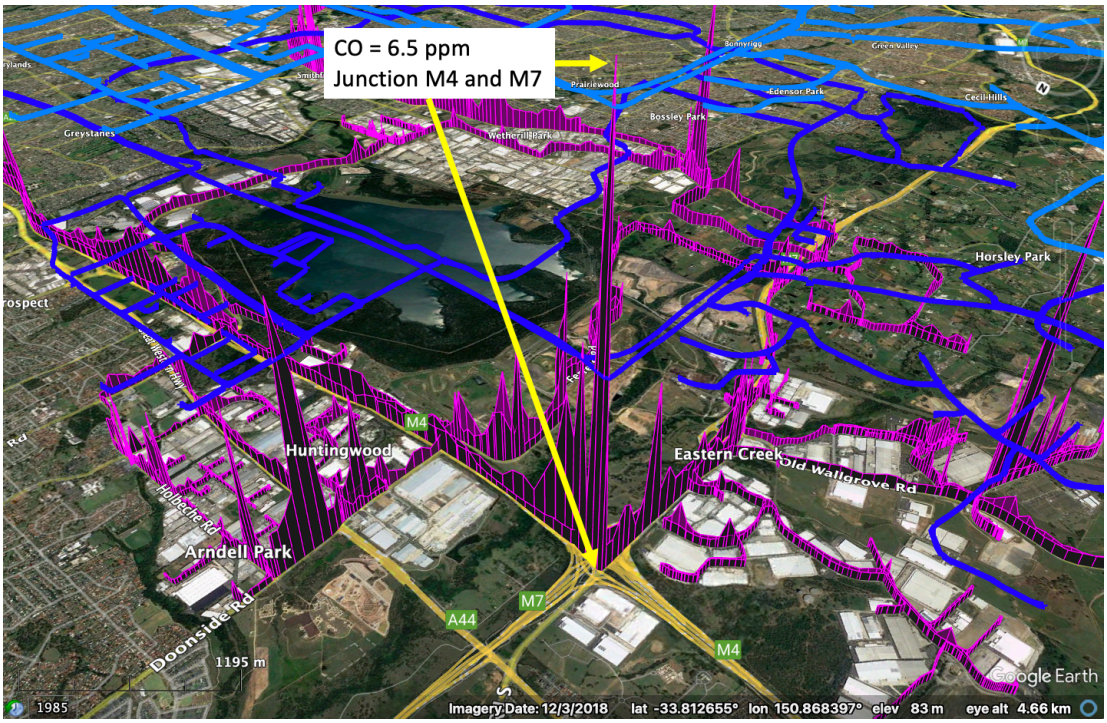


Figure 20. *CO survey 13 and 14 June 2023, looking south-east. The height of the purple curtain is proportional to the concentration of CO in the atmosphere. The colour scale is dark blue = 3 ppm, mid blue = 6 ppm, and cyan = 9 ppm. The maximum recorded value on 13 June was 6.5 ppm (latitude -33.797015, longitude 150.853708, at 124115 UTC), at the junction of the M4 and M7 freeways.*

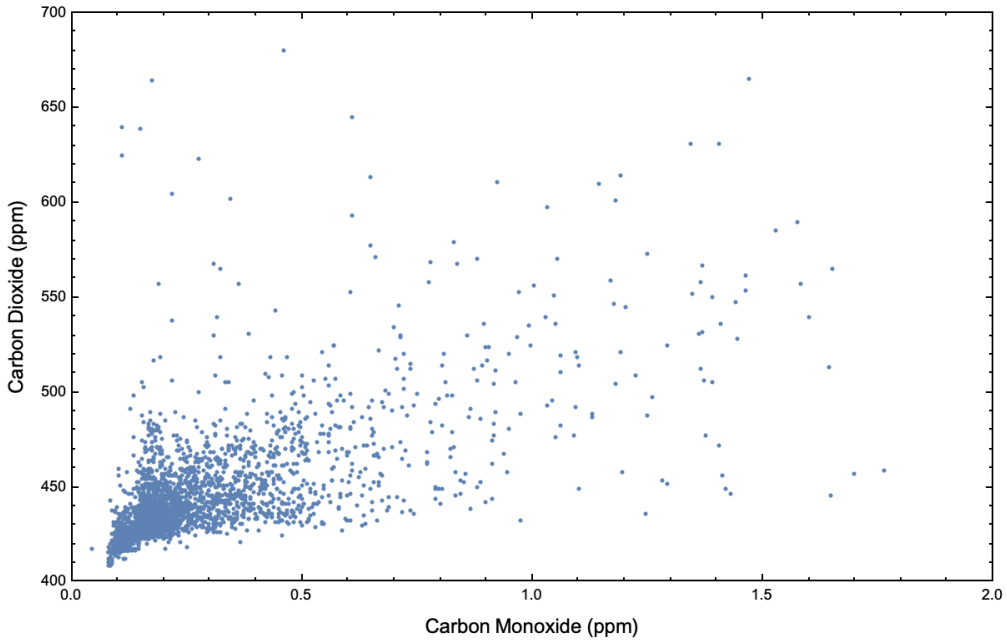


Figure 21. *Correlation between CO_2 and CO for data collected 13 June 2023. This graph highlights that in many locations there is a strong correlation between the CO_2 and CO readings. In an urban setting, this strong correlation highlights inputs mostly from the burning of fossil fuels in vehicles, and domestic wood heaters, although there can be other sources.*

5 Recommendations

This two-evening car-based measurement survey of greenhouse gases in the atmosphere in a region of potential sources of CH_4 and CO_2 has highlighted the value of these types of studies. At the start of the project there were ten sites of interest for the NSW EPA (Table 1). On the evenings of 13 and 14 June 2023, only three sites had significant CH_4 plumes:

- EPL 13426 - Dial a Dump - Bingo Eastern Creek Landfill
- EPL 5272 - Waste Assets Management - Eastern Creek Waste Management Centre
- EPL 20339 - Veolia - Horsley Park Resource Recovery Facility.

It is recommended that on-site studies be undertaken at EPL 13426, EPL 5272 and EPL 20339. It is not possible to say what the best method would be to quantify emissions from EPL 13426 - Dial a Dump - Bingo Eastern Creek Landfill without better understanding the sources of the emissions from the facility.

The Eastern Creek / Horsley complex is a large area covering approximately five square kilometres. Methods that could be used to better understand the source of the CH_4 and CO_2 at this complex would be trolley-based surveys over the landfills, or drone-based low-altitude in situ surveys over the whole area. Once the CH_4 and CO_2 sources have been identified the rates of emissions could be determined using drone-based in situ surveys, tracer gas studies, open-path laser, or solar absorption spectrometer systems.

A relatively high CH_4 plume was mapped along Hassall St in Wetherill Park. To the north of this site is the Sustainable Resource Centre. It is recommended that an on-site survey be undertaken at this facility. Initially this could be a simple trolley-based survey.

Of lower priority, a CO_2 survey is recommended for EPL 3511 - George Borg Piggery. This survey could be done using drone-based in situ surveys, tracer gas studies, open-path laser, or solar absorption spectrometer systems.

Additional car-based surveys of the atmospheric concentration of CH_4, CO_2 and CO throughout Sydney and priority areas of NSW would assist the NSW EPA optimise where detailed on-site inspections should be undertaken and help with prioritising mitigation action. Because greenhouse gases are colourless and odourless, facility owners and managers are often not aware of the extent of emissions that are released from their facilities. Simply being able to visualise the extent of the emissions will facilitate better management practices, which will assist the NSW Government achieve its net zero goals.

Only one major CO_2 plume was intersected as part of the surveys, downwind of EPL 3511 - George Borg Piggery. Of lower priority, a CO_2 survey is recommended for this site. A plume of CH_4 was also intersected downwind of the piggery. This plume had a peak concentration of only 2.8 ppm, but it was moderately wide and had a cross section of approximately 1 km, which suggests persistent emissions. This site is ranked as a relatively low priority for further greenhouse gas studies, but a study at this site would help better characterise the emission factor for piggeries. Surveys at this facility could be done using drone-based in situ surveys, tracer gas studies, open-path laser, or solar absorption spectrometer systems.

The CO_2 survey results show that for large portions of the surveying throughout Sydney there is a correlation between the CO_2 and CO emissions. This is in part related to the use of fossil fuels. Repeated surveys of CO_2 and CO would assist in tracking net zero progress as vehicles transition from being powered by fossil fuel to electric batteries.

On-site studies are a low priority for EPL 7119 - NSW Electrical Network – Transgrid, EPL 546 Austral Bricks (three locations: 546a, 546b, and 546c), 123 PGH Bricks and Pavers, and EPL 6152 Toll Chemical Logistics. On the evenings of 13 and 14 June 2023, no CH_4, CO_2, or CO emissions of concern were recorded at the time of surveying downwind of these facilities.

Given that there are many potential sources of greenhouse gases in the suburbs surrounding Eastern Creek, it is recommended that at least two permanent monitoring stations be installed. One ideal location is the Bureau of Meteorology Horsley Park station. The position of the other station should be selected based on priority monitoring and modelling objectives. Permanent monitoring stations would enable rigorous tracking of net zero progress.

6 References

Australian Government (2007) National Greenhouse and Energy Reporting Act, 2007. https://www.cleanenergyregulator.gov.au/NGER/Legislation (accessed 17 June 2023).

Australian Government (2023) National Inventory Report 2021. https://www.dcceew.gov.au/climate-change/publications/national-inventory-report-2021 (accessed 21 June 2023)

Bingo (2022a) Permanent flares now operational at Eastern Creek. https://www.bingoindustries.com.au/news/permanent-flares-now-operational-at-eastern-creek (accessed 22 June 2023)

Bingo (2022b) Permanent flare system for Eastern Creek. https://www.bingoindustries.com.au/news/permanent-flare-system-for-eastern-creek (accessed 22 June 2023).

CSIRO (2023) Cape Grim Greenhouse Gas Data. https://capegrim.csiro.au/ (assessed 18 Jun 2023).

Etminan, M., Myhre, G., Highwood, E. J., and Shine, K. P. (2016). Radiative forcing of carbon dioxide, methane and nitrous oxide: A significant revision of the methane radiative forcing. Geophysical Research Letters,43, 12,614–12,623. https://doi.org/10.1002/2016GL071930

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., and Van Dorland, R. (2007) Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf

Lu, Y., and Khalil, M.A.K. (1993) Methane and carbon monoxide in OH chemistry: The effects of feedbacks and reservoirs generated by the reactive products. Chemosphere, 26(1-4), pp. 641–655. https://doi.org/10.1016/0045-6535(93)90450-J.

Lu, X., Harris, S. J., Fisher, R. E., France, J. L., Nisbet, E. G., Lowry, D., Röckmann, T., van der Veen, C., Menoud, M., Schwietzke, S., and Kelly, B. F. J. (2021) Isotopic signatures of major methane sources in the coal seam gas fields and adjacent agricultural districts, Queensland, Australia, Atmospheric Chem. Phys., 21, 10527–10555, https://doi.org/10.5194/acp-21-10527-2021.

Nisbet, E. G., Fisher, R. E., Lowry, D., France, J. L., Allen, G., Bakkaloglu, S., Broderick, T. J., Cain, M., Coleman, M., Fernandez, J., Forster, G., Griffiths, P. T., Iverach, C. P., Kelly, B. F. J., Manning, M. R., Nisbet-Jones, P. B. R., Pyle, J. A., Townsend-Small, A., al-Shalaan, A., Warwick, N., and Zazzeri, G. (2020) Methane Mitigation: Methods to Reduce Emissions, on the Path to the Paris Agreement, Rev. Geophys., 58, e2019RG000675, https://doi.org/10.1029/2019RG000675.

NSW Government (2020) Net Zero Plan, Stage 1:2020-2030. Department of Planning, Industry and Environment. https://www.energy.nsw.gov.au/sites/default/files/2022-08/net-zero-plan-2020-2030-200057.pdf (accessed 17 June 2023)

NSW Government (2021) NSW annual air quality statement 2021: Gases https://www.environment.nsw.gov.au/topics/air/nsw-air-quality-statements/annual-air-quality-statement-2021/gases (assessed 18 Jun 2023).

NSW Government (2022) EC REP MOD 10 - Landfill gas capture and treatment project. https://www.planningportal.nsw.gov.au/major-projects/projects/ec-rep-mod-10-landfill-gas-capture-and-treatment-project (accessed 22 June 2023).

Myhre, G., Shindell, D., Bréon, F.M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H. (2013) Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, US https://ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf (accessed 18 June 2023).

Skerman, A., Willis, S., Marqardt, B., and McGahan, E. (2018). *PigBal4 user manual,* Version 2.6. Department of Agriculture, Fisheries and Forestry, State of Queensland.

https://www.australianpork.com.au/sites/default/files/2021-06/PigBal_v4_manual_v2.6-1.pdf (accessed 21 June 2023).

United Nations Environment Programme and Climate and Clean Air Coalition (2021). Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. Nairobi: United Nations Environment Programme. ISBN: 978-92-807-3854-4 https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions (assessed 18 Jun 2023).

Wang, Y., Zhang, H., Zhang, H., Kang, X., Xu, X., Wang, R., Zou, H., Chen, W., Pan., D., Lü, F., and He, P. (2023) Flare exhaust: An underestimated pollution source in municipal solid waste landfills. Chemosphere, 325, 138327.

7 Supplementary Information

S1 - Picarro 2401-m Specification Sheet

PICARRO

The World's Leading Instruments for Carbon and Water Cycle Measurements

CRDS Analyzer
$CO + CO_2 + CH_4 + H_2O$ for Flight
PICARRO G2401-*m*

The world's only 4-species greenhouse gas analyzer – ready for continuous in-flight measurements

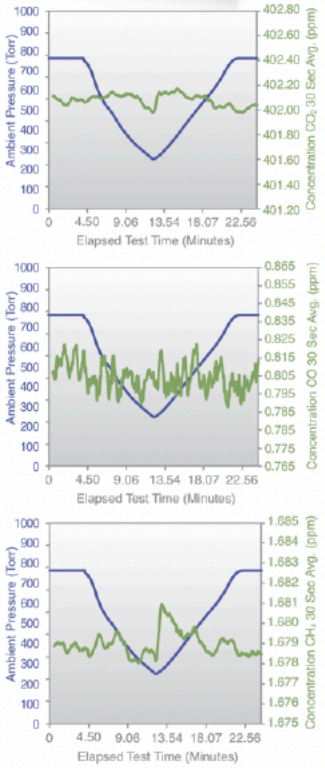
- Global #1 in precision, accuracy, and portability
- Guaranteed lowest drift of any continuous greenhouse gas measurement instrument
- Unique water correction automatically reports dry gas mol fractions

Advantage Note: The G2401-m utilizes Picarro's Cavity Ring-Down Spectroscopy (CRDS) technology to enable measurements of the anthropogenic tracer gas CO along with the green house gases CO_2, CH_4 and water vapor down to parts-per-billion (ppb) sensitivity. The G2401-*m* also features Picarro's unique water correction software, which automatically reports dry gas mol fractions to help reduce research complexity and consumable costs. And with Picarro's guaranteed drift spec, months of flights can be made with negligible drift. From airborne measurements over the Amazon Rainforest to vertical profiles in the Central Valley of California, Picarro flight analyzers have been field-proven to reliably provide high quality data.

Picarro's Patented CRDS Technology: The heart of the Picarro analyzer is a sophisticated time-based measurement that uses a laser to quantify spectral features of gas phase molecules in an optical cavity. Picarro's patented CRDS technology enables an effective measurement path length of up to 20 kilometers in a compact cavity, which results in exceptional precision and sensitivity with a small footprint. Because lasers drift in all instruments, Picarro uses a patented, high-precision wavelength monitor to maintain absolute spectral position and the most accurate peak quantification of any instrument. For researchers, Picarro analyzers deliver a best-in-class combination of precision, accuracy, and ease of use.

Portable, Rugged & Easy to Use: The Picarro's small size makes it easy to transport in any vehicle to the field, lab, or plane, where it can be running within minutes out of the box, and can operate for months without user interaction. In order to ensure measurement fidelity over long periods of time, even in the harshest environments, Picarro's optical cavities incorporate amazingly precise temperature and pressure control along with careful material selection and meticulous mechanical design. Scientists using these systems have reported the highest quality data, day in and day out, with fewer calibrations than other spectral absorption-based instruments.

Easy Data Management & Instrument Control: The analyzer can be configured to automatically deliver data in the format best suited to the application. Digital (RS-232) data can be transmitted via Ethernet at user-defined intervals or output in real-time and there is also an analog data output option. Using a standard Remote Desktop connection, users can remotely check and control the analyzer's internal, Windows-based PC.



Picarro pressure tests all flight analyzers in a hyperbaric chamber to guarantee performance at altitude. During the test, the chamber pressure cycles between 760 and 250 Torr as the analyzer measures a constant-concentration gas stream delivered at the same pressure as the hyperbaric chamber. Pressure test results for CO, CO_2 and CH_4 of an actual production analyzer are shown.

© 2018 PICARRO, INC. · 3105 Patrick Henry Drive Santa Clara, CA 95054 · 408.962.3900 · info@picarro.com · www.picarro.com

PICARRO

The World's Leading Instruments for
Carbon and Water Cycle Measurements

Performance Specifications	CO_2 Specification	CH_4 Specification	CO Specification	H_2O Specification
Raw Precision (1-σ over 300 secs, vibration @ 20 Hz, 1g): *Guaranteed over below range & operating conditions*	≤ 200 ppb	≤ 2 ppb	≤ 30 ppb	≤ 150 ppm
Drift at STP (over 24 hrs) *(Peak to peak 50 min average: Guaranteed over below range & operating conditions)*	≤ 200 ppb	≤ 1.5 ppb	≤ 15 ppb	≤ 100 ppm ± 5% of reading
Drift with Changing Temp *(Peak to peak 30 sec average over 3 hrs; 15°C/hr for below operating conditions):*	≤ 7.5 ppbv/°C	≤ 0.05 ppbv/°C	≤ 1.5 ppb/°C	N/A
Drift with Changing Pressure *(Peak to peak 30 sec average; < 1.4 Torr/sec for below operating conditions):*	≤ 700 ppb	≤ 7.5 ppb	≤ 50 ppb	N/A
Operating Range	0 - 1000 ppm	0 - 20 ppm	0 - 5 ppm	0 – 7 %v H_2O / 39 °C dew pt (non-condensing)
Guaranteed Specifications Range	300 – 500 ppm	1 ppm – 3 ppm	0 – 1 ppm	0 – 3 %v H_2O / 25 °C dew pt (non-condensing)
Measurement Interval	≤ 3.5 seconds	≤ 3.5 seconds	≤ 3.5 seconds	≤ 3.5 seconds
Rise/Fall time *(10-90%/90-10%)*	≤ 3 seconds	≤ 3 seconds	≤ 3 seconds	N/A

System Specifications	
Parameter	**Value**
Measurement Technique	CRDS
Measurement Cell Temperature Control	+/- 0.005 °C
Measurement Cell Pressure Control	+/- 0.0002 atm
Sample Temperature	-10 °C to 45 °C
Sample Flow Rate	< 0.6 slm over 250 - 1000 Torr, no filtration required
Sample Pressure	250 to 1000 Torr (40 to 133 kPa)
Sample Humidity	< 99% R.H. non-condensing @ 40°C (oil free)
Ambient Temperature Range	+10 °C to +35 °C operating (-10 to 50 °C storage)
Max Rate of Change in Ambient Temp.	15 °C/hr
Ambient Humidity	< 99% R.H. non-condensing
Maximum Altitude	Altitude @ 250 Torr
Max Rate of Change in Altitude	1,000 meters / minute
Accessories (Included)	Pump (external), Keyboard, Mouse, LCD monitor (optional)
Outputs	RS-232, Ethernet, USB, Analog (optional) 0-10 V
Inlet Fittings	¼" Swagelok ®
Dimensions	Analyzer: 17.55" L x 7" h x 17" w (44.57 x 17.78 x 43.18 cm) not incl. 0.5" feet External Pump: 12.8" L x 8.9" h x 6.2" w (32.4 x 22.6 x 15.8 cm)
Weight	70 lbs (31.75 kg) including pump
Power Requirements	100 – 240 VAC, 47 – 63 Hz (auto-sensing), < 260 W start-up (total): 110 W (analyzer), 120 W (pump) at steady state
Steady State Power Dissipation	≤ 370 Watts

© 2018 PICARRO, INC. · 3105 Patrick Henry Drive Santa Clara, CA 95054 · 408.962.3900 · info@picarro.com · www.picarro.com

S2 - Australian Bureau of Meteorology latest weather observations for Horsley Park

Table SI-1. Australian Bureau of Meteorology latest weather observations for Horsley Park 13 June 2023**.**

Latest Weather Observations for Horsley Park 13 June 2023														
Date/Time	Time	Temp	App	Dew	Rel	Delta-T	Wind	Spd	Gust	Spd	Gust	Press	Press	Rain since
EST	UTC	°C	Temp	Point	Hum	°C	Dir.	km/h	km/h	kts	kts	QNH	MSL	9am
			°C	°C	%							hPa	hPa	mm
13/11:30pm	133000	9	8.5	7.8	92	0.6	CALM	0	4	0	2	-	-	0
13/11:00pm	130000	9.1	8.4	6.9	86	1	CALM	0	4	0	2	-	-	0
13/10:30pm	123000	10	9.4	7.3	83	1.3	CALM	0	4	0	2	-	-	0
13/10:00pm	120000	10.2	8.8	7.1	81	1.5	N	4	7	2	4	-	-	0
13/09:30pm	113000	11.3	9.8	7	75	2.1	N	4	6	2	3	-	-	0
13/09:00pm	110000	12.5	11.3	6.5	67	2.9	NNW	2	6	1	3	-	-	0
13/08:30pm	103000	13.4	11.9	7	65	3.1	NW	4	7	2	4	-	-	0
13/08:00pm	100000	13.8	11.8	6.9	63	3.4	NNW	7	11	4	6	-	-	0
13/07:30pm	93000	13.4	11.7	5.8	60	3.6	NNW	4	6	2	3	-	-	0
13/07:00pm	90000	14.1	12.4	5.7	57	4	NW	4	6	2	3	-	-	0
13/06:30pm	83000	15.3	12.3	5.8	53	4.6	WSW	11	24	6	13	-	-	0
13/06:00pm	80000	15.9	14.3	8.2	60	3.9	NW	6	7	3	4	-	-	0
13/05:30pm	73000	14.6	13.7	7.9	64	3.4	NW	2	4	1	2	-	-	0
13/05:00pm	70000	16.9	15.3	8.1	56	4.5	NNW	6	9	3	5	-	-	0
13/04:30pm	63000	18.2	16.6	8.2	52	5.2	NNW	6	11	3	6	-	-	0
13/04:00pm	60000	19.1	18.1	8.7	51	5.4	NW	4	9	2	5	-	-	0
13/03:30pm	53000	19.2	17.6	8.8	51	5.5	N	7	17	4	9	-	-	0
13/03:00pm	50000	19.8	18.1	8.5	48	5.9	NNW	7	13	4	7	-	-	0
13/02:30pm	43000	20	18.2	9.6	51	5.6	NNW	9	19	5	10	-	-	0
13/02:00pm	40000	18.7	16	8.9	53	5.1	NNW	13	22	7	12	-	-	0
13/01:30pm	33000	19.4	16.7	9	51	5.5	NNW	13	24	7	13	-	-	0
13/01:00pm	30000	19.2	16.7	9.7	54	5.1	NNW	13	22	7	12	-	-	0
13/12:30pm	23000	17.7	14.4	9.6	59	4.3	N	17	30	9	16	-	-	0
13/12:00pm	20000	16.9	14.9	10.3	65	3.5	N	11	19	6	10	-	-	0
13/11:30am	13000	16.7	15.5	10.3	66	3.4	N	7	13	4	7	-	-	0
13/11:00am	10000	15.4	14.1	10	70	2.8	N	7	13	4	7	-	-	0
13/10:30am	3000	15	13.7	9.8	71	2.7	NNW	7	17	4	9	-	-	0
13/10:00am	0	14.1	12.6	10.5	79	1.9	N	9	15	5	8	-	-	0

Table SI-2. Australian Bureau of Meteorology latest weather observations for Horsley Park 14 June 2023**.**

Latest Weather Observations for Horsley Park 14 June 2023														
Date/Time	Time	Temp	App	Dew	Rel	Delta-T	Wind	Spd	Gust	Spd	Gust	Press	Press	Rain since
EST	UTC	°C	Temp	Point	Hum	°C	Dir.	km/h	km/h	kts	kts	QNH	MSL	9am
			°C	°C	%							hPa	hPa	mm
14/11:30pm	133000	7.5	5.7	1.4	65	2.5	CALM	0	0	0	0	-	-	0
14/11:00pm	130000	9	6	1.7	60	3	SW	7	11	4	6	-	-	0
14/10:30pm	123000	6.2	4.4	0.9	69	2.1	CALM	0	6	0	3	-	-	0
14/10:00pm	120000	7.3	5.4	0.5	62	2.7	CALM	0	0	0	0	-	-	0
14/09:30pm	113000	9.3	6.4	1.2	57	3.3	SW	6	9	3	5	-	-	0
14/09:00pm	110000	7.8	5.9	0.8	61	2.8	CALM	0	0	0	0	-	-	0
14/08:30pm	103000	9.6	7.3	0.2	52	3.8	WNW	2	4	1	2	-	-	0
14/08:00pm	100000	10.5	7.5	0.5	50	4.1	NW	6	11	3	6	-	-	0
14/07:30pm	93000	11.2	7.6	0.6	48	4.4	WNW	9	17	5	9	-	-	0
14/07:00pm	90000	11	7.9	0.1	47	4.5	WNW	6	9	3	5	-	-	0
14/06:30pm	83000	12.4	8.3	-0.1	42	5.2	W	11	20	6	11	-	-	0
14/06:00pm	80000	13.2	9.5	-0.1	40	5.5	WSW	9	24	5	13	-	-	0
14/05:30pm	73000	13.7	8.8	-0.7	37	5.9	WSW	15	26	8	14	-	-	0
14/05:00pm	70000	13.7	10.3	-0.7	37	5.9	W	7	13	4	7	-	-	0
14/04:30pm	63000	15.5	12.1	-0.7	33	6.8	W	7	13	4	7	-	-	0
14/04:00pm	60000	16.3	11.7	-0.8	31	7.2	WNW	13	26	7	14	-	-	0
14/03:30pm	53000	16.7	11.3	-1.4	29	7.6	WNW	17	30	9	16	-	-	0
14/03:00pm	50000	17.6	13.9	-0.2	30	7.7	WSW	9	19	5	10	-	-	0
14/02:30pm	43000	17.7	13.6	-0.1	30	7.7	WSW	11	20	6	11	-	-	0
14/02:00pm	40000	17.7	13.3	0.4	31	7.6	W	13	22	7	12	-	-	0
14/01:30pm	33000	17.4	13	0.6	32	7.4	W	13	20	7	11	-	-	0
14/01:00pm	30000	17.1	11.9	0.3	32	7.3	W	17	30	9	16	-	-	0
14/12:30pm	23000	17.3	13	0.9	33	7.2	W	13	24	7	13	-	-	0
14/12:00pm	20000	17.4	14.4	2.2	36	6.9	W	7	15	4	8	-	-	0
14/11:30am	13000	16.4	12.7	2.1	38	6.4	W	11	19	6	10	-	-	0
14/11:00am	10000	16.5	13.3	2.9	40	6.2	W	9	19	5	10	-	-	0
14/10:30am	3000	15.6	12.3	2.7	42	5.8	WNW	9	15	5	8	-	-	0
14/10:00am	0	15.2	12.4	3.4	45	5.4	NW	7	13	4	7	-	-	0