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Methane emissions from underground gas storage in California

Andrew K Thorpe[1,9], **Riley M Duren**[2,1], **Stephen Conley**[3], **Kuldeep R Prasad**[4], **Brian D Bue**[1], **Vineet Yadav**[1], **Kelsey T Foster**[5], **Talha Rafiq**[6], **Francesca M Hopkins**[6], **Mackenzie L Smith**[3], **Marc L Fischer**[7], **David R Thompson**[1], **Christian Frankenberg**[8], **Ian B McCubbin**[1], **Michael L Eastwood**[1], **Robert O Green**[1] and **Charles E Miller**[1]

[1] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109, United States of America
[2] University of Arizona, Tucson, AZ 85721, United States of America
[3] Scientific Aviation, 3335 Airport Rd suite b, Boulder, CO 80301, United States of America
[4] National Institute of Standards and Technology, Gaithersburg, Maryland, United States of America
[5] Stanford University, 450 Serra Mall, Stanford, CA 94305, United States of America
[6] University of California Riverside, 900 University Ave, Riverside, CA 92521, United States of America
[7] Energy Technology Area, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS 90R3029-B Berkeley, CA 94720, United States of America
[8] California Institute of Technology, 1200 E California Blvd, Pasadena, CA 91125, United States of America
[9] Author to whom any correspondence should be addressed.

E-mail: Andrew.K.Thorpe@jpl.nasa.gov

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Supplementary material for this article is available online

Abstract

Accurate and timely detection, quantification, and attribution of methane emissions from Underground Gas Storage (UGS) facilities is essential for improving confidence in greenhouse gas inventories, enabling emission mitigation by facility operators, and supporting efforts to assess facility integrity and safety. We conducted multiple airborne surveys of the 12 active UGS facilities in California between January 2016 and November 2017 using advanced remote sensing and *in situ* observations of near-surface atmospheric methane (CH_4). These measurements where combined with wind data to derive spatially and temporally resolved methane emission estimates for California UGS facilities and key components with spatial resolutions as small as 1–3 m and revisit intervals ranging from minutes to months. The study spanned normal operations, malfunctions, and maintenance activity from multiple facilities including the active phase of the Aliso Canyon blowout incident in 2016 and subsequent return to injection operations in summer 2017. We estimate that the net annual methane emissions from the UGS sector in California averaged between 11.0 ± 3.8 $GgCH_4\,yr^{-1}$ (remote sensing) and 12.3 ± 3.8 $GgCH_4\,yr^{-1}$ (*in situ*). Net annual methane emissions for the 7 facilities that reported emissions in 2016 were estimated between 9.0 ± 3.2 $GgCH_4\,yr^{-1}$ (remote sensing) and 9.5 ± 3.2 $GgCH_4\,yr^{-1}$ (*in situ*), in both cases around 5 times higher than reported. The majority of methane emissions from UGS facilities in this study are likely dominated by anomalous activity: higher than expected compressor loss and leaking bypass isolation valves. Significant variability was observed at different time-scales: daily compressor duty-cycles and infrequent but large emissions from compressor station blow-downs. This observed variability made comparison of remote sensing and *in situ* observations challenging given measurements were derived largely at different times, however, improved agreement occurred when comparing simultaneous measurements. Temporal variability in emissions remains one of the most challenging aspects of UGS emissions quantification, underscoring the need for more systematic and persistent methane monitoring.

1. Introduction

Underground gas storage (UGS) facilities play an important energy security role in the United States by supplementing during seasonal demand spikes and providing contingency inventories of natural gas. The United States maintains over a third of the world's working gas storage volume and nearly two thirds of

UGS facilities, primarily in the form of depleted oil and gas fields (Evans 2009). California itself has 12 currently operating facilities responsible for approximately 7% of the US total gas storage and delivery capacity (EIA 2017). The benefits of UGS are balanced by risks including the potential for product loss and safety hazards. Methane (CH_4) is the primary constituent of natural gas and in sufficiently high concentrations ($>5\%$) can become flammable and ultimately an asphyxiant. These risks were recently highlighted by the largest reported release of natural gas in US history at the Aliso Canyon storage facility in southern California following a blowout at single injection well (Department of Energy DOE 2016). Loss of containment at UGS facilities are neither new nor limited to California with incidents beginning with their first use in the early 1900s. However, California has seen a disproportionate 44% of reported US UGS incidents at depleted oil and gas fields and the increasing proximity of UGS to urban population centers motivates additional scrutiny of the risks (Evans 2009). An emergency order by the Governor of California to assess the safety and long-term viability of UGS in the state in the wake of the Aliso Canyon incident provides another incentive (California Council on Science and Technology CCST 2018).

Additionally, methane is a powerful greenhouse gas and is targeted for emissions mitigation by the State of California including legislation focused on natural gas leak detection and repair (California SB1371, California Air Resources Board CARB 2014, California Air Resources Board CARB 2017) and identification of emission hotspots (California AB1496, California Air Resources Board (CARB) 2015). Methane is also a precursor for tropospheric ozone and is strongly linked with co-emitted reactive trace gases that are the focus of air quality and public health policies in California. Efforts to understand California's methane emissions offer mixed results: inventory-based estimates of regional methane emissions are often inconsistent with estimates based on atmospheric observations (Wecht *et al* 2014, Turner *et al* 2015, Wong *et al* 2016, Jeong *et al* 2017). Most of the methods currently available for studying regional emissions are not able to isolate individual methane point sources such as UGS facilities. Historically, most methane emission estimates for UGS facilities have been limited to inventory-based methods such as applying activity data and standard emission factors. More recently a field campaign studied methane emissions from compressor stations at 9 UGS facilities outside of California using component leak detection and quantification to develop a facility-scale emission inventory as well as downwind atmospheric tracer-tracer measurements to independently estimate a facility total emission flux (Subramanian *et al* 2015). The tracer-tracer method revealed super-emitter activity at one of the facilities in that study with an emission rate of 350 $kgCH_4\ h^{-1}$, nearly 100 times that predicted by the inventory method. Subramanian *et al* (2015) attributed that source to temporary maintenance activity and venting from leaking isolation valves. They also highlighted the inability to safely measure the venting gas directly with available surface-based measurement methods—a challenge common in many areas given the physical scale of many facilities and complicating factors such as terrain and the height above ground of key equipment types. Subramanian *et al* (2015) and Zimmerle *et al* (2015) underscored the need to account for skewed emission distributions and highlighted challenges with current greenhouse gas reporting programs and standard emission factors. Those studies also indicate the challenges in characterizing highly variable and stochastic emissions processes.

The sustained loss of containment due to the Aliso Canyon blowout incident over nearly a four-month period resulted in an estimated total emission of 99 650 ± 9300 metric tons of methane or roughly equivalent to 5% of California's total methane inventory for 2015 (California Air Resources Board CARB 2016, Conley *et al* 2016). While significant, such events are infrequent and their long-term impact is likely dwarfed by smaller but persistently under-reported fugitives and venting from normal operations. Fischer *et al* (2017) conducted an initial airborne survey of natural gas facilities in California including 9 of the State's gas storage fields between 2014 and 2016, identifying significant discrepancies between measured and reported emissions. However, the need for additional study was highlighted given the high variability in emissions observed in that study and relatively sparse temporal sampling–e.g. 35 samples spread across nine sites some of which were only sampled once (Fischer *et al* 2017).

In this study we combined high spatio-temporal resolution airborne remote-sensing and *in situ* observations of UGS facilities in California in 2016 and 2017 to detect, pinpoint and quantify methane emissions from those facilities, and attribute them to key components and processes. The study was focused on California but was also intended to evaluate observational strategies for addressing UGS emission modes beyond California and potentially other industrial sectors as well.

2. Methods

2.1. Survey design

The observational strategies applied in this study address many of the aforementioned challenges for measuring UGS methane emissions including the ability to efficiently and reliably sample the total emissions of facilities and to attribute emissions to individual components and activity within those facilities. We conducted multiple airborne surveys of the 12 active California UGS facilities using a combination of advanced remote-sensing (infrared imaging spectroscopy) over-flights and *in situ* sampling of atmospheric boundary layer methane plumes from those facilities. This integrated approach offers three primary advantages: (a) denser temporal sampling to better constrain variability and minimize sample bias (e.g. 229 over flights in this study compared to 35 in the Fischer *et al* 2017 study), (b) spatially resolved measurements of individual emission sources for improved attribution, and (c) cross-validation between independent estimation methods for improved confidence.

The locations and key attributions of our study population of UGS facilities are described in figure S1 which is available online at stacks.iop.org/ERL/15/045005/mmedia. Spatially, each survey was designed to address all surface infrastructure in a given facility including well heads, gas lines, compressors, vent stacks, and dehydrators, including several where the compressor station is located several kilometers distant from the storage field (e.g. Wild Goose and Lodi). This degree of spatial completeness was possible given the combination of high spatial resolution (typically < 3 m) from the remote sensing instrument and the unfettered access offered by both aircraft methods. Temporally, the survey flights were conducted between January 2016 and November 2017 with most facilities sampled across at least three seasons to assess potential seasonal variability. Intensive campaigns were also conducted with revisit intervals ranging from minutes to days, particularly during Fall 2016 and Fall 2017. The study spanned a range of normal operations, malfunctions and maintenance activity from multiple facilities including the active phase of the Aliso Canyon blowout incident in 2016 and subsequent return to injection operations in summer 2017.

2.2. Airborne imaging spectroscopy

The classic version of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-C, Green *et al* 1998) and the next generation instrument (AVIRIS-NG, Hamlin *et al* 2011) measure ground-reflected solar radiation from the visible to infrared spectral regions (380–2500 nm). Both instruments have a 34° field of view while the spectral resolution and sampling of AVIRIS-C and AVIRIS-NG is approximately 10 nm and 5 nm respectively. With the exception of a few flights during the Aliso Canyon blowout incident in early 2016 with AVIRIS-C in the NASA ER-2, the remote sensing portion of this study was conducted with AVIRIS-NG in a King Air B-200—typically at flight altitudes of 3 km above ground level, equivalent to 1.8 km swath width and 3 m pixel size. The AVIRIS-C and AVIRIS-NG methane retrieval is based on absorption spectroscopy between 2100 and 2500 nm and uses a linearized matched filter to calculate a mixing ratio length in units of ppm-m representing the thickness and concentration within a volume of equivalent absorption (Thompson *et al* 2015). This and related techniques have been demonstrated in a number of previous airborne campaigns (Thompson *et al* 2015, Frankenberg *et al* 2016, Thompson *et al* 2016, Thorpe *et al* 2017, Krautwurst *et al* 2017, Duren *et al* 2019). Thorpe *et al* (2016) demonstrated that plumes for controlled releases as low as 10 $\mathrm{kgCH_4\ h^{-1}}$ were consistently observed by AVIRIS-NG across multiple flight altitudes and wind conditions and a minimum detection limit of 2 $\mathrm{kgCH_4\ h^{-1}}$. Frankenberg *et al* (2016) quantified emission rates ranging from 2 to 5000 $\mathrm{kgCH_4\ h^{-1}}$ for the Four Corners region primarily from natural gas production and Duren *et al* (2019) reported methane emissions between 9 and 2600 $\mathrm{kgCH_4\ h^{-1}}$ for methane plumes observed from the landfill, agriculture, and waste management sectors of California.

Two methods were used to estimate methane emission rates: a Large Eddy Simulation (LES) scaling applied to AVIRIS-C data during the Aliso Canyon blowout and a mass balance approach for the AVIRIS-NG results. A LES model was run using an initial prescribed emission flux during the Aliso Canyon blowout (Conley *et al* 2016) and a linear scalar was applied iteratively until the Integrated Methane Enhancement (IME, kg $\mathrm{CH_4}$) matched the retrieved AVIRIS-C IME. This scalar was then multiplied by the initial LES flux to estimate the flux for each observed plume. Given LES modelling is computationally expensive it was not feasible to generate LES model runs for the 135 remaining plumes observed with AVIRIS-NG. Instead, a mass balance method was used to estimate the emission flux by combining AVIRIS-NG IME values and contemporaneous wind speed measurements to estimate the emission flux. Building upon previous studies that have reported emission uncertainties solely derived from wind measurements (Frankenberg *et al* 2016), this study provides a more realistic uncertainty estimate derived from both the IME calculation and wind measurements. In section S1.2, the Large Eddy Simulation (LES) scaling and mass balance approach are discussed in further detail.

2.3. Airborne *in situ* sampling

The *in situ* air sampling approach used by Scientific Aviation provides accurate methane flux estimates at the scale of individual facilities. This mass balance approach involves executing a cylindrical flight pattern (i.e. stacked, approximately constant altitude circles at altitudes from the minimum safe flight altitude to the top of the emissions plume) while measuring methane concentrations and wind speeds and the application of Gauss's Theorem to estimate the flux divergence through the cylinder (Conley *et al* 2014, Conley *et al* 2017). The airborne system is flown on a fixed wing single engine mooney aircraft, extensively modified for research as described in (Conley *et al* 2014).

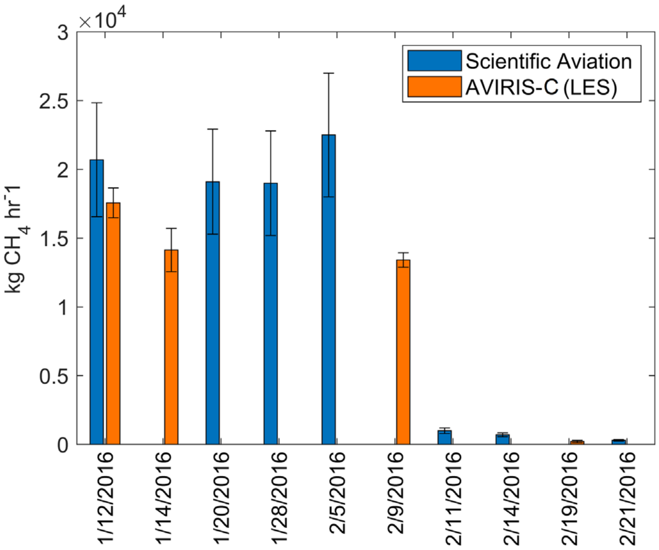

Figure 1. Time series of Aliso Canyon methane emissions for January–February 2016 comparing independent estimates from contemporaneous Scientific Aviation *in situ* estimates (blue) and AVIRIS-C remote sensing combined with LES modeling (orange). Emission estimates derived with AVIRIS-C are shown as daily averages. Both AVIRIS-C and Scientific Aviation capture the step function reduction in emissions following the February 11, 2016 bottom kill of the leaking well and subsequent slow decay from soil outgassing.

Ambient air is collected through ~5 m of tubing that protrudes out of backward-facing inlets mounted below the right wing. *In situ* methane, carbon dioxide, and water vapor are measured with a Picarro 2301 f cavity ring down spectrometer (Crosson 2008) operated in its precision mode at 1 Hz.

The horizontal wind speed and direction was derived from measurements of true airspeed and GPS-derived ground speed. Winds were sampled at 1 Hz using a dual GPS compass that determines aircraft heading and ground speed with sufficient accuracy to resolve the horizontal wind components to about 0.2 m s^{-1} accuracy (Conley *et al* 2014). The horizontal wind is calibrated periodically by flying ~5 km L-patterns in the free troposphere; a heading rotation and airspeed adjustment is made to the wind calculation to minimize the dependence of the wind on aircraft heading (Conley *et al* 2014). This method of estimating emissions has been demonstrated across multiple flight campaigns (Smith *et al* 2015, Conley *et al* 2017, Schwietzke *et al* 2018) and uncertainties typically range from 10% to 30% depending on factors such as number of laps conducted and wind variability (Conley *et al* 2017).

2.4. Integrated analysis

Facility total methane emission estimates were derived on a daily basis—either using a single Scientific Aviation mass-balance estimate when available and/or the daily average of emission estimates derived from AVIRIS-NG data. These daily estimates are plotted as time-series for a number of facilities that were revisited at high frequency, like Aliso Canyon, Honor Rancho, and McDonald Island (figures 1, 4, 6 and 8). The combination of Scientific Aviation and AVIRIS-NG emission estimates provide a time-series with denser temporal sampling than available with a single data set. Additionally, results were cross-validated on dates where both Scientific Aviation and AVIRIS-NG were flown as part of coordinated intensive campaigns (e.g. January 12, 2016 and September 16, 2017 for Aliso Canyon, October 6, 2017 for McDonald Island, and October 16, 2017 for Honor Rancho). An average emission rate was also calculated from all observations at a given facility, which was scaled by the source persistence (ratio of the number of observed plumes to the total number of overflights) to estimate annual emissions for gas storage facilities surveyed by AVIRIS-NG and Scientific Aviation (see section S1.3). Annual emission estimates are shown in table 3 and figure 9 and compared with reported emissions from EPA and CARB databases (California Air Resources Board CARB 2018, Environmental Protection Agency EPA 2018).

3. Results

In terms of survey completeness, excluding the Aliso Canyon blowout incident we obtained 229 unique facility samples during this study: 178 from AVIRIS-NG, reflecting overflights of multiple sources (table 1), and 51 from Scientific Aviation (table 2). AVIRIS-NG surveyed all 12 active UGS facilities during flight campaigns in 2016 (fall) and 2017 (spring, summer, fall) and the distribution of samples by sources within a given facility varied from 4 (Kirby Hills) to 66 (Honor Ranch) with diurnal to seasonal revisit intervals. Scientific Aviation was unable to survey Playa Del Rey due to the adjacent airport airspace restrictions and

Table 1. Summary of methane sources for each gas storage facility observed with AVIRIS-NG, frequency of observations (n), and annual emissions and uncertainties. For each facility, total annual emissions and uncertainties are provided in the last two columns.

Facility	Source latitude (deg)	Source longitude (deg)	Source type	Total overflights	Observed plumes (n)	Source persistence (f)	Average source emissions (kg h^{-1})	Uncertainty (kg h^{-1})	Emissions adjusted for source peristence (kg h^{-1})	Uncertainty (kg h^{-1})	Annual emissions (MtCH$_4$ yr^{-1})	Annual uncertainty (MtCH$_4$ yr^{-1})	Facility total annual emissions (MtCH$_4$ yr^{-1})	Facility total uncertainty (MtCH$_4$ yr^{-1})
Aliso Canyon (post blow-out)	34.3214	−118.5823	Pumpjack	29	2	0.07	728.0	155.0	50.0	11.0	438.0	96.4		
	34.3078	−118.5499	Blowdown stack	60	14	0.23	210.0	76.0	49.0	18.0	429.2	157.7		
	34.3179	−118.5733	Tank	25	1	0.04	263.0	130.0	11.0	5.0	96.4	43.8		
	34.3127	−118.5507	Drill rig	48	1	0.02	246.0	142.0	5.0	3.0	43.8	26.3	1007.4	324.1
Gill Ranch	36.7927	−120.2528	Blowdown stack	17	13	0.76	287.0	84.0	219.0	64.0	1918.4	560.6	1918.4	560.6
Honor Rancho	34.4471	−118.5883	Emergency shutdown stack	66	50	0.76	370.0	124.0	280.0	94.0	2452.8	823.4		
	34.4474	−118.5867	Gas compressor	66	19	0.29	419.0	174.0	121.0	50.0	1060.0	438.0		
	34.4508	−118.5992	Unknown	30	2	0.07	376.0	123.0	25.0	8.0	219.0	70.1		
	34.4449	−118.5874	Unknown	66	4	0.06	175.0	42.0	11.0	3.0	96.4	26.3		
	34.4459	−118.5868	Dehydrator	66	2	0.03	112.0	35.0	3.0	1.0	26.3	8.8	3854.4	1366.6
Kirby Hills	38.1598	−121.9058	Blowdown stack	4	1	0.25	100.0	18.0	25.0	4.0	219.0	35.0	219.0	35.0
Lodi	38.2016	−121.2130	Dehydrator	5	2	0.4	80.0	32.0	32.0	13.0	280.3	113.9	280.3	113.9
McDonald Island	37.9953	−121.4781	Blowdown stack	17	11	0.65	328.0	145.0	213.0	94.0	1865.9	823.4		
	37.9864	−121.4738	Gas compressor	20	10	0.5	148.0	53.0	74.0	27.0	648.2	236.5		
	37.9954	−121.4780	Gas compressor	17	2	0.12	95.0	35.0	11.0	4.0	96.4	35.0	2610.5	1095.0
Wild Goose	39.3484	−121.8205	Gas compressor	6	1	0.17	724.0	212.0	121.0	35.0	1060.0	306.6	1060.0	306.6
Totals													10 950.0	3 801.8

Table 2. Summary of methane sources for each gas storage facility observed with Scientific Aviation, frequency of observations, and annual emissions and uncertainties. For each facility, total annual emissions and uncertainties are provided in the last two columns.

Facility	Total overflights	Flights with discernable emissions	Source persistence (f)	Average source emissions (kg h^{-1})	Uncertainty (kg h^{-1})	Emissions adjusted for source peristence (kg h^{-1})	Uncertainty (kg h^{-1})	Facility total annual emissions (MtCH$_4$ yr^{-1})	Facility total uncertainty (MtCH$_4$ yr^{-1})
Aliso Canyon (post blow-out)	6	6	1	226.3	78.0	226.3	78.0	1982.7	683.3
Gill Ranch	4	4	1	33.0	27.6	33.0	27.6	288.9	242.0
Honor Rancho	3	3	1	309.6	117.0	309.6	117.0	2712.4	1024.6
Kirby Hills	2	2	1	35.4	10.2	35.4	10.2	310.1	88.9
La Goleta	1	1	1	237.7	34.6	237.7	34.6	2082.3	303.1
Los Medanos	3	3	1	19.7	17.7	19.7	17.7	172.9	155.1
Pleasant Creek	3	3	1	19.9	4.8	19.9	4.8	174.0	42.0
Princeton	2	2	1	25.9	5.7	25.9	5.7	226.9	49.5
McDonald Island	26	26	1	326.1	93.5	326.1	93.5	2857.0	819.1
Wild Goose	1	1	1	169.1	46.5	169.1	46.5	1481.3	407.3
Totals								12 288.4	3814.9

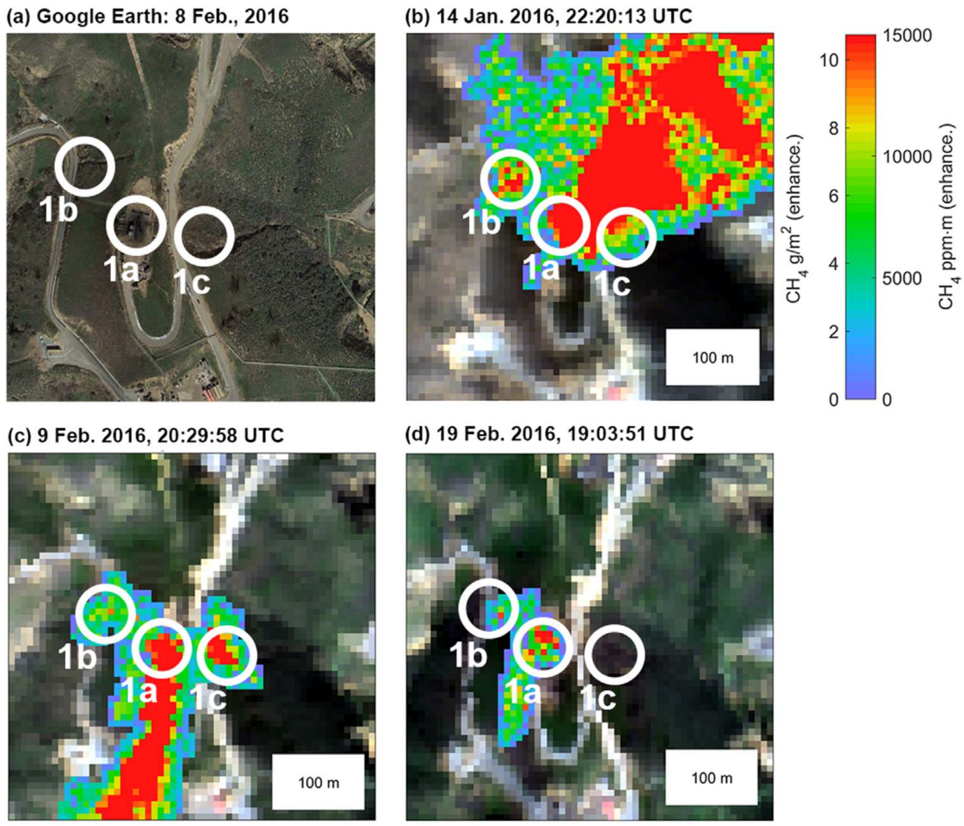

Figure 2. Remote-sensing by AVIRIS-C (from 8 km altitude) identified multiple individual methane sources during the Aliso Canyon loss of containment incident (sub-surface blowout at well SS25). Methane results are overlaid on true color imagery from AVIRIS-C. (a) Locations of primary source (1a, at the SS25 wellhead) and two secondary sources (1b and 1c, venting on the west and east hillsides below the wellhead). (b) Methane plumes detected on January 14, 2016. (c) Methane plumes on February 9, 2017, shortly before the SS25 well was plugged (February 11). (d) Methane plumes on February 19, 2017 are consistent with residual soil outgassing. AVIRIS-C also detected a venting oil well to the northwest (not shown). All sources were subsequently verified by follow-up surface observations.

emissions at La Goleta were only detected by one flight. AVIRIS-NG detected no plumes at Playa Del Rey, La Goleta, Los Medanos, Princeton, and Pleasant Creek despite multiple overflights, suggesting emissions there are infrequent and/or below our detection limit.

The methane plume imaging capability of AVIRIS-C/AVIRIS-NG—combined with visible (red, green, blue) images and high-resolution satellite imagery—was used to spatially resolve and attribute plumes to sources within each facility. This provided more insight into the key emission modes for some of the facilities. We begin with a summary of observations during the Aliso Canyon blowout incident and subsequent return to operations followed by observations of plumes at Honor Rancho, McDonald Island, and other facilities.

3.1. Aliso Canyon blowout incident

The largest reported loss of containment at a UGS facility (and indeed the largest reported single methane point source to date) was due to a blowout of storage well Standard Sesnon 25 (SS25) at Aliso Canyon on October 23, 2015 (Department of Energy DOE 2016). Natural gas was released from the wellhead and a subsurface breach in the annular casing for nearly four months. In an effort to quantify the leak rate, Scientific Aviation conducted 11 mass balance flights from early November 2015 through early February 2016 (Conley *et al* 2016). AVIRIS-C also conducted 21 overflights of Aliso Canyon during the active phase of the leak on January 12, January 14, and February 9, 2016. On January 12, 2016 the two airborne systems conducted simultaneous overflights and reported similar emission rates of 17 564 ± 1086 kgCH_4 h^{-1} derived from AVIRIS-C and 20 700 ± 4140 kgCH_4 h^{-1} from Scientific Aviation (figure 1). As expected, AVIRIS-C detected the central methane plume associated with gas venting at the well head itself, however it also detected two secondary emission locations from the hillsides below the wellhead (figure 2). The secondary emission locations were subsequently confirmed by onroad methane surveys by South Coast Air Quality Management District (SC-AQMD) personnel.

After the storage well was successfully plugged on February 11, 2016, a dramatic reduction in emission estimates was observed (figure 1) for both AVIRIS-C (220 ± 88 kgCH_4 h^{-1} for February 19) and Scientific Aviation (310 ± 62 kgCH_4 h^{-1} for February 21). The February 19, 2016 AVIRIS-C flights confirmed the presence of residual methane outgassing from soil at both the well head and one of the secondary emission locations (figure 2(d)). Serendipitously, AVIRIS-C detected a relatively small methane plume at an oil well

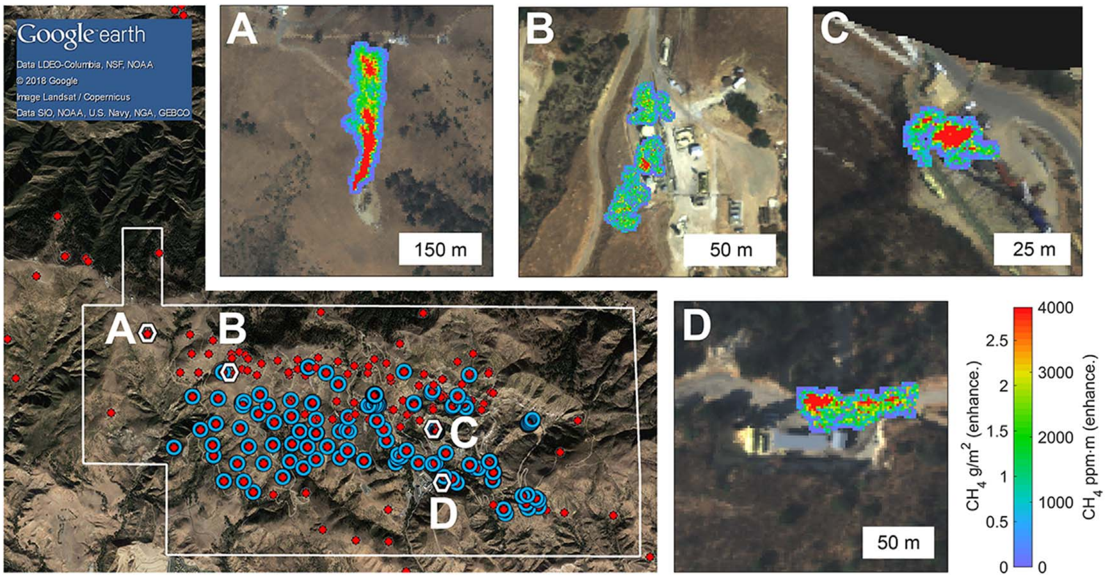

Figure 3. Characterizing methane emissions from Aliso Canyon following return to operations. Aliso Canyon field spans roughly 14 km^2 and records (Division of Oil, Gas, and Geothermal Resources DOGGR 2018) indicate 251 wells (red dots)—115 of which are linked to the gas storage reservoir (blue circles) and the rest connected to shallower oil-producing formations (combination of active, idle, and plugged wells). Subpanels (a) through (d) indicate methane plumes observed with AVIRIS-NG overlain on true color imagery that correspond to the locations shown in the map of the Aliso Canyon field from an oil well (a), tank (b), drill rig (c), and shutdown stack near the storage facility's compressor station (d).

several kilometers to the northwest. That source was also confirmed by a SC-AQMD ground survey and attributed to associated gas venting. While technically this was leakage from the shallower oil formation rather than the deeper gas storage reservoir, the operator reported that the venting was in part a response to the temporary termination of injection into the storage reservoir during the blowout.

3.2. Aliso Canyon return to operations

After over a year of well repairs, testing, and inspections, gas injection resumed at the Aliso Canyon UGS facility in late July 2017. Scientific Aviation conducted a series of overflights in August and September 2017 to assess the possibility of additional leakage. Those flights led to mixed results including highly variable emissions (~50–500 kgCH_4 h^{-1}) that could not be readily explained.

Source attribution in Aliso Canyon can be challenging given the limited surface access, steep terrain, and the co-location of hundreds of gas storage and oil production wells (figure 3). AVIRIS-NG overflights began in late August 2017 on a Dynamic Aviation King Air B200 aircraft with typical flight altitudes of 3 km above ground level, resulting in a 1.8 km swath width and 3 m pixel size. Maps of plumes observed with AVIRIS-NG provided source attribution by identifying intermittent venting from a blowdown stack near the main compressor facility (figure 3(d)), an oil well (figure 3(a)), tank (figure 3(b)), and drilling rig (figure 3(c)). These results suggest that the large variability in Aliso Canyon methane emissions following return to operations could be a combination of reservoir gas vented from the blowdown stack and emissions associated from the shallower oil reservoir present at the oil well, tank, and drilling rig.

Figure 4 shows the time series of emission estimates derived by both AVIRIS-NG and Scientific Aviation from March 2016 through October 2017 ranging from ~50 to 500 kgCH_4 h^{-1}. Daily emission estimates are derived from AVIRIS-NG either using a single observation or the average of multiple observations in a given day (see section S.1.2.2). Coincident flights occurred on September 16, 2017 and emission estimates varied between 221 ± 68 kgCH_4 h^{-1} for AVIRIS-NG and 193 ± 108 kgCH_4 h^{-1} for Scientific Aviation.

3.3. Honor Rancho, McDonald Island, and other facilities

AVIRIS-NG surveys of all 12 active UGS facilities conducted in 2016 (fall) and 2017 (spring, summer, fall) provided a unique opportunity to quantify emissions from a range of emission modes. Here we focus primarily on the Honor Rancho and McDonald Island facilities given the diversity of source type and variability observed there. The most commonly observed methane plumes at Honor Rancho were associated with a persistent source to the west of the compressor station (later confirmed by the operator to be a leaking bypass/isolation valve in the facility's emergency shutdown stack) and plumes at 1 or 2 of the 5 large reciprocating compressors on the east side of the station (figure 5). The bypass valve leakage at Honor Rancho persisted through 2017 and represents an emission mode not observed at any other California UGS facility. The plumes that were observed episodically at two of the compressors suggest rod pack venting that is

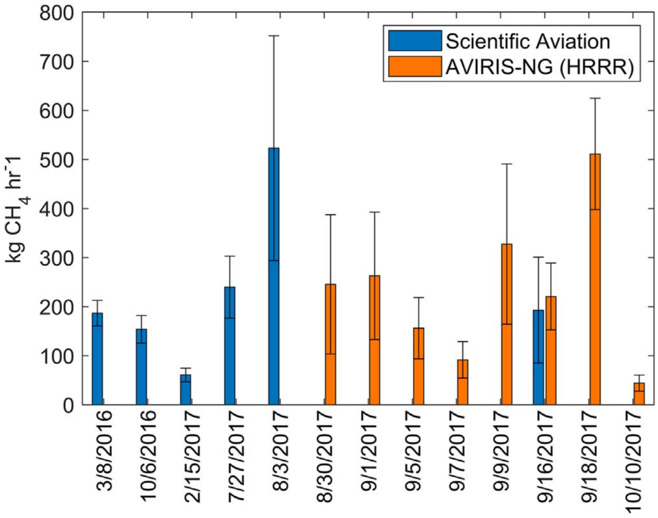

Figure 4. Estimated methane emissions for the Aliso Canyon UGS facility following return to operations using Scientific Aviation *in situ* estimates (blue) and AVIRIS-NG estimates using the mass balance method with HRRR wind speeds (orange). On 9/16/2017, methane emissions were estimated at 193 ± 108 kg h^{-1} for Scientific Aviation compared to 221 ± 68 kg h^{-1} using AVIRIS-NG and HRRR winds.

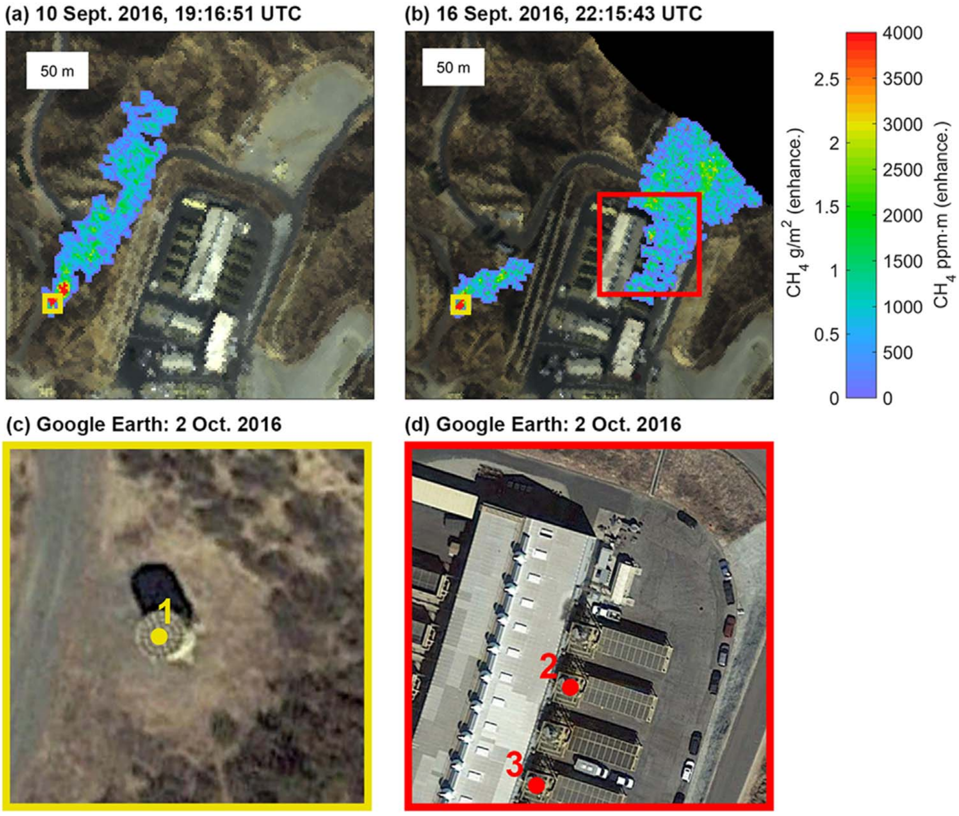

Figure 5. Attribution of multiple methane emission sources detected at Honor Rancho. (a) AVIRIS-NG result shows a persistent methane plume for source 1 (yellow box in (a) and (c)). (b) Source 2 and/or source 3 appeared episodically (red box) for 29% of flights. (c) Close-up of source 1 with high-resolution satellite imagery (Google Earth). The facility operator confirmed that source 1 is the facility's emergency shut down stack—likely due to a leaking isolation valve. (d) Close-up of sources 2 and 3—likely from the rod pack vents for reciprocating compressor units 2 and 4.

higher than reported for those two units (no plumes were observed at the other 3 units). The compressor plumes at Honor Rancho were observed 29% of the time—consistent with activity data for these two units reported to EPA in 2015 (e.g. they were reported to be in the operating state 16% and 28% of the time, respectively).

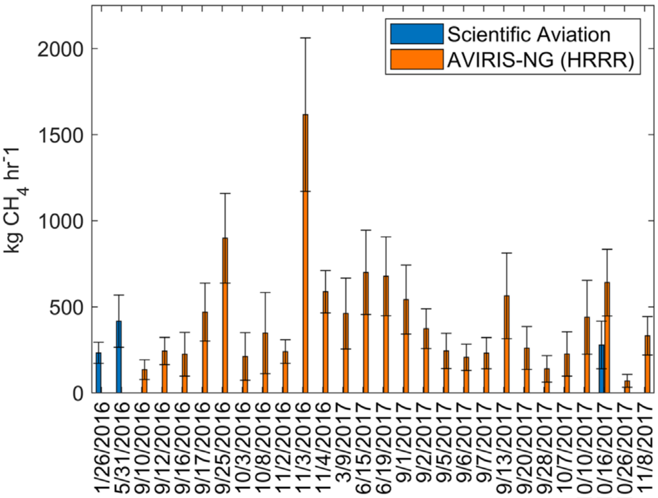

Figure 6. Estimated methane emissions for the Honor Rancho UGS facility using Scientific Aviation *in situ* estimates (blue) and AVIRIS-NG estimates using the mass balance method with HRRR wind speeds (orange).

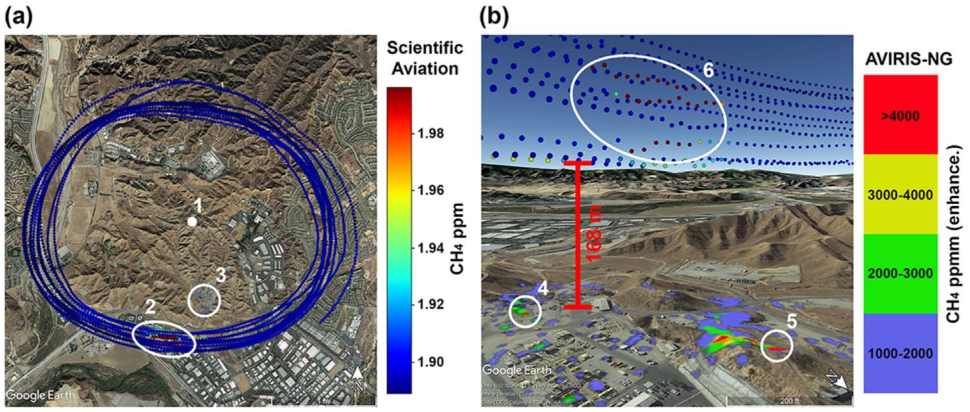

Figure 7. Results from Scientific Aviation and AVIRIS-NG surveys of Honor Rancho on October 16, 2017. (a) Location 1 denotes the center of the cylindrical flight path of Scientific Aviation and location 2 indicates regions where higher *in situ* methane concentrations were observed. Two AVIRIS-NG CH$_4$ plumes were observed at location 3 with plume shapes and Scientific Aviation enhancements consistent with local winds towards the southwest. (b) Perspective view showing AVIRIS-NG CH$_4$ plumes at location 3 overlaid on terrain for an unknown source (location 4) and an emergency shutdown stack (location 5). The lowest altitude Scientific Aviation flight paths were around 168 m above the main facility hence only enhancements at greater than 168 m above the ground were measured (location 6).

Other sources observed at Honor Rancho include a dehydrator and two unknown sources associated with visible infrastructure (table 1).

The time series for Honor Rancho is shown in figure 6 and both instruments indicate highly variable emission estimates between January 2016 and November 2017. On October 16, 2017 coincident flights indicated higher estimated emissions from AVIRIS-NG than Scientific Aviation. Figure 7(a) shows October 16 results from both instruments with the center of the cylindrical flight path of Scientific Aviation shown at location 1 and location 2 indicating those regions where higher *in situ* CH$_4$ concentrations were observed. At location 3, two AVIRIS-NG CH$_4$ plumes were observed with plume shapes consistent with local winds towards the south and the Scientific Aviation enhancements (location 2). The AVIRIS-NG CH$_4$ plumes are close to the cylindrical flight path and figure 7(b) indicates that even the lowest altitude Scientific Aviation flight paths were around 168 m above the main facility where the AVIRIS-NG plumes were observed for an unknown source (location 4) and an emergency shutdown stack (location 5). As a result, the cylindrical flight path of Scientific Aviation resolved a portion of the enhancements at greater than 168 m above the ground (location 6) but missed the enhancements below 168 m, which suggests an underestimate. AVIRIS-NG results from 2016 and 2017 were shared with the Honor Rancho facility operators and subsequent flights performed in the fall of 2018 indicated that the persistent emissions from the emergency shutdown stack (figures 5(a) and (c)) was likely mitigated while emissions from the compressor plume continued to be observed intermittently (figures 5(b) and (d)).

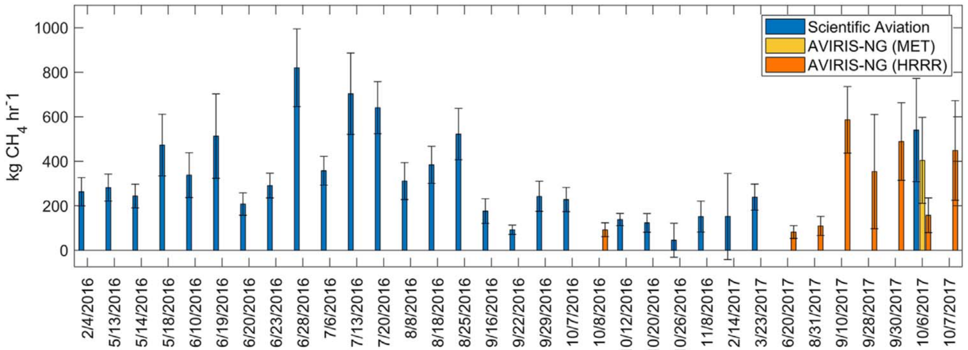

Figure 8. Time-series of estimated methane emissions for McDonald Island using Scientific Aviation *in situ* estimates (blue) and AVIRIS-NG estimates using the mass balance method with HRRR wind speeds (orange). On 10/6/17, methane emissions were estimated at 540 ± 232 kg h^{-1} for Scientific Aviation compared to 158 ± 78 kg h^{-1} using AVIRIS-NG and HRRR winds. As shown in yellow, the AVIRIS-NG emissions increase to 404 ± 193 kg h^{-1} when using winds derived from CIMIS Holt #248 meteorological station (MET), resulting in improved agreement with Scientific Aviation. The large values shown in September and October 2017 is likely due to combined blowdown events observed at the north and south station vent stacks (figures S4(c), (d)).

McDonald Island UGS exhibited two primary methane sources as confirmed by facility operators that are associated with both compressor stations from blowdown stack venting associated with maintenance activities (figure S4(c)) and compressor loss (figure S4(d)). Emission estimates indicate high variability between February 2016 and October 2017 that range between 83.7 and 763.0 $kgCH_4\,h^{-1}$ (figure 8). On October 6, 2017 coincident AVIRIS-NG and Scientific Aviation flights resulted in significantly different emission estimates. The Scientific Aviation aircraft measures wind speed according to Conley *et al* (2014), using true airspeed and GPS-derived ground speeds to derive an average wind speed of 2.3 m s^{-1} for the period of measurement between 19:24 and 19:41 UTC (corresponding to the duration of 4 AVIRIS-NG scenes), significantly higher than wind speeds of 0.7 m s^{-1} derived from HRRR (Benjamin *et al* 2016) that were used in the AVIRIS-NG mass balance analysis (Duren *et al* 2019). Local meteorological station wind data (CIMIS Holt #248 station) indicated a higher wind speed (1.7 m s^{-1}) compared to HRRR, and the resulting emission estimate (see figure 8, orange) showed improved agreement with results from Scientific Aviation on October 6, 2017.

Additional examples of different emission modes at other UGS facilities are summarized in figure S4 and table 1 including: blowdown stack venting at Gill Ranch, hydrator venting at Lodi, blowdown stack venting at Kirby Island, and compressor loss at Wild Goose. Note that source attribution to component scale was not possible for dates that only had Scientific Aviation flights hence in cases where AVIRIS-NG only detected one plume at a given facility (see table 1, Kirby Island and Wild Goose) there is lower confidence in the dominant emission mode.

3.4. Annual emissions

Annual emissions estimates were calculated using the same approach for both AVIRIS-NG and Scientific Aviation. An average emission rate was calculated from all observations at a given source or facility and scaled based on the frequency of observed emissions from a given source or facility (section S1.3). Next, the average emission rate across observed plumes was scaled by the source persistence to estimate per-hour methane emissions, which was multiplied by 8760 h to generate an annual emissions estimate. Additional details on these calculations are provided in section S1.3 and Scientific Aviation frequency values are presented in table 2. Because AVIRIS-NG often observed a number of sources for a given facility, annual emission estimates are calculated by source (table 1) before the results are aggregated by facility to permit direct comparison with Scientific Aviation (table 3). For AVIRIS-NG, the 2018 flights were used only to improve the calculation of the frequency of observed emissions.

The estimated annual methane emissions for each facility are summarized in figure 9 and table 3. The Honor Rancho and McDonald Island UGS facilities have the highest measured annual emissions of the gas storage facilities where emissions were observed. We estimate that the total annual methane emissions from the UGS sector in California averaged between 11.0 ± 3.8 $GgCH_4\,yr^{-1}$ (AVIRIS-NG) and 12.3 ± 3.8 $GgCH_4\ yr^{-1}$ (Scientific Aviation). Total annual methane emissions for the 7 facilities that reported emissions in 2016 were estimated between 9.0 ± 3.2 $GgCH_4\,yr^{-1}$ (AVIRIS-NG) and 9.5 ± 3.2 $GgCH_4\,yr^{-1}$ (Scientific Aviation), in both cases around 5 times higher than reported (see table 3; California Air Resources Board CARB (2018)). Figure 9 shows a comparison of annual methane emissions estimates from AVIRIS-NG (orange), Scientific Aviation (blue), as well as reported emissions from the EPA (dark red, Environmental Protection Agency EPA (2018)) and CARB (light red, California Air Resources Board CARB (2018)). Under-reporting of emissions appears most pronounced for Honor Rancho and McDonald Island, consistent with evidence from AVIRIS-NG and

Table 3. Summary of results from the 12 UGS facilities that were active during this study, including total storage capacity and annual mean injected natural gas values. Emission mechanism are derived from analysis of AVIRIS-NG methane imagery. Annual emissions and uncertainty are provided for both AVIRIS-NG and Scientific Aviation results. For reference, reported emissions from EPA and CARB databases are provided in the last three columns.

	Facility specifications		Measured emissions							Reported emissions		
	EIA	DOGGR	AVIRIS-NG				Scientific Aviation			EPA		CARB
Facility	Storage capacity (2015) (BCF)	Annual mean NG injected (2012-2014) (BCF/yr)	Emission mechanism	Annual emissions (MtCH$_4$ yr^{-1})	Annual uncertainty (MtCH$_4$ yr^{-1})	Number of days plumes were observed	Annual emissions (MtCH$_4$ yr^{-1})	Annual uncertainty (MtCH$_4$ yr^{-1})	Number of days plumes were observed	Annual mean emissions (2016, 2017) (MtCH$_4$ yr^{-1})	Annual mean uncertainty (2016, 2017) (MtCH$_4$ yr^{-1})	Annual emissions (2016) (MtCH$_4$ yr^{-1})
Aliso Canyon (post blow-out)	86.2	54.5	Persistent venting from shutdown stack; episodic venting from oil well, tank, drill rig	1007.4	324.1	8.0	1982.7	683.3	6.0	324.3	7.5	317.4
Gill Ranch	20.0	5.2	Episodic compressor loss; blowdown	1918.4	560.6	8.0	288.9	242.0	4.0			
Honor Rancho	27.0	27.8	Persistent venting from shutdown stack; episodic compressor loss, blowdowns	3854.4	1366.6	26.0	2712.4	1024.6	3.0	622.2	11.2	622.7
Kirby Hills	15.0	4.2	Unknown	219.0	35.0	1.0	310.1	88.9	2.0			68.2
La Goleta	19.7	11.6	None observed	None observed	None observed	0.0	2082.3	303.1	1.0			
Lodi	17.0	12.5	Possibly dehydration unit	280.3	113.9	1.0	None observed	None observed	0.0	4.6	1.0	14.0
Los Medanos	17.9	9.2	None observed	None observed	None observed	0.0	172.9	155.1	3.0	22.45	1.42	21.59
McDonald Island	82.0	34.9	Persistent maintenance, episodic compressor loss, blowdown	2610.5	1095.0	8.0	2857.0	819.1	26.0			456.3
Playa Del Rey	2.4	3.7	None observed	None observed	None observed	0.0	Not flown	Not flown	0.0			
Pleasant Creek	2.3	2.0	None observed	None observed	None observed	0.0	174.0	42.0	3.0			

Table 3. (Continued.)

	Facility specifications		Measured emissions							Reported emissions		
	EIA	DOGGR	AVIRIS-NG				Scientific Aviation			EPA		CARB
Princeton	11.0	5.6	None	None observed	None observed	0.0	226.9	49.5	2.0			
Wild Goose	75.0	30.9	Episodic compressor loss	1060.0	306.6	1.0	1481.3	407.3	1.0	109.2	22.6	247.7
Totals	375.5	202.1		10 950.0	3801.8		12 288.4	3814.9		1082.8	43.7	1747.9

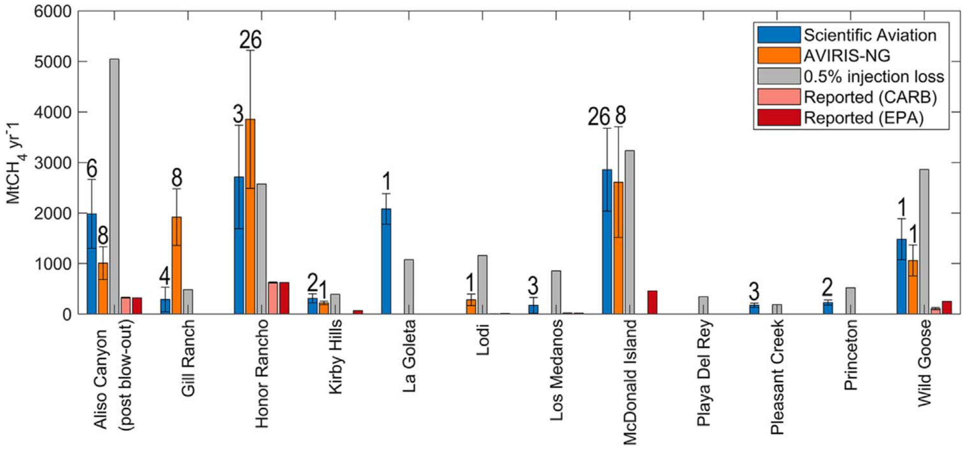

Figure 9. Mean annual emissions in metric tons methane for the 12 active gas storage facilities estimated using Scientific Aviation *in situ* estimates (blue) and AVIRIS-NG with the mass balance method (orange). Over selected bars, the number of days plumes were observed for Scientific Aviation and AVIRIS-NG are shown. Reported emissions (red) are shown for some facilities participating in the CARB and EPA reporting programs, indicating significant under-reporting. Annual emission rates assuming 0.5% loss based on annual mean natural gas injected (DOGGR) are plotted in light gray, indicating that measured emissions are typically below a 0.5% loss rate. The measured emissions shown here for Aliso Canyon are based on observations from August to October 2017 (return to normal operations).

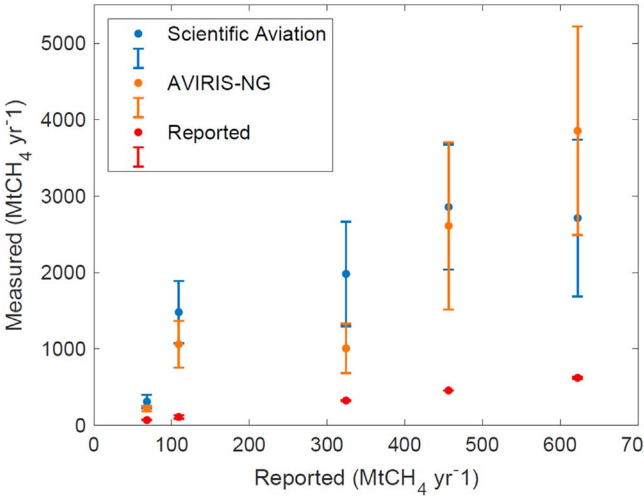

Figure 10. Comparison of mean annual emissions for those gas storage facilities where Scientific Aviation, AVIRIS-NG, and reported emissions are available. In all cases, Scientific Aviation and AVIRIS-NG results agree within the reported errors and are significantly higher than the reported emissions.

discussions with facility operators to determine that malfunctions and leakage associated with maintenance activity were present at these facilities.

For further comparison, annual emission rates assuming 0.5% loss based on DOGGR annual mean natural gas injected are plotted in light gray, indicating that measured emissions are typically below a 0.5% loss rate. Figure 10 compares only those gas storage facilities where Scientific Aviation, AVIRIS-NG, and reported emissions are available. In all cases, Scientific Aviation and AVIRIS-NG results agree within the reported errors and are significantly higher than the reported emissions.

A comprehensive comparison between AVIRIS-NG and Scientific Aviation measurements acquired both simultaneously and time-averaged over several months of repeat observations was presented in Duren *et al* (2019). As shown in figure 3(a) and S.12b from Duren *et al* (2019), there was good agreement between coincident AVIRIS-NG and Scientific Aviation measurements and greater divergence for measurements acquired at different times due to the highly variable nature of emissions.

For this study, a direct comparison between Scientific Aviation and AVIRIS-NG results is shown in figure 11 with a linear fit with a R^2 of 0.45. This emphasizes the challenge in comparing results that were derived largely from measurements acquired at different times due to the highly intermittent nature of these emissions (table 1), consistent with findings reported in Duren *et al* (2019). Comparing simultaneous measurements from four same day sets of flights

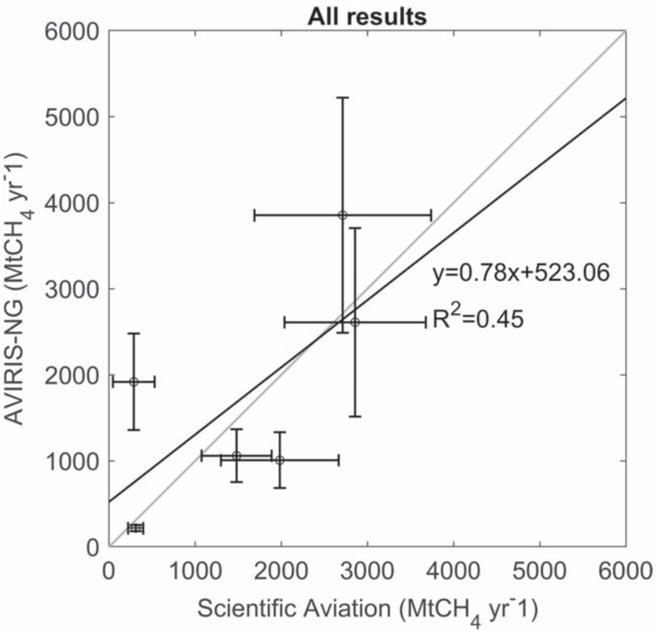

Figure 11. Scatterplot of annual emissions estimated by Scientific Aviation and AVIRIS-NG with a linear fit with a R^2 of 0.45. This emphasizes the challenge in comparing results that were derived largely from measurements acquired at different times due to the highly intermittent nature of these emissions (table 1).

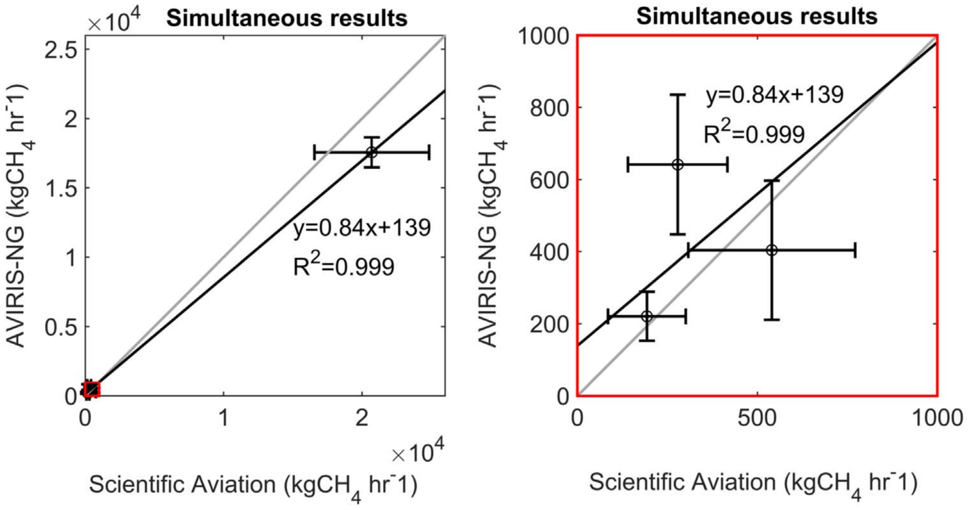

Figure 12. Simultaneous measurements between Scientific Aviation and AVIRIS-NG using a linear regression results in improved agreement with a R^2 value of 0.99. All 4 results are shown on the left while 3 results at lower emission rates are shown on the right.

(figure 12) using a linear regression results in improved agreement with a R^2 value of 0.99.

4. Discussion

Our analysis reveals significant discrepancies with the State's accounting of UGS emissions as well as under reporting by individual facilities which if unresolved could impede efforts to meet future mitigation targets. This finding is consistent across both airborne emission estimation techniques reported here. While UGS emissions represent a small fraction of the statewide methane budget (only about 10% of the natural gas portion of the inventory) the majority of the emissions measured in this study are associated with readily identifiable equipment, which suggests low-hanging fruit for mitigation.

The application of high spatial resolution infrared imaging spectroscopy with multiple revisits revealed 7 distinct methane emission modes at California's UGS facilities (table 1). Compressor loss (most likely rod pack venting) and leaking isolation and blowdown valves appear to dominate emissions—consistent with model studies and field testing for other regions in the US (Zimmerle *et al* 2015, Subramanian *et al* 2015). This study —with the combination of multiple airborne remote-sensing and *in situ* surveys—adds to previous work by dramatically increasing the spatial and temporal sampling of methane plumes and directly attributing them to key components.

More broadly speaking, the advanced remote-sensing methods described here may be applicable to characterizing and enabling mitigation of methane point source emissions from other regions and sectors globally (Duren *et al* 2019). This study underscores the critical need for both spatially and temporally resolved observational strategies. Given the stochastic and episodic nature of many sources, it further suggests the need for more persistent and/or higher frequency sampling. Effective carbon monitoring systems may benefit from systematic expansion and application of these techniques including strategic deployment of aircraft resources and potentially satellite platforms (Cusworth *et al* 2019, Ayasse et al 2019). Additionally, while this study was focused on resolving individual point source emissions, future efforts may benefit from integrating this class of observational methods with coarser resolution but persistent regional scale monitoring frameworks.

5. Conclusion

We conducted multiple airborne surveys of the 12 active UGS facilities in California between January 2016 and November 2017 using advanced remote-sensing and *in situ* observations of near-surface atmospheric methane enhancements. These measurements combined with wind data yield spatially and temporally resolved methane emission estimates for California UGS facilities and key components with spatial resolutions as small as 1–3 m and revisit intervals ranging from minutes to months. The study spanned a range of normal operations, malfunctions, and maintenance activity from multiple facilities including the active phase of the Aliso Canyon blowout incident in 2016 and subsequent return to injection operations in summer 2017. During the Aliso Canyon blowout, estimated emission rates from AVIRIS-C were consistent with those obtained by Scientific Aviation. Michanowicz *et al* (2017) identified 160 UGS facilities that use wells that were not designed for gas storage, like the well that failed at Aliso Canyon, suggesting the possibility for future blowouts. Airborne imaging of methane plumes offers the potential to quantify methane emissions while locating primary and secondary emission sources, as demonstrated in this study for Aliso Canyon.

This analysis also reveals significant discrepancies with the representation of UGS emissions in the California's methane budget and large variance in self-reported emissions. The fact that the majority of those emissions are due to malfunctioning but readily identifiable equipment suggests low-hanging fruit for mitigation with benefits both to California's climate policies, facility operators and natural gas rate payers. Future efforts that extend the spatial and temporal coverage of this study will likely be necessary to answer unresolved questions about the full distribution of normal and abnormal activity, component emission factors, and the prevalence of the different methane emission modes for this critical segment of the US natural gas supply chain. This work demonstrated that airborne imaging spectroscopy is an efficient observing strategy for rapidly surveying large areas and/or repeatedly sampling priority facilities. Our findings suggest several avenues of potential improvement for carbon monitoring systems for methane inventory development and validation as well as facility scale leak detection and repair for UGS and other key industrial sectors.

Acknowledgments

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Data availability

The data that support the findings of this study are openly available. AVIRIS-NG radiance products can be ordered from the AVIRIS-NG data portal at https://avirisng.jpl.nasa.gov/alt_locator/. Retrieved methane images from flight lines in this study are available for download at https://doi.org/10.3334/ORNLDAAC/1727 and images of methane plumes for California can be viewed at https://methane.jpl.nasa.gov/.

ORCID iDs

Andrew K Thorpe https://orcid.org/0000-0001-7968-5433
Riley M Duren https://orcid.org/0000-0003-4723-5280
Stephen Conley https://orcid.org/0000-0001-6753-8962
Kuldeep R Prasad https://orcid.org/0000-0002-5817-7306
Brian D Bue https://orcid.org/0000-0002-7856-3570
Kelsey T Foster https://orcid.org/0000-0002-2471-7319
Talha Rafiq https://orcid.org/0000-0003-1348-3219
Francesca M Hopkins https://orcid.org/0000-0002-6110-7675
Marc L Fischer https://orcid.org/0000-0001-7956-2361
David R Thompson https://orcid.org/0000-0003-1100-7550
Christian Frankenberg https://orcid.org/0000-0002-0546-5857
Charles E Miller https://orcid.org/0000-0002-9380-4838

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