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Toxic Air Contaminant and Greenhouse Gas Measurements near Oil and Gas Operations and Proximate Communities

CARB contract 18ISD023

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Acknowledgement

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Abstract

Emissions of toxic air pollutants and other VOCs and greenhouse gases from the oil & gas sector in California and their concentrations in communities were studied on behalf of the California Air Resources Board (CARB). This 2-year study was comprised of 3 field measurement campaigns that were carried out in September/October 2019, in June/July 2021 and in September/October 2021. In addition, a dispersion modeling study was carried out for neighborhood impacts based on these recently quantified facility emissions. The measurements used unique optical techniques and combined remote sensing gas column measurements with concentration measurements on a mobile platform. The methodology was developed for quantification and characterization of point- and diffuse emission sources.

This approach makes it possible to measure facility level emissions, measure co-pollutant emissions, and capture larger spatially extensive or distributed operations such as oil fields with diffuse emissions. These measurements allow better understanding of real-world emissions of complex sources.

The target gases were non-methane volatile organic compounds (NMVOCs) which cause the formation of photochemical smog, and methane which impacts climate. Other gases that were screened for in the measurements were NO_2, which contributes to the formation of ground level ozone, and SO_2 which causes the formation of particulate matter. Several of the targeted species are of major health concern and could have a direct health impact on surrounding communities. However, health impacts are not examined in this study.

The main results are:

- Emissions of VOCs, methane and air toxics from several of California's largest producing oil fields in Kern County were measured. A total of 6100 kg/h of alkanes and 10300 kg/h of methane were measured from 11 fields.
- NMVOC plumes were detected at all oil field fencelines, however, BTEX and benzene concentrations were only measurable above detection limit (low ppb) for some of the fields. For field plumes with detectable BTEX and benzene concentrations, the ratio of BTEX or benzene mass fraction to alkane mass fraction was of the order of 5% and 1%, respectively. Some processing sites or facilities close to the fenceline had evident BTEX emissions reaching neighboring communities.
- Emissions of alkanes and methane from Inglewood Oil Field in Los Angeles County were 101 kg/h alkanes and 121 kg/h, respectively. BTEX and benzene emissions were 16 kg/h and 7.7 kg/h, respectively.
- Plume dispersion measurements within the field campaigns showed that evening and nighttime plumes of air toxics can be traced at measurable levels often kilometers away from an isolated source.
- Modeling of plume dispersion and contaminant concentrations were carried out for two sites in San Joaquin Valley and were validated with measurements. Although cross wind dispersion may be underestimated by the simulation, the results showed that plumes likely carry far into residential areas and this was supported by measurements.

Executive summary

BACKGROUND

CARB has initiated several programs and studies that respond to the recommendation to "assess public health as a function of proximity to all oil and gas development" from a report by California Council on Science and Technology (2015). This contract supports the following programs, studies, and regulation:

- SNAPS – The Study of Neighborhood Air near Petroleum Sources is a CARB program that aims to characterize air quality in communities near oil and gas extraction and related operations.
- CAPP - The Community Air Protection Program, initiated by Assembly Bill 617 (Garcia 2017), is a separate community monitoring effort that aims to better understand air quality and air pollution sources in disadvantaged communities.
- Fenceline air sampling pursuant to Senate Bill 4 (SB 4; Pavley 2013) and the resultant SB4 Well Stimulation Treatment Regulations.
- CARB regulation intended to reduce methane emissions from oil and gas sources.

The target gases for this work are methane, non-methane volatile organic compounds (NMVOCs), benzene, separately and with other aromatics as BTEX (benzene, toluene, ethylbenzene and xylene), NO_2 and SO_2. Methane directly affects climate, while NMVOCs (combined with NOx emissions in the presence of sunlight) contribute to the formation of ground level ozone, which is harmful to human health and crop yields. Additionally, both NMVOC and ozone are greenhouse gases, although with generally short atmospheric lifetimes. Sources emitting significant amounts of NMVOCs may also co-emit BTEX and other air toxics that could directly impact health in surrounding communities. SO_2 contributes to the formation of particulate matter on the regional level, which is also a health concern.

Oil and gas are produced throughout California. Some of this production occurs in relatively close proximity to residential communities, especially in the San Joaquin Valley (SJV) and South Coast Air Basin (SCAB) regions. More broadly, a 2017 study (Czolowski, 2017) found that over two million Californians live within 1 mile of an active oil or gas well, making the quantification of emissions essential for future air quality management.

Three multiple-week field campaigns were conducted over the period September 2019 to October 2021, focusing on oil and gas related emissions of NMVOC and methane and concentration mapping of alkanes, methane, benzene and BTEX compounds at fenceline of production fields, and in nearby communities. The first survey in San Joaquin Valley in September-October 2019 involved in-field measurements of the Lost Hills oil and gas field, fenceline and community monitoring. The second project survey was conducted in the South Coast Air Basin from June-July 2021, and the final survey of a large number of oil fields and residential community areas in Kern County, SJV was conducted in September-October 2021.

OBJECTIVES AND METHODS

The objectives of this project are to:

1. Provide a better understanding of the emissions (composition and rate) from oil and gas sources in SJV and SCAB.
2. Trace the transport of enhanced VOC concentrations from oil and gas point sources.
3. Assess the impact of oil and gas emissions on local air quality.
4. Quantify toxic levels in communities close to the sources, adding on to the SNAPS and CAPP programs.

This study used an advanced mobile air pollution measurement lab equipped with four optical instruments for gas monitoring. Alkane emissions were measured by Solar Occultation Flux (SOF). Methane and alkane ground level concentrations were measured by MeFTIR, and in parallel MeDOAS (2021) (or MWDOAS (2019)) measured benzene and BTEX concentrations. Indirect emissions of methane, benzene and BTEX were obtained by combining the mass ratios to alkanes with the alkane emissions measured by SOF. SkyDOAS was applied to screen for sources of SO_2, NO_2 and H_2CO emissions. Wind data was obtained by a wind LIDAR that was applied at locations in the vicinity to the VOC measurements, providing vertical profiles of wind speed and wind direction in the 10 - 300 m range above ground.

Mobile lab driving routes varied by objective. Emissions were measured by driving around sources (e.g. entire oil fields) in a box pattern or downwind sources where no box was possible. Upwind source emissions were accounted for when present. Gas concentration mapping was conducted by driving through communities usually in a zig-zag fashion, distance decay measured by driving at successively farther distances from a suspected source, and in a few instances by parked van to get a stationary time series measurement.

In support of the second and third objective, the project involved application and adaptation of a dispersion model based on the Weather Research and Forecasting (WRF) model. Initialization and boundary conditions for WRF were taken from the High Resolution Rapid Refresh (HRRR) model. Model simulations were conducted using measured emissions from two locations (Lost Hills and Mountain View areas) where frequent emission measurements and concentration measurements had been made.

In this project the emissions of several air pollutants and greenhouse gases have been studied from Oil & Gas sites in the SJV and South Coast areas during three multiple-week surveys in the period October 2019 – October 2021.

RESULTS

Oil and gas emissions

The area surveyed in this report represents a significant portion of the oil and gas production in California. To give an indication of size, the sum of emissions for the fields in Kern County in San Joaquin Valley, wholly or partially measured, amount to 6100 kg/h of alkanes and 10300 kg/h methane (Table ES 1). This includes emissions from the Elk Hills, Asphalto, North and South Belridge, Coles Levee North, Cymric, McKittrick, Kern Front, Kern River, Edison, Mountain View and Lost Hills fields, and is based on measurements from at least one survey in 2019 or 2021.

For the South Coast region, Inglewood was the only oil field included in its entirety in this project, showing an alkane emission of 101 kg/h in June-July 2021. The corresponding methane emissions were 121 kg/h. It should be noted that there are many other strong sources in the South Coast region, such as the Long Beach field (Signal Hill) and refineries (Mellqvist, 2015a, 2015b) and the study area was primarily chosen based on its inclusion in the SNAPS project.

BTEX and benzene emissions were only measurable above detection limit at some of the fields over the entirety of the oil field NMVOC plume, and thus only reported for a fraction of the oil fields. For field plumes with detectable BTEX and benzene to alkane mass fractions, measurements showed fractions on the order of 5% and 0.6-1.5%, respectively. For the most part, measurable fields (e.g. Lost Hills, Kern River, Inglewood) had processing facilities near the fenceline with detectable BTEX and benzene emissions.

Table ES 1. Summary of results from the 2019 and 2021 measurement surveys for Oil & Gas fields. Note: only oil fields with sufficient statistics (>3 valid measurements) are presented here. BDL – **concentration** below detection limit. NM – not measured. Note that individual field measurements and combined field measurements of emissions and concentration mass fractions may differ in time and number of measurements and therefore may not add up exactly.

Region	Oil & Gas field, survey year	Alkanes [kg/h]	BTEX [kg/h]	Benzene [kg/h]	CH_4 [kg/h]
SJV	Lost Hills, 2019	522	BDL	BDL	224
	Lost Hills 2021	452	22	6.7	453
	Cymric & McKittrick, 2019	1377	BDL	BDL	2433
	Cymric & McKittrick, 2021	1209	BDL	BDL	2184
	Cymric & McKittrick & Belridge, 2019	2968	BDL	BDL	NM
	Cymric 2021	841	BDL	BDL	819
	McKittrick, 2021	242	BDL	BDL	1749
	Elk Hills, 2021	2246	101	BDL	4432
	Coles Levee - North, 2021	226	BDL	BDL	98
	Kern Front, 2021	143	BDL	BDL	501
	Kern River, 2021	243	11	1.5	714
	Kern Front & Kern River, 2021	385	18	2.4	1133
	Edison & Mountain View, 2021	112	BDL	BDL	104
South Coast	Inglewood, 2021	101	16	7.7	121

A few selected facilities that were accessible by road (to within a few hundred meters of the source) and showed evidence of emissions that could be isolated in measurements and were analyzed in more detail as area sources, Table ES 2. In the Buena Vista field, a site located just north of the Midway Rd and Taft Highway crossing showed recurrent emissions, with large variability. On average alkane emissions here were 153 kg/h. Corresponding emissions of methane, BTEX and benzene were 248 kg/h, 4.0 kg/h and 2.6 kg/h, respectively.

A site located within the Asphalto field, just north of Skyline Rd, was measured to have alkane emissions of 13 kg/h and methane emissions of 3.5 kg/h.

The Kern Oil refinery site is located at the western border of the Mountain View field, just north of Lamont. Emissions from the main refinery area as well as a tank farm to the east of the refinery were measured on multiple days, showing overall alkane emissions of 88 kg/h. Methane, BTEX and benzene emissions were 22 kg/h, 6.6 kg/h and 1.2 kg/h, respectively.

Four well sites, part of the Las Cienegas field in the South Coast region, were measured in June-July 2021 showing alkane emissions on the order of 6 kg/h in total. The Honor Rancho and Playa Del Rey gas storage facilities showed emissions of about 25 kg/h of alkanes all together. Corresponding methane emissions were 6 kg/h from the four Las Cienegas well sites and 107 kg/h from the Honor Rancho and Playa Del Rey gas storage sites.

Table ES 2. Summary of results from the 2019 and 2021 measurement surveys for Refineries, Processing and Well Sites. Note: only sites with sufficient statistics (>3 valid measurements) are presented here. BDL – **concentration** below detection limit.

Region	Site, survey year	Alkanes [kg/h]	BTEX [kg/h]	Benzene [kg/h]	CH_4 [kg/h]
SJV	Lost Hills - Processing 1, 2019	54	2.0	0.2	18
	Lost Hills - Processing 1, 2021	58	1.6	0.3	41
	Kern Oil Refinery - Main Area, 2021	75	6.3	1.0	19
	Kern Oil Refinery - East Tank Park, 2021	13	0.3	0.2	2.9
	Buena Vista - Processing Site, 2021	153	4.0	2.6	248
	Asphalto - Facility Skyline Rd, 2021	13	0.5	0.1	3.5
South Coast	Las Cienegas - St. James Lease, 2021	0.5	0.03	BDL	0.7
	Las Cienegas - Jefferson, 2021	2.2	0.11	0.05	2.9
	Las Cienegas - Murphy, 2021	3.3	0.30	BDL	2.2
	Playa Del Rey - Gas Storage, 2021	12	0.80	0.22	15
	Honor Rancho - Gas Storage, 2021	13	0.45	0.30	92

In both the October 2019 and October 2021 surveys, a larger facility within the southern part of the Lost Hills field (Processing 1 in Table ES 2) was measured to have alkane emissions of 54 kg/h and 58 kg/h, respectively. Corresponding methane emissions here were 18 kg/h in 2019 and 41 kg/h in 2021. The BTEX emissions were measured in the range 1.6-2.0 kg/h both survey years and correspond to 0.2-0.3 kg/h benzene emissions.

In-field measurements at the Lost Hills oil field in October 2019 were screened into sub-sections of the field to identify specific sectors and facilities that had higher emissions relative to others. Sector measurements by SOF averaged alkane emissions from 100-200 well heads, to yield mean specific wellhead emission rates of 0.06-0.35 kg/h with the higher end estimate correlated with a sector that contained more production/treatment facilities. Complementary measurements of individual well units showed emissions in the 0.02 – 0.66 kg/h range. Normalizing the overall Lost Hill field emissions of 452 kg/h of alkanes and 453 kg/h of methane to the number of active wells only (2397, October 2021) would give a specific average wellhead emission rate of 0.19 kg/h/wellhead each for alkanes and methane.

To put observed VOC emissions in context, another CARB study applying the same methodology (Mellqvist, 2021) showed alkane emissions from 5 refineries in the Bay area to be in the 140-330 kg/h range. Corresponding emission range for 6 South Coast refineries were 70-270 kg/h (Mellqvist, 2015a).

Dispersion modeling and plume tracing

Modeled dispersion results were validated with wind and alkane column measurements. Column measurements showed good reproducibility in terms of shape and integrated concentration. Both modeling and measurements confirmed that under strong daytime convective conditions, concentration dispersion occurred rapidly. Nighttime simulations were dominated by shallow inversion layers and minimal plume dispersion. This allowed modeled plume concentrations to continue for several kilometers without decreasing to less than half of initial concentrations. Compared to the simulation, evening plume tracing observations showed a more rapid initial decrease near the facility but also revealed occasions with transport of plumes over several kilometers.

Though not a target of the distance decay measurements, methane was also examined for plume tracing and dispersion purposes, however, the multitude of methane sources (industry, production, residential) hindered interpretation of methane plume decay over longer distances, especially for methane measurements in residential areas.

Concentration monitoring in communities

Concentration mapping was conducted in several communities in all three surveys October 2019 to October 2021. For San Joaquin Valley, the community areas are in Lost Hills, McKittrick, Derby Acres, Taft, Oildale (Bakersfield), Fuller Acres (Mountain View) and Arvin. In the South Coast region the community in proximity to the Inglewood oil field (Baldwin Hills) was monitored for enhanced VOC concentrations, as well as communities near four well sites within the Las Cienegas field in Los Angeles county.

Repeated concentration mapping on multiple days in the Lost Hills residential area showed enhanced alkane concentrations in the range from 200 to above 400 $\mu g/m^3$ during evenings when the wind direction transported emissions from the Lost Hills field. Corresponding BTEX enhancement was 2.5-7.5 ppb on average and benzene less than 1 ppb on average in the plume. Concentration mapping around Oildale in Bakersfield showed BTEX concentrations of 5-7.5 ppb about 800 m away from the nearest oil and gas source, and above 10 ppb closer by (200 – 400 m depending on exact source location). Benzene was on average 1 – 2 ppb for the nearer measurements. Mobile concentration mapping in Arvin detected a source in the western part of town, with alkane concentrations up to 400 $\mu g/m^3$ and above in the immediate nearby community (within 200 m) with corresponding BTEX enhancement of 2.5 – 5 ppb.

Stationary measurements, lasting 30-90 minutes each, were conducted with the mobile lab at four specific locations around Inglewood oil field and one location in Lost Hills residential area as directed by CARB in relation to the SNAPS program. Winds were blowing from west-south-west in all measurements at Inglewood oil field. The Sentinel Peak Resources site #1 and the

Hillcrest Dr site were the ones where highest concentrations were measured among the four Inglewood locations. Measurements at the Sentinel Peak Resources site #1 on the 26th and 28th of June showed several episodes of correlating alkane, methane and BTEX enhancements likely originating from upwind oil and gas wells and production/treatment facilities. Alkane peaks up to 40 ppb were observed, with corresponding BTEX and benzene peaks of about 7 ppb and 4 ppb respectively. Methane and ethane concentrations in the 400 ppb and 40 ppb ranges were observed here, respectively. At the Hillcrest Dr location about 30 ppb alkane enhancement (expressed as butane equivalents) and 4 ppb BTEX were detected. For the Lost Hills location (2019), alkanes reached up to 60 ppb, ethane and methane reached 100 ppb, while corresponding BTEX was about 10 ppb.

CONCLUSIONS

Cumulative emissions for the fields in Kern County in San Joaquin Valley, wholly or partially measured, amount to 6100 kg/h of alkanes and 10300 kg/h methane. This includes emissions from the Elk Hills, Asphalto, Belridge, Coles Levee North, Cymric, McKittrick, Kern Front, Kern River, Edison, Mountain View and Lost Hills fields.

For the South Coast region, Inglewood was the only oil field included in its entirety, showing an alkane emission of 101 kg/h. Corresponding methane emissions were 121 kg/h. The Honor Rancho and Playa Del Rey gas storage facilities showed emissions of about 25 kg/h of alkanes and 107 kg/h of methane when combined.

Both modeling and plume tracing measurements in SJV confirmed that under strong daytime convective conditions, concentration dispersion occurred rapidly downwind the source. Nighttime model simulations showed plume concentrations to continue several kilometers downwind from source. Evening plume tracing measurements showed that concentrations comparably dropped off more rapidly near the source facility but also showed plumes being transported over long distances (kilometers) on numerous occasions.

Recommendations for further work include:

- Monitoring and characterization of emissions at all existing oil and gas fields.
- Performance of complementary measurements close to the sources (in-field) to identify sources and leakage processes to be able to provide recommendations how to abate the emissions.
- Improved emission measurements by complementary drone studies and modelling.
- Further WRF model development and streamlining for SOF and indirect concentration measurements.
- Running WRF model over longer time frames and combining with wind field assessment for SOF measurements.
- Combining mobile community monitoring with stationary 24/7 measurements to study temporal variability as well as spatial.

1 INTRODUCTION

Oil and gas are produced across many regions of California. Some of this production occurs in relatively close proximity to communities, especially in the San Joaquin Valley and South Coast. According to a 2017 study (Czolowski, 2017), over two million Californians live within 1600 m (~1 mile) of an active oil or gas well. Emissions from oil and gas production equipment, such as wells and produced water ponds, are not well measured nor understood. Due to this limited understanding, a 2015 report by the California Council on Science and Technology (2015) recommended that studies should be conducted "in California to assess public health as a function of proximity to all oil and gas development." CARB has initiated several programs and studies that respond to this need. This contract supports all of the following programs, studies, and regulation:

- SNAPS - The Study of Neighborhood Air near Petroleum Sources is a CARB program that aims to characterize air quality in communities near oil and gas extraction and related operations. The study involves measuring pollutant concentrations within each selected community, with a focus on toxic air contaminants, and determining which sources or source categories are contributing to air pollution. This will be accomplished using stationary air monitoring trailers and a supplementary mobile platform.

- CAPP - The Clean Air Protection Program, initiated by Assembly Bill 617 (Garcia 2017), is a separate community monitoring effort that aims to better understand air quality and air pollution sources in disadvantaged communities.

- Pursuant to Senate Bill 4 (SB 4; Pavley 2013) and the resultant Well Stimulation Treatment Regulation, CARB is recommending fenceline air sampling during some well stimulation treatments (WST), such as hydraulic fracturing, and has completed a contract to study emissions from produced water ponds.

- The Greenhouse Gas Emission Standards for Crude Oil and Natural Gas Facilities regulation, adopted by CARB 2017 and in effect since January 2018, includes requirements for quarterly leak detection and repair; standards for equipment such as tanks, compressors, and pneumatic devices and pumps; detailed monitoring requirements for natural gas underground storage facilities; and other measurement, record keeping, and reporting requirements.

In this project the emissions of several air pollutants and greenhouse gases have been studied from Oil & Gas activity in the SJV and South Coast areas during three multiple-week surveys in the period October 2019 – October 2021. The target gases were methane, which impacts climate, and non-methane volatile organic compounds (NMVOC) which contribute to the formation of ground level ozone. Both NMVOC and ozone are greenhouse gases, although with generally short atmospheric lifetimes. Facilities emitting significant amounts of NMVOCs may also emit BTEX and other air toxics that could have a direct health impact on surrounding communities. The survey measurements included emission measurements (daytime) and ground level concentration mapping of methane, NMVOC, benzene and BTEX compounds during both daytime and nighttime conditions. In addition, sources of SO_2, NO_2 and formaldehyde were screened for in the study. SO_2 contributes to the formation of particulate matter, which is a health concern. Ozone (formed from NMVOC and NO_2 emissions in presence of sunlight) also constitutes a public health concern and is known to reduce crop yields.

This was an extensive study demonstrating a variety of measurement methods and targeted gas emissions, with diverse sources and applications. The studied emissions are generally diffuse in character and there are few methods available for direct measurement. This study employed unique optical techniques and a methodology combining gas column measurements by remote sensing with concentration measurements on a mobile platform.

Real-time measurements of ground level plume concentrations were carried out at different distances from various sources and locations, complemented by the adaptation and application of a WRF (Weather Research and Forecasting) model for two locations, in Lost Hills and Mountain View, to improve understanding of concentration decay and impact on nearby communities.

The results from this project will help to:

- Provide a better understanding of the actual emissions from oil and gas sources in the San Joaquin Valley and in the South Coast Basin
- Provide insights and real observations on how far from oil and gas sources enhanced VOC concentrations are detected
- Assess the impact of oil and gas emissions on air quality/air
- Study concentration levels of toxics in communities close to the sources, adding on to the SNAPS and CAPP programs

2 MATERIALS AND METHODS

2.1 Methods overview

This study used an advanced mobile air pollution measurement lab equipped with four optical instruments for gas monitoring which were used during the survey: SOF (Solar Occultation Flux), SkyDOAS (Differential Optical Absorption Spectroscopy), MeFTIR (Mobile extractive Fourier Transformed Infrared spectrometer) and MeDOAS (Mobile extractive White cell DOAS) or MWDOAS (Mobile open path White cell DOAS). The emissions measurement methodology is described shortly in the subsections below and has been applied in several international projects studying emissions to the atmosphere (for instance, Johansson et al 2014). Additional information on the measurement methods and instruments can be found at: www.fluxsense.com.

SOF and SkyDOAS both measure gas columns through the atmosphere by means of light absorption. SOF utilizes infrared light from the direct sun whereas SkyDOAS measures scattered ultraviolet light from the sky. SOF is considered Best Available Technique (BAT) for emission quantification of refinery VOC emissions in Europe since 2015 (European Commission, 2015). MeFTIR and MeDOAS (or MWDOAS) measure ground level concentrations (measurement vehicle roof height, approx. 3 m) of alkanes and BTEX (benzene, toluene, ethylbenzene, p-xylene, m-xylene) respectively.

Both concentrations and columns are shown as enhancements above the background level, i.e. the value relative to a reference outside the plume. This is generally the first measurement in the measurement series assuming a start outside of the source plume. This helps better visualize the contribution from the nearest sources. For species without significant background concentrations such as benzene, the measured relative concentration approaches the absolute concentration. For other species such as methane, the background concentrations and columns can vary significantly especially near widespread sources such as in agricultural, wetlands or oil producing areas, and enhancement in some cases can be negative.

In order to calculate gas emissions, wind data (direction and magnitude) is required. Wind information for the survey was derived from several different sources. A wind LIDAR was used to measure vertical profiles of wind speed and wind direction from 10-300 m height. This was re-located for each measurement day and measurement area to a suitable site within the vicinity downwind of the measured areas. The LIDAR data was compared with data from several wind masts from fixed met network- and mobile stations to extend the measurements to times when LIDAR was unavailable.

Figure 1 gives a general overview of the instrument methodology and Figure 2 illustrates how the measurements with the mobile laboratory are carried out in a circle (box) around the source, measuring both downwind and upwind the emission source to remove the influence of upwind sources. In order to derive final emission flux estimates, the GPS-tagged gas column measurements by SOF and SkyDOAS are combined with wind data and integrated across plume transects at the various source locations. Gas mass ratio measurements by MeFTIR and MeDOAS (or MWDOAS) are then used to indirectly estimate the emissions for methane, benzene and BTEX.

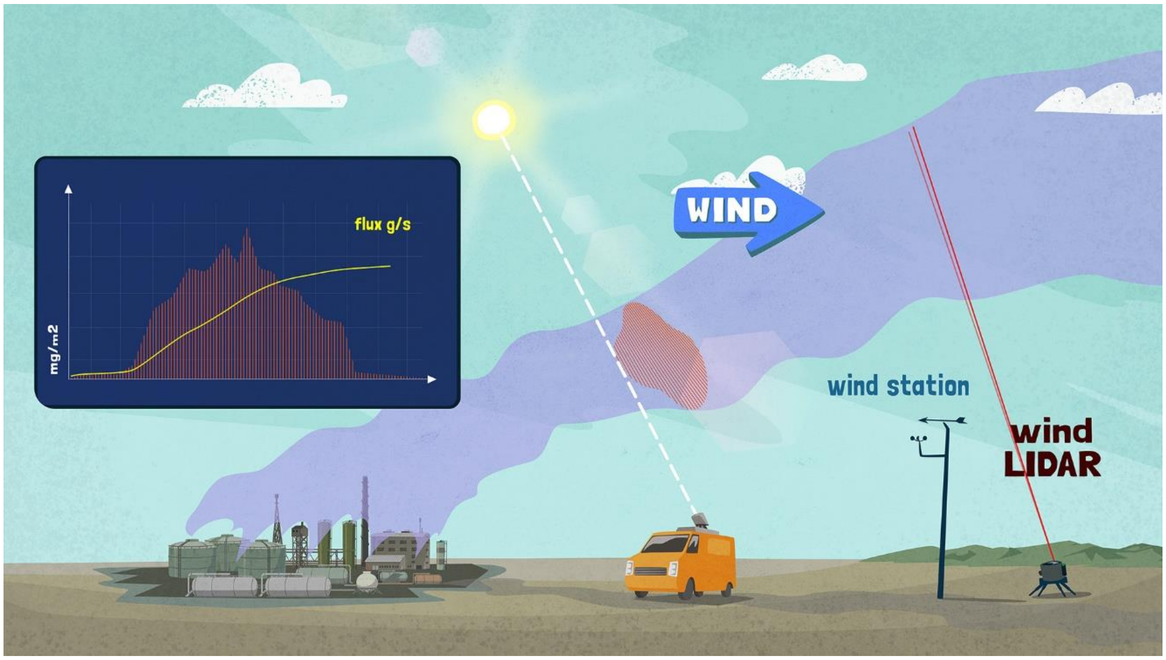

Figure 1. Methodology. The VOC mass (or other compound of interest) is integrated through the plume cross section by means of mobile solar and scattered skylight absorption spectroscopy (SOF and SkyDOAS) measurements. Gas emission rates (g/s) are then derived by combining the gas column (mg/m^2) measurements with wind speed and wind direction data measured by LIDAR and wind masts. Ground level concentrations (mg/m^3) are measured by mobile IR and UV absorption spectroscopy (MeFTIR and MeDOAS).

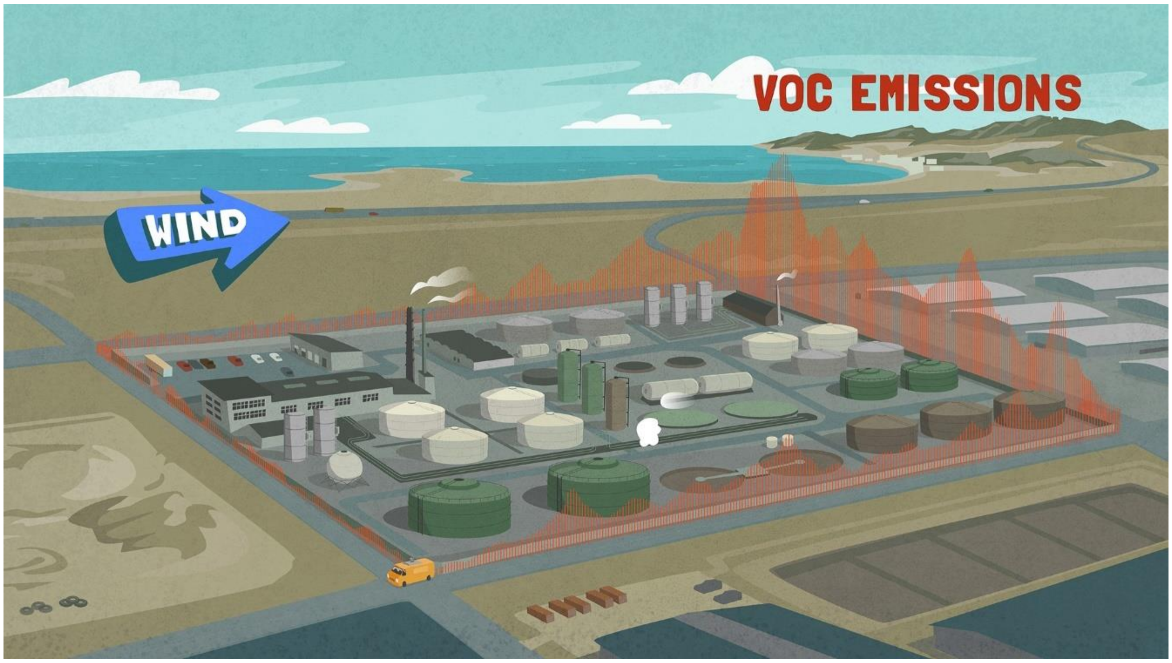

Figure 2. Schematic of SOF and SkyDOAS measurement where the vehicle is driven across the prevailing wind so that the solar beam or zenith sky light beam cuts through the emission plume while the sun is locked into the FTIR spectrometer by the solar tracking device on the roof. The VOC mass (or other compound of interest) is integrated through the plume cross section. Usually, the measurements are carried by encircling the individual sources, in order to remove the influence of the upwind (background) emissions.

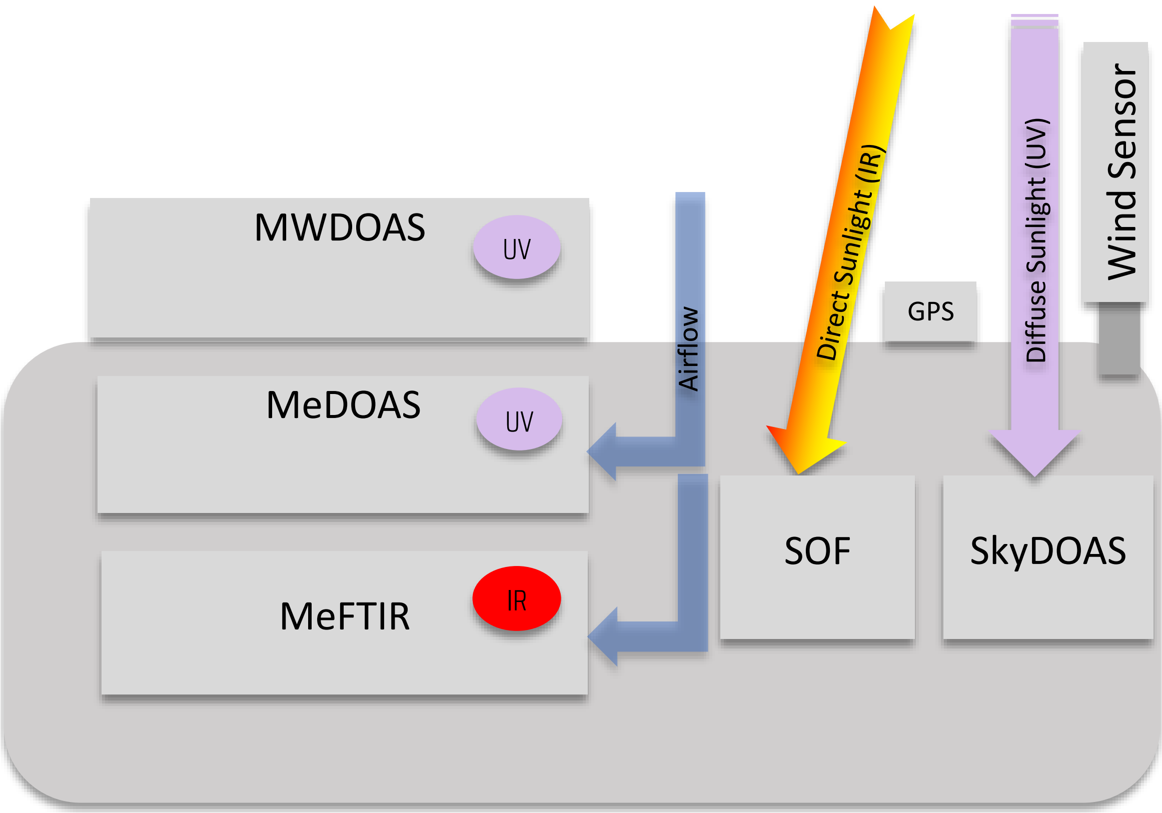

Figure 3. Overview of the mobile lab main instruments ; SOF, MeFTIR, MeDOAS (or MWDOAS) and SkyDOAS. SOF and SkyDOAS are column integrating passive techniques using the sun as the light source while MeFTIR and MeDOAS (or MWDOAS) measure near ground-level concentrations using active internal light sources.

Figure 4. Internal and external view of the mobile laboratory.

Table 1. Summary of the gas measurement techniques in this study.

Method	SOF	SkyDOAS	MeFTIR	MeDOAS/MWDOAS
Compounds	Alkanes: (C_nH_{2n+2}) Alkenes: C_2H_4, C_3H_6 NH_3	SO_2, NO_2, H_2CO	CH_4 Alkanes: (C_nH_{2n+2}) Alkenes: C_2H_4, C_3H_6 NH_3	BTEX
Detection limit column	0.1-5 mg/m^2	0.1-5 mg/m^2	1-10 ppbv	0.5-3 ppbv
Wind Speed Tolerance	1.5-12 m/s	1.5-12 m/s		
Sampling Time Resolution	1-5 s	1-5 s	5-15 s	8-10 s
Measured Quantity [unit]	Integrated vertical column mass [mg/m^2]	Integrated vertical column mass [mg/m^2]	Mass concentration at vehicle height [mg/m^3]	Concentration at vehicle height [mg/m^3]
Derived Quantity [unit]	Mass Flux [kg/h]	Mass Flux [kg/h]	1) Alkane and methane mass concentration ratio of ground plume combined with SOF gives mass flux [kg/h] and plume height information [m] 2) Alkane and CH_4 flux [kg/h] via tracer release	Combined with MeFTIR and SOF gives Mass Flux [kg/h]
Complementary data	Vehicle GPS-coordinates, Plume wind speed and direction	Vehicle GPS-coordinates, Plume wind speed and direction	Vehicle GPS-coordinates Plume wind direction	Vehicle GPS-coordinates, Plume wind direction

2.2 Measurement Methodology

2.2.1 Principal Equations

This report includes three different techniques to measure emission mass fluxes as specified below. The primary methods in this project are the direct flux measurements of alkanes from SOF and NO_2, SO_2 and formaldehyde measurements by SkyDOAS. In the secondary method benzene, BTEX and methane fluxes are measured indirectly from MeDOAS/MeFTIR gas mass ratios combined with SOF alkane emissions.

2.2.2 Direct flux measurements

The emission mass flux (Q) of species (j) measured by SOF for a single transect (T) across the plume (P) along path (l) can be expressed by the following integral (units in gray brackets):

$$Q_T^j[\mathrm{g/s}] = \overline{v}_T[\mathrm{m/s}] \cdot \int_P C_l^j[\mathrm{mg/m^2}] \cdot \cos(\theta_l) \cdot \sin(\alpha_l) \; dl \; [\mathrm{m}]$$

Where,

$\overline{v}_T$ = the average wind speed at plume height for the transect,

C_l^j = the measured slant column densities for the species j as measured by SOF or SkyDOAS,

θ_l = the angle of the light path from zenith ($\cos(\theta_l)$ gives vertical columns),

α_l = the angle between the wind direction and driving direction

dl = the driving distance across the plume

Note that SOF and SkyDOAS have different light paths, where the SkyDOAS telescope is always looking in the zenith direction while the SOF solar tracker is pointing toward the sun. Hence, the measured SOF slant column densities will vary with latitude, season and time of day. To isolate emissions from a specific source, the incoming/upwind background flux must be either insignificant or subtracted. If the source is encircled, the integral along l is a closed loop and the flux calculations are done with sign.

2.2.3 Indirect flux measurements

The indirectly measured flux (indirectly measured emission, IME) is computed using a combination of SOF and MeFTIR/MeDOAS (or MWDOAS) measurements. The indirect mass flux ($\widehat{Q}^i$) for species (i) are calculated from MeFTIR and/or MeDOAS ground level gas ratios integrated over the plume (P) along path (l) are given by (units in brackets):

$$\widehat{Q}^i[\mathrm{g/s}] = \overline{Q}^j[\mathrm{g/s}] \cdot \frac{1}{k} \sum_k \frac{\int_P N_l^i[\mathrm{\mu g/m^3}] \, dl[\mathrm{m}]}{\int_P N_l^j[\mathrm{\mu g/m^3}] \, dl[\mathrm{m}]}$$

$\overline{Q}^j$ = the average flux of species j from multiple transects as measured by SOF,

N_l^i = the mass concentration of species i as measured by MeDOAS or MeFTIR,

N_l^j = the mass concentration of species j as measured by MeFTIR,

k = the number of gas ratio measurements

Note that the average ratio is applicable for sources with low to medium variability in plume composition, such as dairy farms. For larger and more complex sources, such as refineries or oil fields, to reduce sensitivity to extreme values, the median ratio is used instead. Median ratios were used throughout this report.

2.3 Uncertainties and Error Budget

A summary of the typical performance of the measurements is presented in Table 2. Table 2 reports the total expanded uncertainty for the flux measurements which include possible systematic errors and was determined through a series of controlled gas release experiments. In addition, the statistical error is reported for all directly measured source emissions. The statistical error corresponds to the random error in the measurements and does not include possible systematic errors. For instance, systematic errors could include errors in wind speed due to the errors in estimated height of the plume or spectral calibration errors. The statistical error is given by the Confidence Interval (CI 95%) for the mean, $\bar{x}$, according to:

$$CI = \bar{x} \pm t_{.025} \frac{s}{\sqrt{N}}$$

Here t is Student's T distribution and s corresponds to sample standard deviation:

$$s_x = \sqrt{\frac{\sum_{i=1}^{N}(x-\bar{x})^2}{N-1}}$$

Statistical errors are not reported for the median which is typically used for ratio measurements. Instead, interquartile range is presented for the ratios.

Table 2. Estimated performance of applied measurement methods . Note that the total uncertainty includes systematic and random errors.

Measurement Parameter	Analysis Method	Total Uncertainty
SOF column concentrations, alkanes	SOF spectral retrieval	±10%
SkyDOAS column concentrations: NO_2, SO_2, H_2CO	DOAS spectral retrieval	±10%
MeFTIR concentrations: CH_4, VOC	MeFTIR spectral retrieval	±10%
MeDOAS or MWDOAS concentrations: BTEX, Benzene	DOAS spectral retrieval	±10%
SOF mass flux: Alkanes	SOF flux calculations	±30%-40%
SkyDOAS mass flux: NO_2, SO_2, H_2CO	SkyDOAS flux calculations	±30%
Indirect mass flux (e.g. BTEX, Benzene, CH_4)	Concentration ratio times mass flux	±40%-70%

2.4 Annualized emissions

An individual emission measurement is a snapshot of the emissions from an area or a facility for that particular point in time. By combining measurements over a period of time and taking the appropriate statistical measure, the emission measurements can be applied to longer periods or even annualized for comparison to inventory measurements. Variations in operations, meteorology and diurnal and seasonal differences may bias this estimate and these biases depend on the source, e.g. storage tanks are likely to have more variability diurnally and seasonally than pressure-regulated continuous processing.

In this report measured emissions are reported as average emission rates with units of kg/h (kilograms per hour). This is appropriate for single measurements where the time to complete the measurement is on the order of minutes up to one hour for large areas. Where applicable for comparison to inventory and other data, the approach used is to take the averaged emissions over the measurement period and directly scale up to annual figures or vice versa (inventory converted to emission rate). In this report these measurements were made over a few weeks in a single season for each year so variability on longer time scales is not reflected in the data.

2.5 Field survey setups

Three field surveys were conducted within the scope of this contract. The first survey focused on oil and gas emissions and their impact in the Lost Hills area in San Joaquin Valley, along with adjacent oil and gas fields. Measurements were conducted in October 2019 and involved in-field as well as fence-line measurements and community monitoring.

The second survey commenced in the South Coast area in June-July 2021, targeting the Inglewood oil field, the community-near oil well sites in south Los Angeles (Las Cienegas) and the gas storage sites Honor Rancho and Playa Del Rey.

In October 2021, the final survey of the project was conducted, again in SJV. The Lost Hills area was revisited, 2 years after the first survey, essentially covering the same areas without in-field measurements. A larger emphasis of the final survey was obtaining emissions data from other sites in southwest SJV and in the Bakersfield area. The oil fields of Edison and Mountain View southeast of Bakersfield were monitored repeatedly, as well as the Kern Front and Kern River fields north of Bakersfield. Measurements also involved community monitoring and plume decay observations with distance from sources.

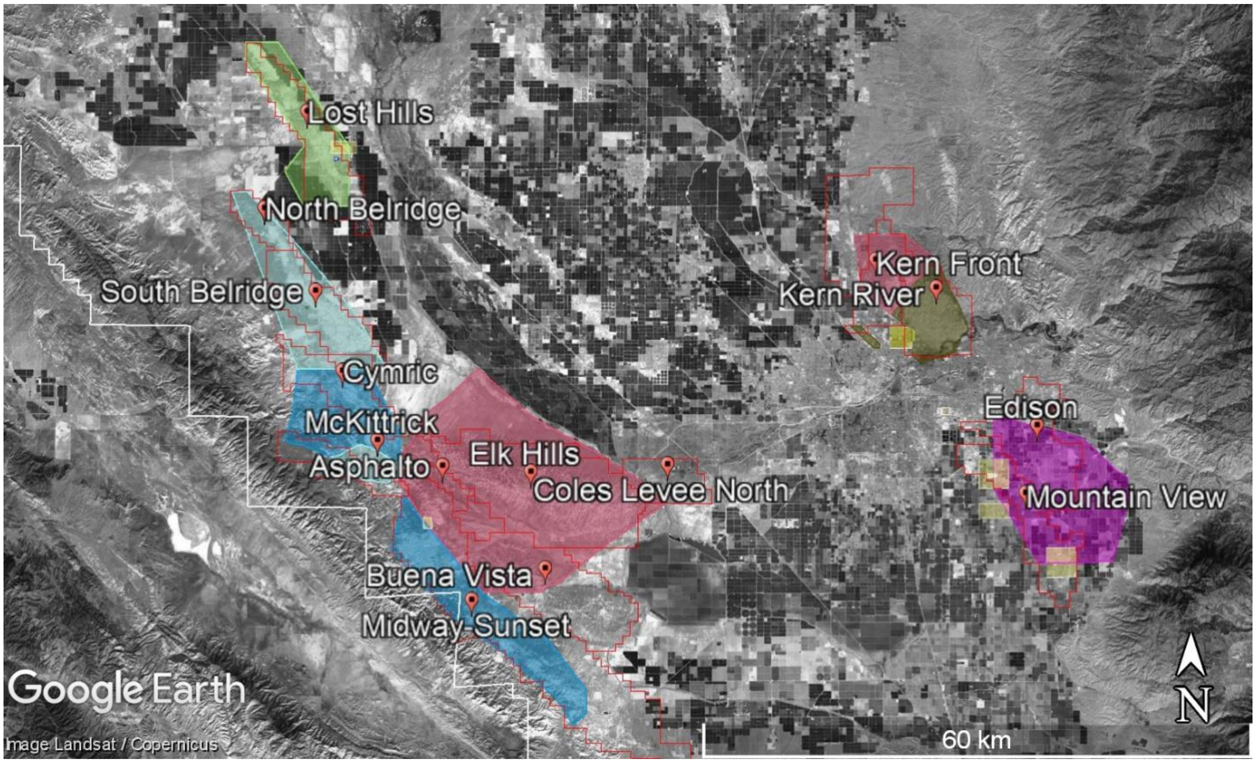

Figure 5 Overview of the Kern County Oil and Gas sites measured during San Joaquin Valley surveys. Red border marks actual oil field boundaries while filled shapes represent areas as defined by the emissions measurements. These areas are named for the dominant oil field within their border and color is used only for differentiation. Also shown in yellow are areas where extensive concentration mapping was undertaken.

2.5.1 Survey A – San Joaquin Valley, October 2019

Mobile measurements with SOF, SkyDOAS, MWDOAS, and MeFTIR were carried out during 16 measurement days between September 30 and October 18, 2019, in the SJV, California (Figure 6).

The campaign focused on methane and NMVOC emissions from oil and gas production in the Lost Hills field and its impact on the neighboring community. The survey also included investigations of other oil and gas production sources in Kern County in support of CARB SNAPS measurements, i.e. Cymric-McKittrick.

The objective was to quantify VOC emissions from the Lost Hills oil field and to identify the largest sources (and possible leaks) within the field. The areas for emissions quantification were limited by traversable roads and prevailing wind direction. The emissions area for the Lost Hills field is delineated in Figure 6. This may exclude some minor producing areas with few active wells in the south, east of Lost Hills Road, and another area in the north, north of Twisselman Road, in some measurements. The survey areas within the Lost Hills field are shown in red in the same figure. An extensive survey of methane point sources and emissions within the State of California was conducted by the Jet Propulsion Laboratory (JPL, 2019) from 2016 – 2017. Of these measurements only 4 sources were positively identified by repeated measurements in the Lost Hills field (marked with S and a 5-digit ID number in Figure 6) out of 1105 for the survey across the entire state.

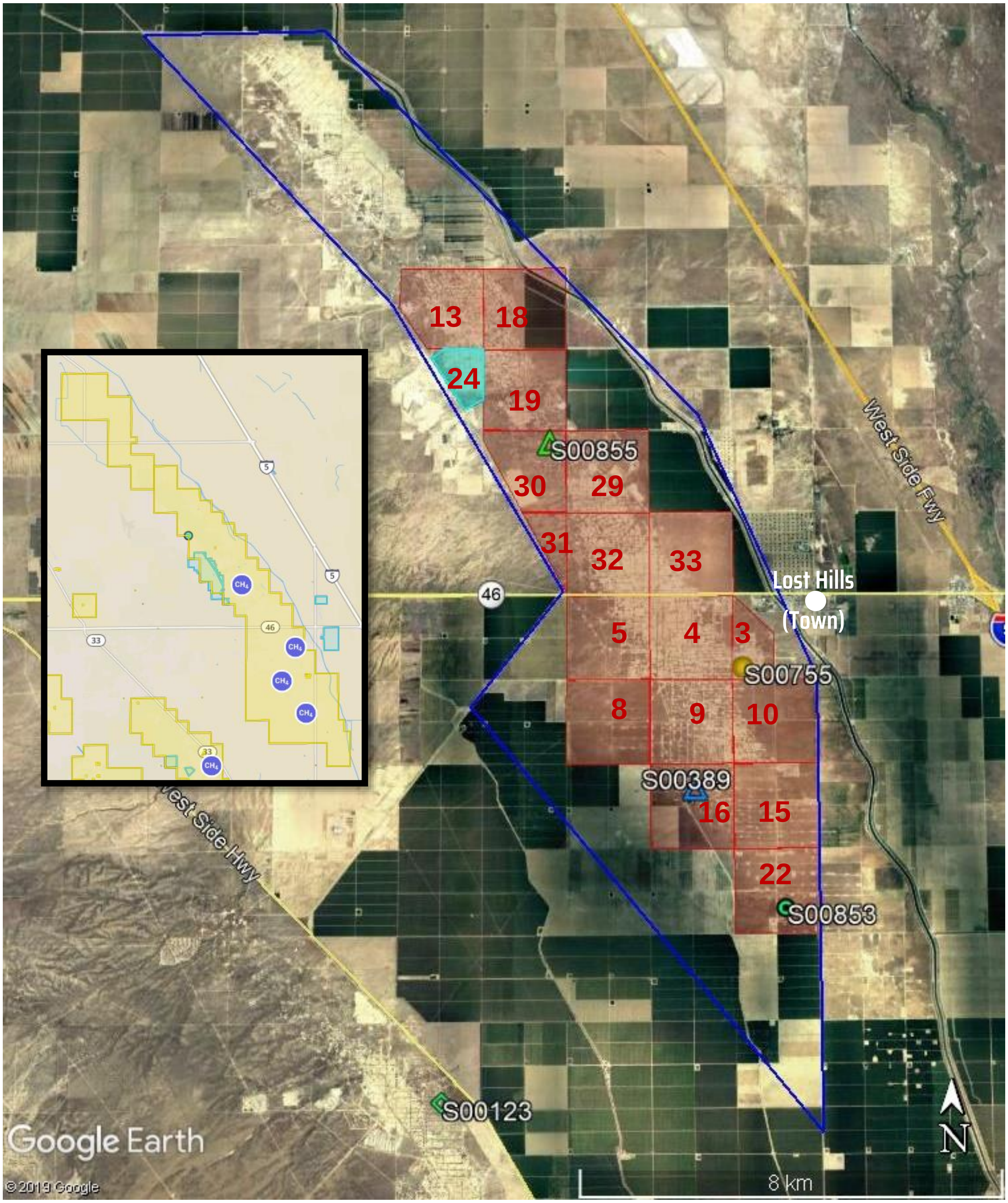

Figure 6. Lost Hills oil field and surroundings. The approximate area covered by the total Lost Hills emissions measurements is shown in blue. Sub-areas that were surveyed within the fields are shown in red with lines indicating the section borders and section numbers. Cyan section indicated area run by an operator outside the current study and was only surveyed from the fenceline. Point markers and inset indicate methane sources within the study area measured by the Jet Propulsion Laboratory (JPL, 2019).

Two operators, called here for convenience, A and B, within the Lost Hills field consented to measurements within their territory. Measurements during the survey were made on publicly accessible roads and for the Lost Hills field on the roads operated by Operator A and Operator B. Some crossing of the areas of other operators was inevitable in trying to reach the full extent of the Operator A or Operator B areas and was unintentional. Active oil and gas wells within Lost Hills and the other major fields of the study along with approximate area boundaries for the emissions survey are shown highlighted in Figure 7 to Figure 9. In 2019 there were over 3900 new or active O&G wells within the Lost Hills fields (CalGEM 2019). Belridge was not measured in its entirety independently during the campaign but was measured indirectly in combination with Cymric-McKittrick.

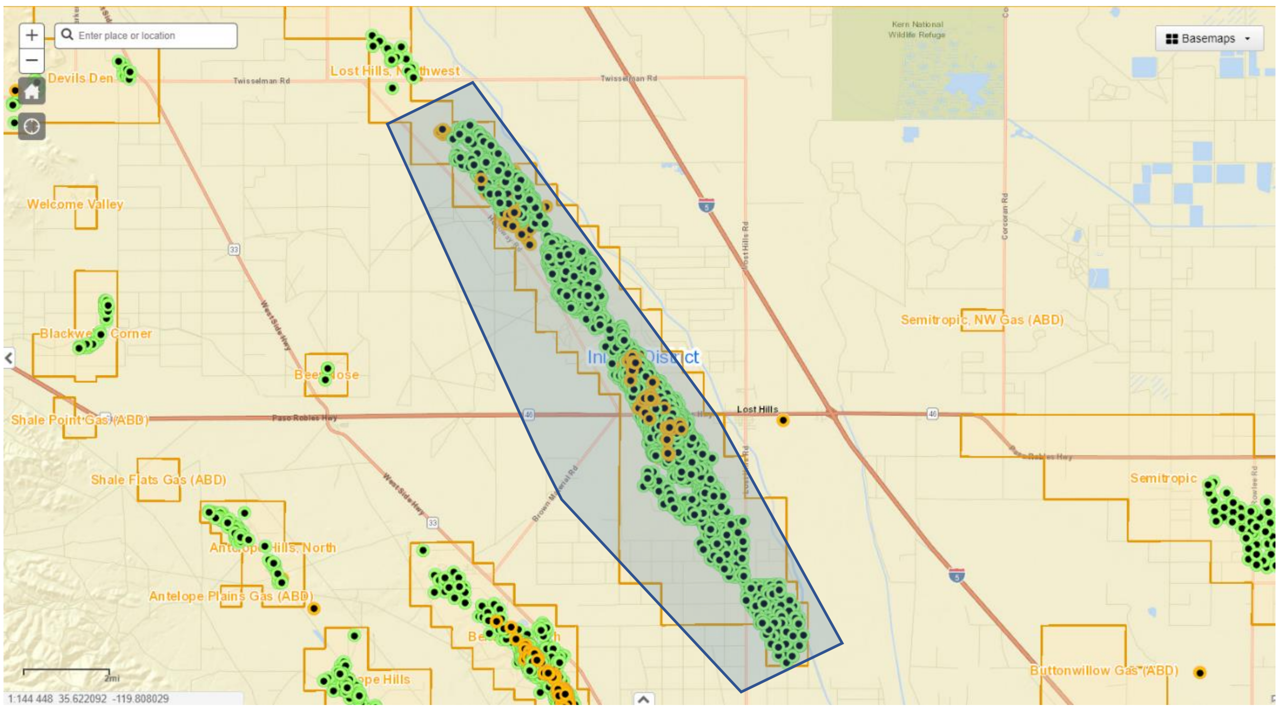

Figure 7. SOF measurement area for the Lost Hills region. Shaded box in dark grey defines the area included in the measurements. The figure also shows new (orange), active wells (green), fields (orange border) and annotations (CalGEM, 2019).

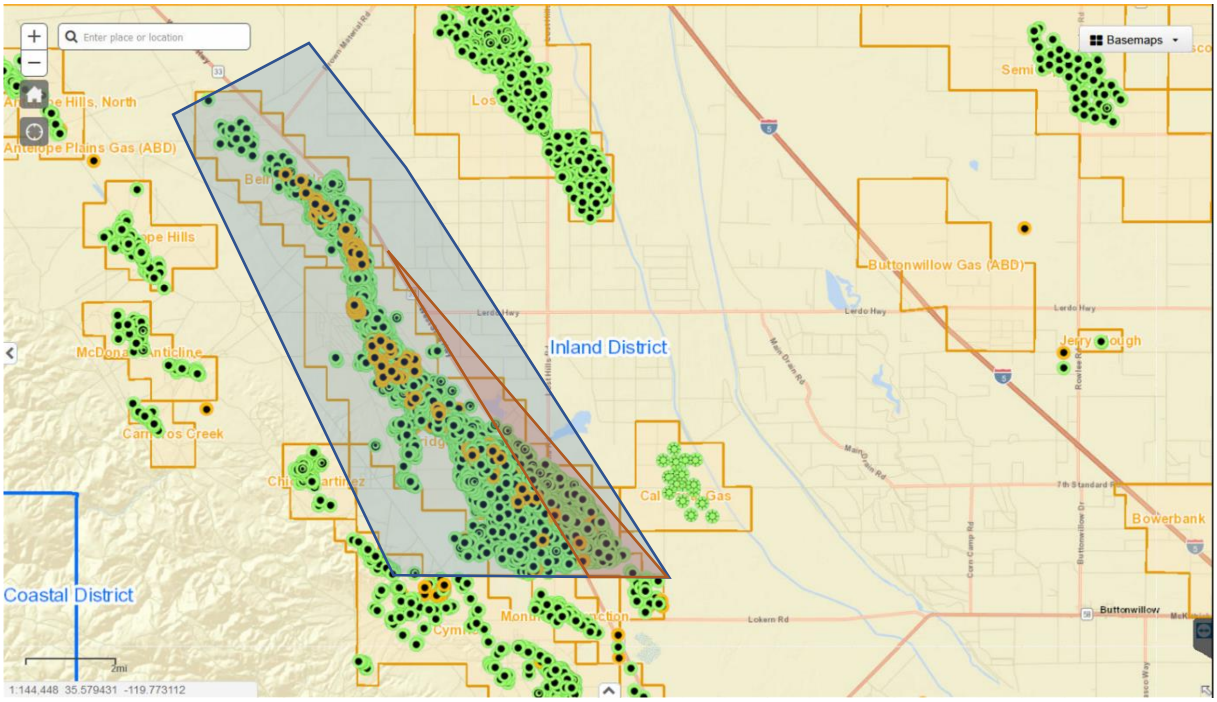

Figure 8. SOF measurement area for the Belridge North and South area. Shaded box in dark-grey defines the approximate area covered by the measurements. The figure also shows new (orange), active wells (green), fields (orange border) and annotations (CalGEM, 2019). Note that wells in Belridge southeast of Highway 33 (highlight in red triangle sector) have been included occasionally.

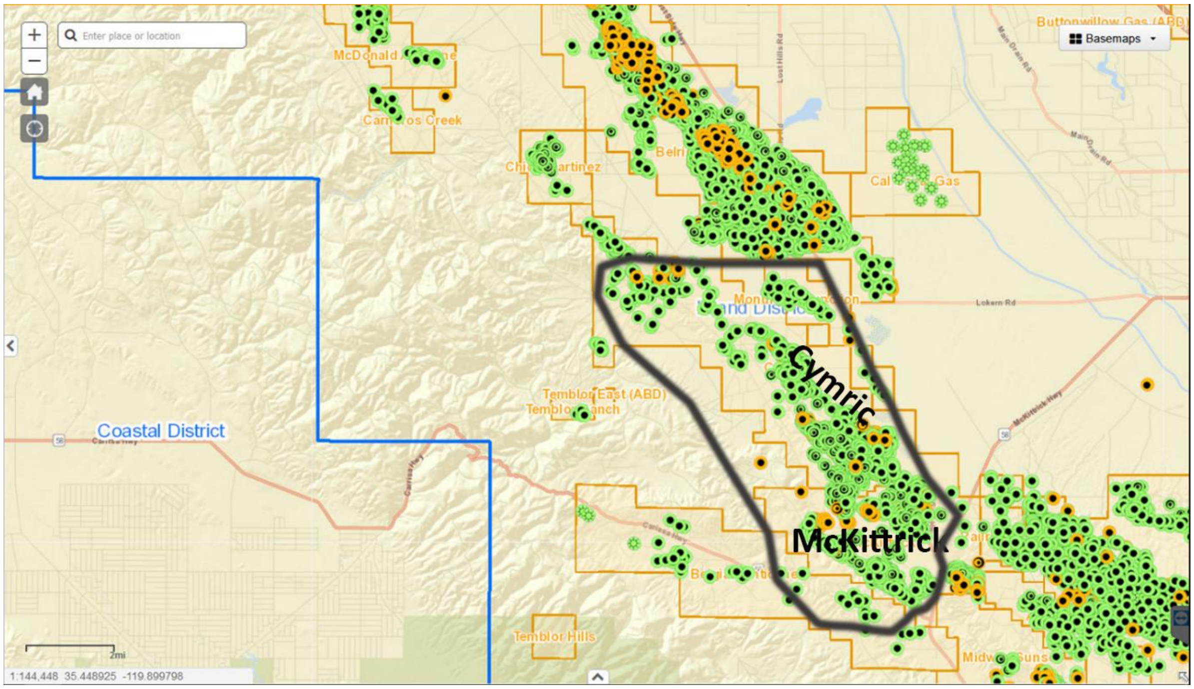

Figure 9. SOF measurement area for the Cymric & McKittrick fields . Shape in dark grey defining the approximate area covered by the measurements. The figure also shows new (orange), active wells (green), field (orange border) and annotations (CalGEM, 2019). The figure also shows new (orange) and active wells (green) (CalGEM, 2019). Note that some McKittrick wells/area east of Hwy 33 is excluded due to the layout of accessible roads.

Table 3 lists measurement days, measurement locations and LIDAR locations during the field survey.

Table 3. Measurements carried out during the campaign and positioning of wind LIDAR.

Date	Lidar Location	Emissions and Fenceline Concentration Measurements	Community Monitoring
30-Sep-2019	Wonderful Park (Lost Hills)	Lost Hills	
1-Oct-2019	Wonderful Park	Lost Hills	
2-Oct-2019	Operator A Lost Hills	Operator A Lost Hills	
3-Oct-2019	Operator A Lost Hills	Operator A Lost Hills	
4-Oct-2019	Operator A Lost Hills	Operator A Lost Hills	
5-Oct-2019	Operator A Lost Hills	Lost Hills	
6-Oct-2019	McKittrick N of Fire Station	Cymric, McKittrick, oil and gas produced water ponds (Ponds)	
7-Oct-2019	Operator A Lost Hills	Operator A Lost Hills	Lost Hills, evening
8-Oct-2019	Operator A Lost Hills	Operator A Lost Hills	
9-Oct-2019	Operator A Lost Hills	Operator B, Outside operator fenceline	Lost Hills, early morning Commercial Gas Leak
10-Oct-2019	Operator A Lost Hills	Operator B, Outside operator fenceline	
13-Oct-2019	McKittrick N of Fire Station	Cymric, McKittrick, Belridge, Ponds	McKittrick, Derby Acres
15-Oct-2019	Wonderful Park	Lost Hills	Lost Hills
16-Oct-2019	Taft Ponds	Taft, Midway-Sunset + Ponds	Taft
17-Oct-2019	McKittrick N of Fire Station		McKittrick, Derby Acres
18-Oct-2019	McKittrick N of Fire Station	Cymric, McKittrick, Belridge	Plume tracing in McKittrick, Derby Acres

2.5.2 Survey B – South Coast Air Basin, June-July 2021

Mobile measurements with SOF, SkyDOAS, MeDOAS, and MeFTIR were carried out during 15 measurements days in 2021 (June 15 - July 15) in the South Coast Air Basin, California. The focus of these measurements was methane and NMVOC emissions from oil and gas production as well as investigating the impact of various sources on communities within the vicinity. Table 4 lists measurement days, number of measurements and LIDAR locations during the field survey. Maps of the individual sites are shown in Figure 11 to Figure 13.

Table 4. Measurements carried out during the South Coast 2021 campaign and positioning of the wind LIDAR.

Date	Lidar Location	Emissions and Fenceline Concentration Measurements	Community Monitoring
19-June-2021	Obama Blvd & La Cienega Blvd	Inglewood Oilfield	
23-June-2021	Obama Blvd & La Cienega Blvd	Inglewood Oilfield, Jefferson, Murphy, Fourth Ave	
24-June-2021	Dalton Ave & W 27th St	Jefferson, St. James Lease, Murphy, Playa Del Rey	Las Cienegas
25-June-2021	Dalton Ave & W 27th St	Murphy, St. James Lease, Jefferson, Fourth Ave	Las Cienegas
26-June-2021	Obama Blvd & La Cienega Blvd, and Fordham Rd & W 80th St	Inglewood Oilfield	SNAPS Sentinel Peak 1, SNAPS Hillcrest Dr
28-June-2021	Obama Blvd & La Cienega Blvd	Inglewood Oilfield	SNAPS Sentinel Peak 1
29-June-2021	Obama Blvd & La Cienega Blvd, and Fordham Rd & W 80th St	Inglewood Oilfield	Playa Del Rey
30-June-2021	Obama Blvd & La Cienega Blvd	Inglewood Oilfield	
1-July-2021	Obama Blvd & La Cienega Blvd, and Fordham Rd & W 80th St	Inglewood Oilfield, Playa Del Rey	
2-July-2021	Dalton Ave & W 27th St	Jefferson, St. James Lease, Murphy	Las Cienegas
3-July-2021	Gateway Village & Newhall Ranch Rd	Honor Rancho	
5-July-2021	Obama Blvd & La Cienega Blvd	Inglewood Oilfield	
7-July-2021	Fordham Rd & W 80th St, and Obama Blvd & La Cienega Blvd, and Dalton Ave & W 30th St	Playa Del Rey, Inglewood Oilfield, Jefferson, St. James Lease, Murphy	Las Cienegas
8-July-2021	Dalton Ave & W 30th St	Las Cienegas	Las Cienegas

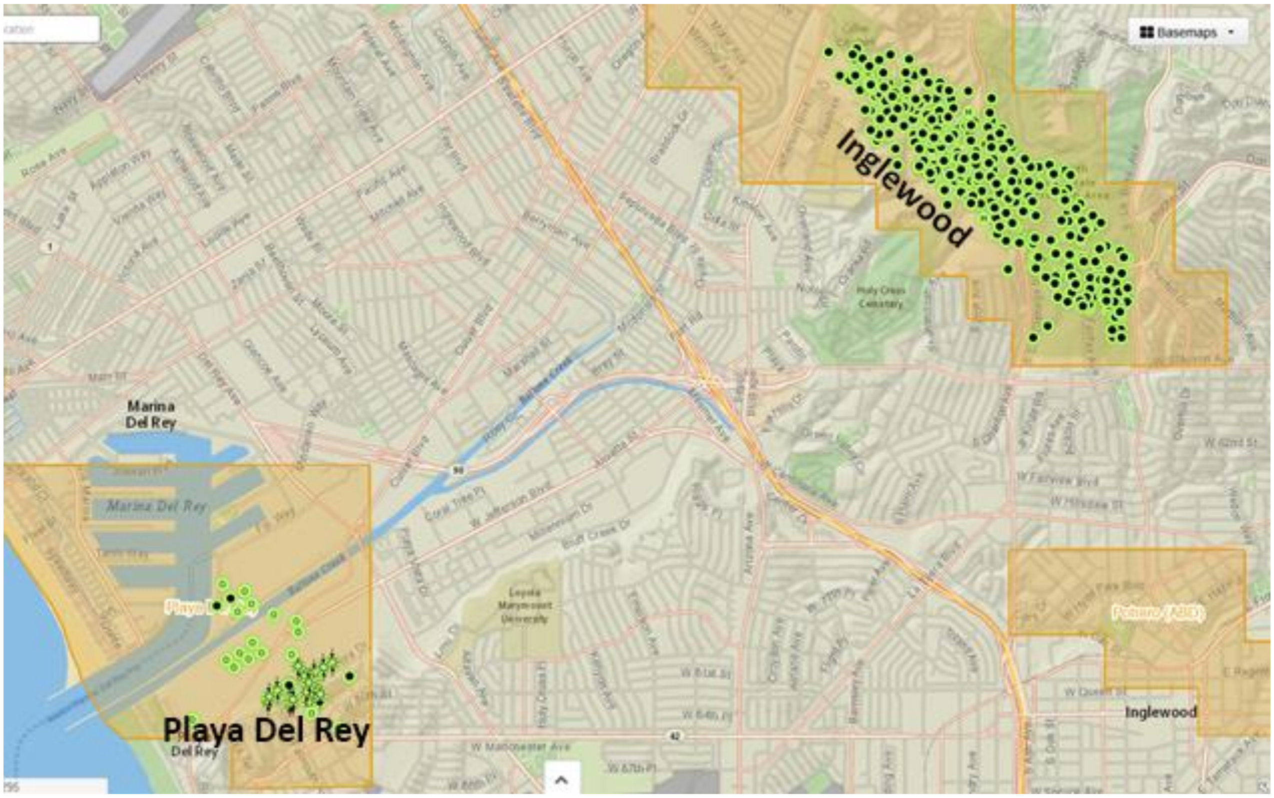

Figure 10. Overview of the Inglewood oilfield (upper right) and Playa Del Rey fields (left) , with active gas storage and oil and gas wells according DOC Cal Gem Well Finder, 2021.

Figure 11. Overview of the measurement areas at Playa Del Rey field (upper) and Inglewood oilfield (lower). Map from Google Earth™, 2021.

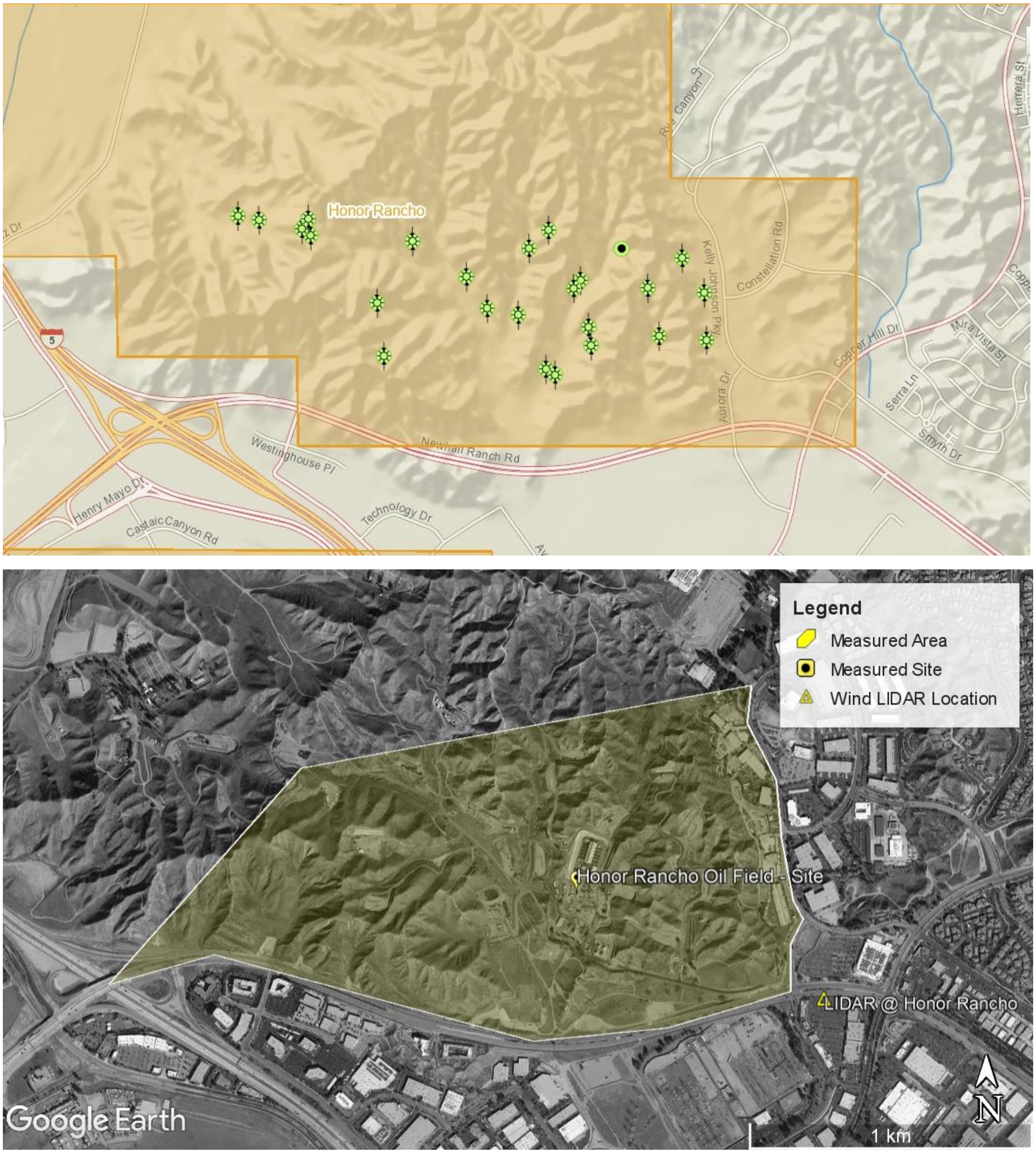

Figure 12. Overview of the Honor Rancho gas storage (upper), with active gas storage and oil and gas wells according DOC Cal Gem Well Finder, 2021. (Lower) Area as defined by emissions measurement. Lower map from Google Earth™, 2021.

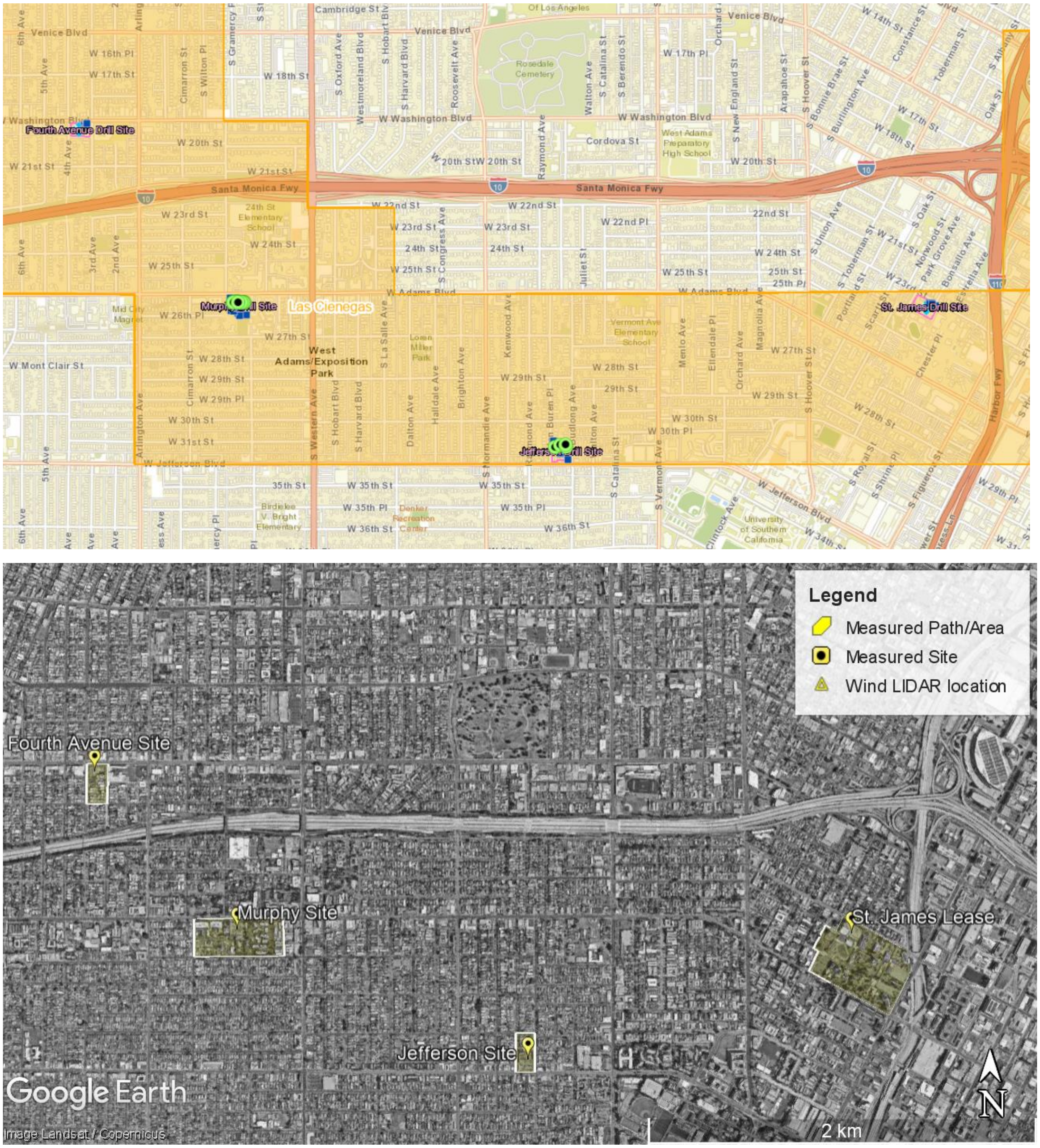

Figure 13. Overview of the Las Cienegas oilfield (upper), with active oil and gas wells and facilities according DOC Cal Gem Well Finder, 2021. (Lower) Area as defined by the emission measurements. Lower map from Google Earth™, 2021.

2.5.3 Survey C – San Joaquin Valley, September-October 2021

The second survey in San Joaquin Valley in this project, was conducted from 27 September to 21 October, 2021. The weather conditions were quite typical for the season with sunny weather and weak to moderate winds in general, with episodes of stronger winds during front passages. During the first couple of weeks forest fires were ongoing in the vicinity of the Sequoia national forest area. Impacts from it were intermittently seen as increased haze and background concentration variations. Table 5 lists measurement days, measurements and LIDAR locations during the field survey. Maps of the individual sites are shown in Figure 18 to Figure 23.

Table 5. Measurements carried out during the campaign and positioning of wind LIDAR.

Date	Lidar Location	Emissions and Fenceline Concentration Measurements	Community Monitoring
27-Sep-2021	McKittrick Park	McKittrick, Cymric, Elk Hills, Midway Sunset	
28-Sep-2021	McKittrick Park	McKittrick	
29-Sep-2021	McKittrick Park	McKittrick, Cymric	
30-Sep-2021	McKittrick Park	Elk Hills, Cymric, McKittrick, Buena Vista	
1-Oct-2021	Panama Rd, Lamont	Edison, Mountain View, Arvin	
2-Oct-2021	Petrol Rd, Bakersfield	Kern Front, Kern River, Poso Creek, Oil City Bakersfield	
4-Oct-2021	McKittrick Park	Cymric, McKittrick, Belridge, Midway Sunset	Taft
5-Oct-2021	Lost Hills	Lost Hills, Cymric, McKittrick, Belridge, Midway Sunset	
6-Oct-2021	Midway, Mocal Rd & C St	Elk Hills, Buena Vista, McKittrick	Derby Acres
7-Oct-2021	Lost Hills and Belridge (West Side Hwy & Lost Hills Rd)	Lost Hills, Cymric, McKittrick, Belridge, Buena Vista, Midway Sunset	
9-Oct-2021	Corregidora Ave	Edison, Mountain View, Lamont, Arvin	
10-Oct-2021	Lost Hills	Lost Hills, Belridge	
11-Oct-2021	McKittrick Park	Lost Hills, Cymric, McKittrick, Belridge	
12-Oct-2021	Kern Oil and Corregidora Ave	Mountain View, Edison, Arvin	
13-Oct-2021	Brundage Ln & Oswell St	Mountain View, Edison, Kern River, Oil City Bakersfield	
14-Oct-2021	Midway Rd & Taft Hwy, and Corregidora Ave.	Elk Hills, Coles Levee N, Buena Vista, Cymric, McKittrick, Oil City	
15-Oct-2021	Manor St	Edison, Mountain View, Kern Front, Kern River	
16-Oct-2021	Manor St	Kern River, Kern Front, Oildale	
17-Oct-2021	Midway Rd & Taft Hwy	Lost Hills, Buena Vista, Elk Hills, Coles Levee N, Midway Sunset	Lost Hills
18-Oct-2021	Arvin (N Walnut St)	Arvin, Mountain View	Arvin
19-Oct-2021	Kern Oil	Arvin, Mountain View, Lamont	
20-Oct-2021	Brundage Ln & Oswell St	Edison, Mountain View, Kern Front, Kern River, Oildale	
21-Oct-2021	Brundage Ln & Oswell St, and Lost Hills	Edison, Mountain View, Lost Hills, McKittrick	Derby Acres, Lost Hills, McKittrick

Figure 14. Additional measured sites in the SJV survey C during September-October 2021 – Lost Hills. Map from Google Earth™, 2021.

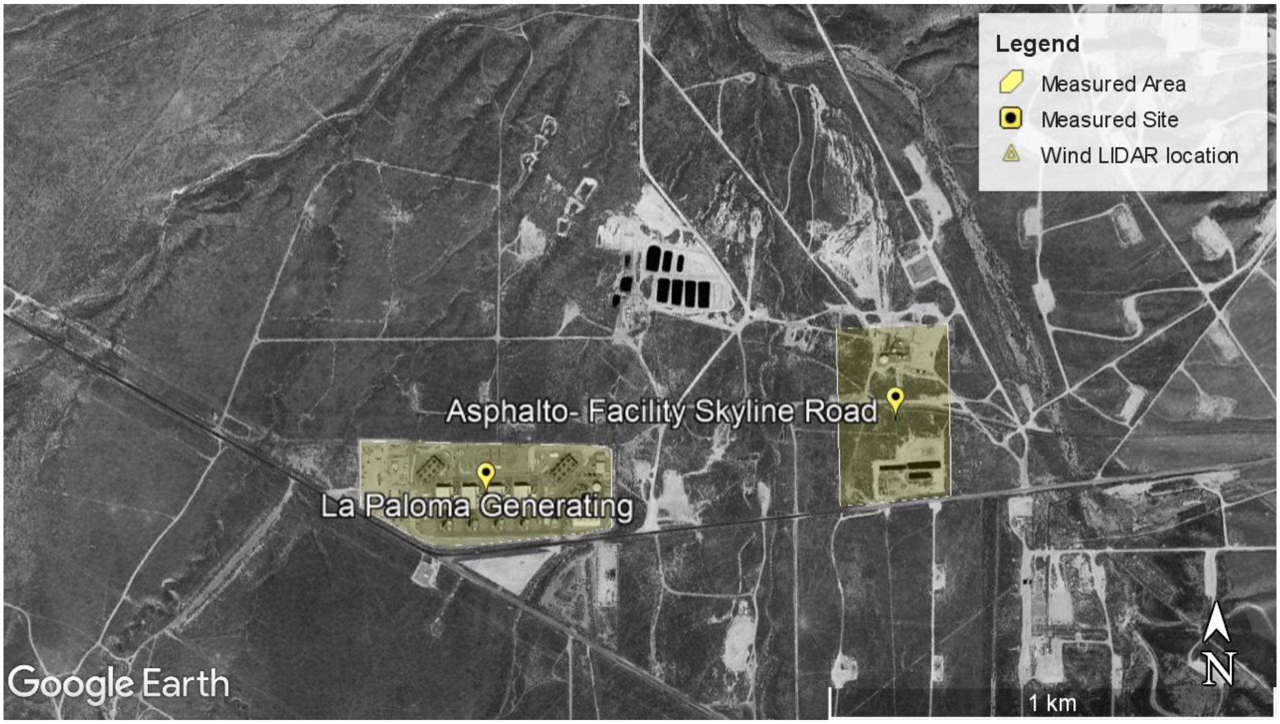

Figure 15. Additional measured sites in the SJV survey C during September-October 2021 – Asphalto/McKittrick. Map from Google Earth™, 2021.

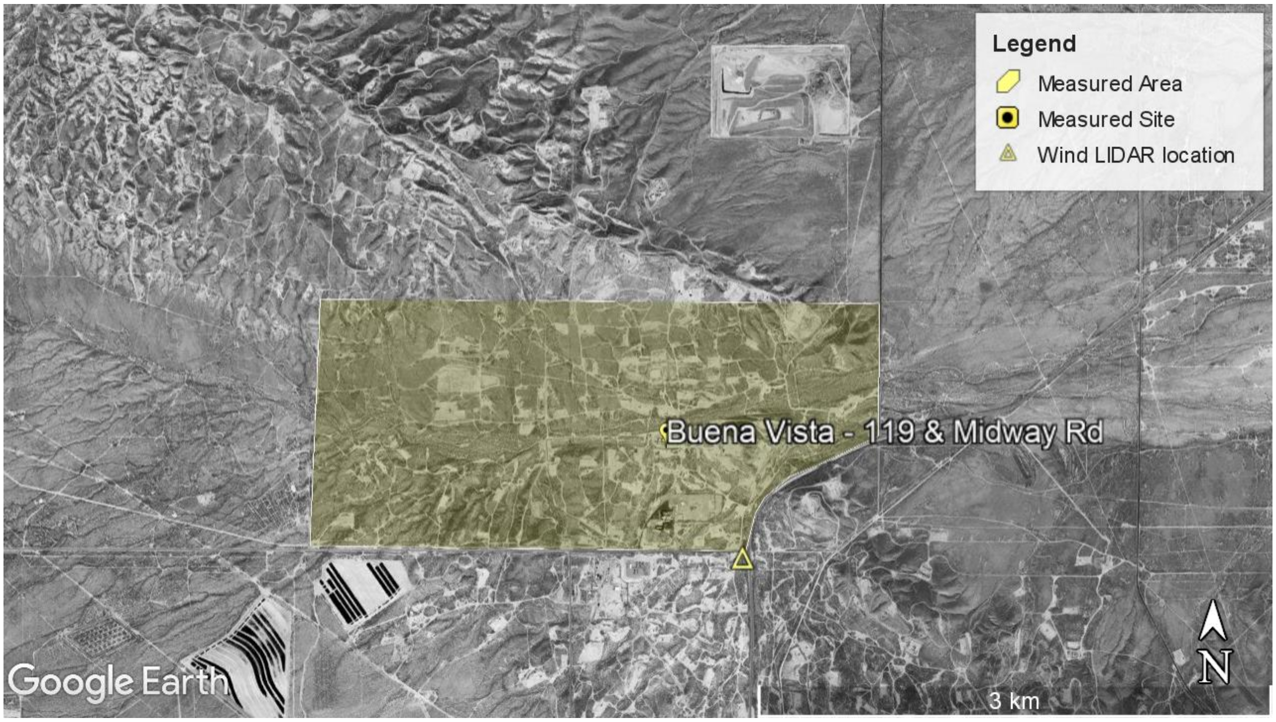

Figure 16. Additional measured sites in the SJV survey C during September-October 2021 – Buena Vista. Map from Google Earth™, 2021.

Figure 17. Additional measured sites in the SJV survey C during September-October 2021 – Kern Oil, Mountain View. Map from Google Earth™, 2021.

Figure 18. Additional measured sites in the SJV survey C during September-October 2021 -- Arvin, Mountain View. Map from Google Earth™, 2021.

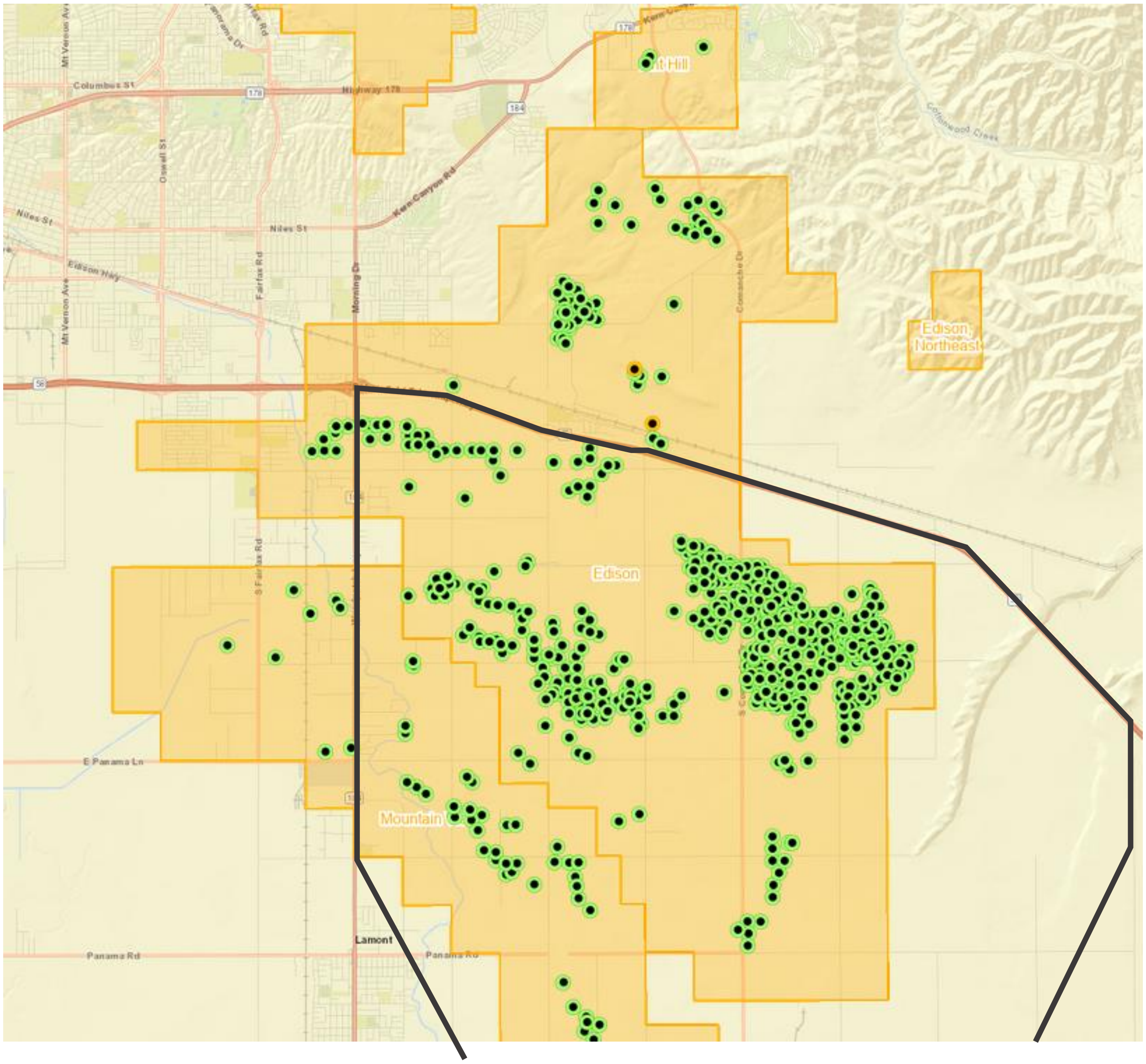

Figure 19. Overview of the Edison and northern portion of Mountain View oil fields southeast of Bakersfield , with new (orange) and active (green) oil and gas wells according DOC Cal Gem Well Finder, 2022. Approximate boundary for emissions measurements shown with dark gray border and continues south covering Mountain View. See also Figure 20.

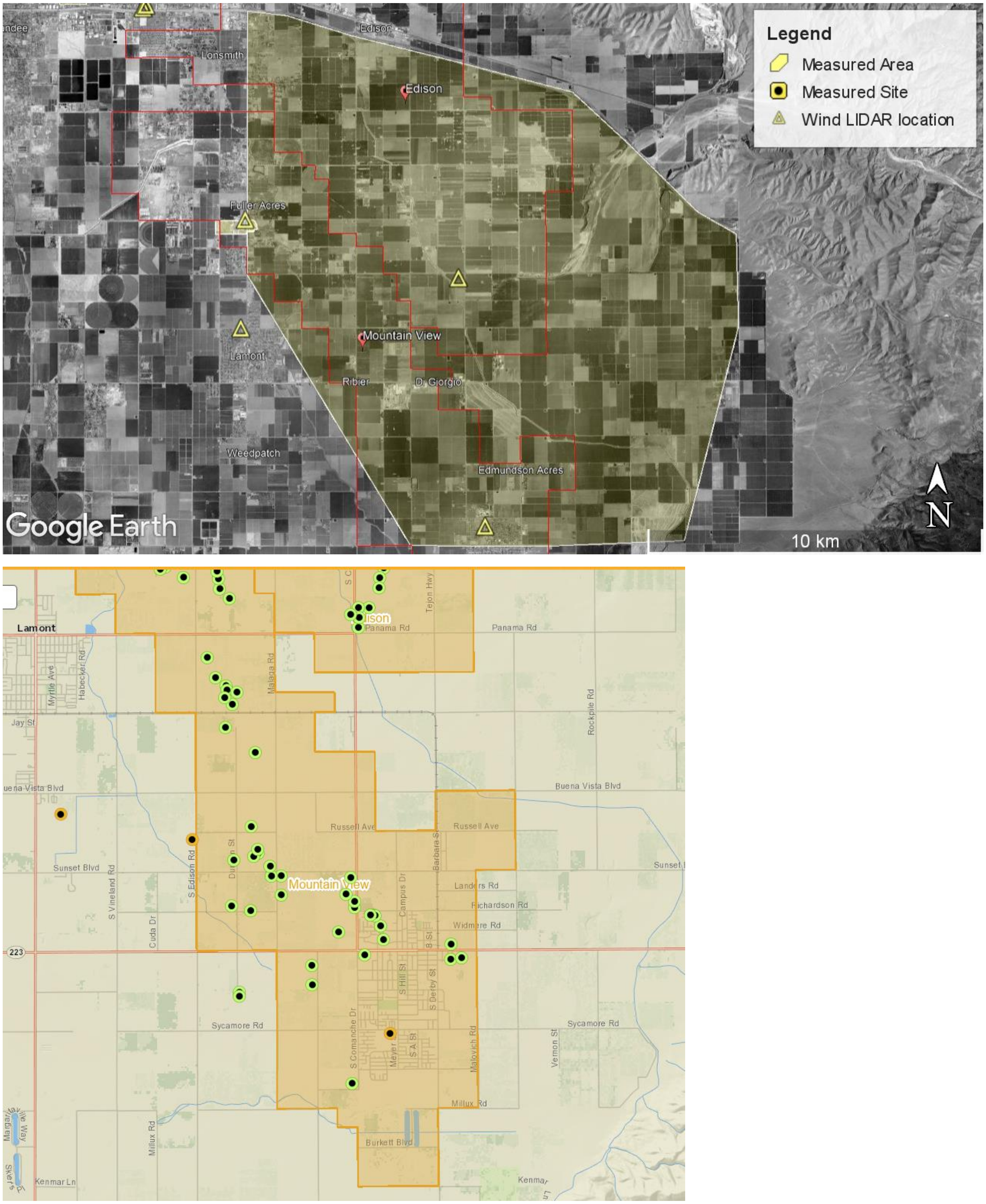

Figure 20. Emissions measurement area for Edison-Mountain View (Upper image, field boundaries in red), Map from Google Earth™. (Lower) Overview of the southern portion of Mountain View oil fields southeast of Bakersfield , with new (orange) and active (green) oil and gas wells according DOC Cal Gem Well Finder, 2021.

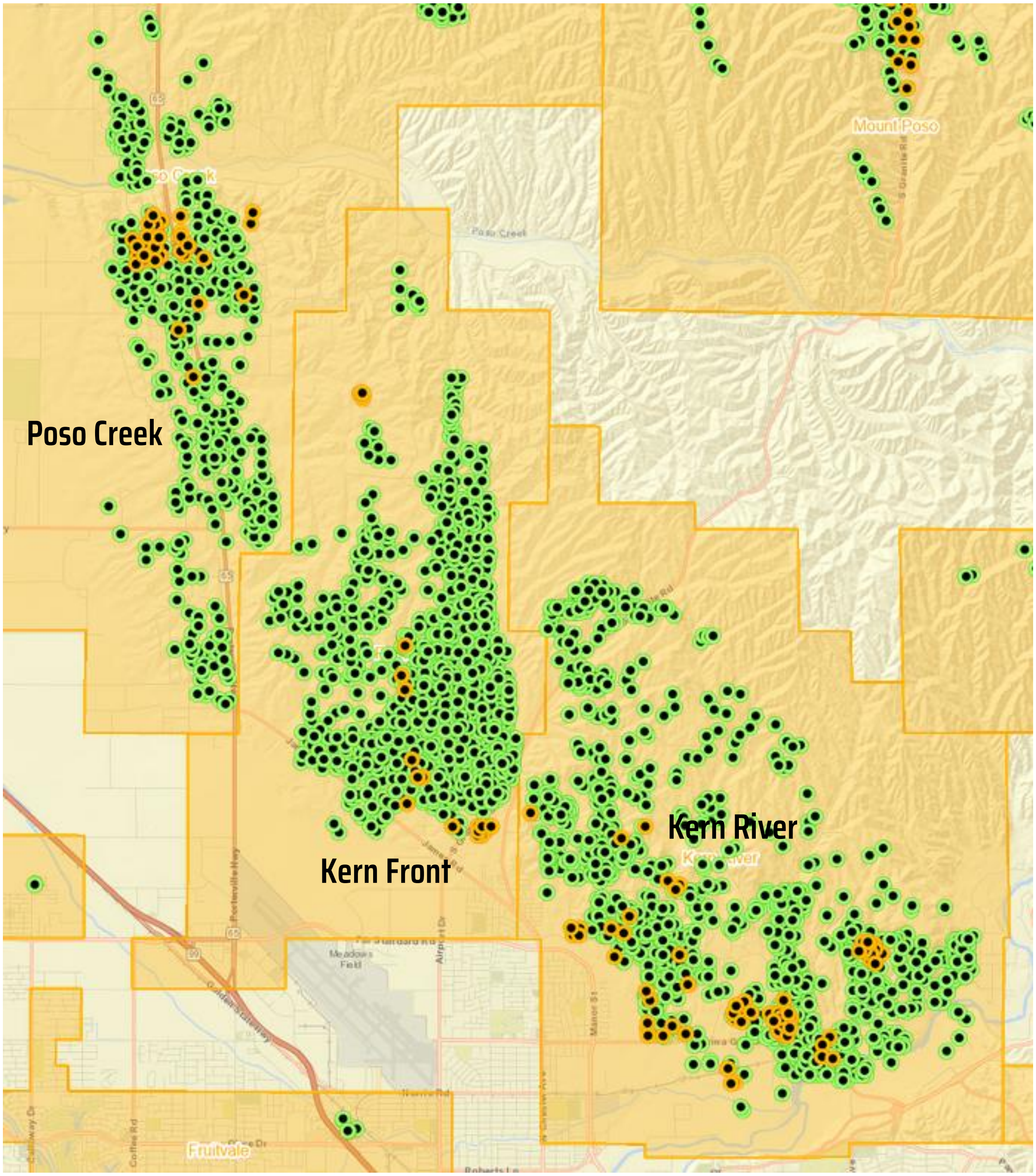

Figure 21. Overview of the Kern Front, Kern River and Poso Creek oil fields north of Bakersfield , with new (orange) and active (green) oil and gas wells according DOC Cal Gem Well Finder, 2022.

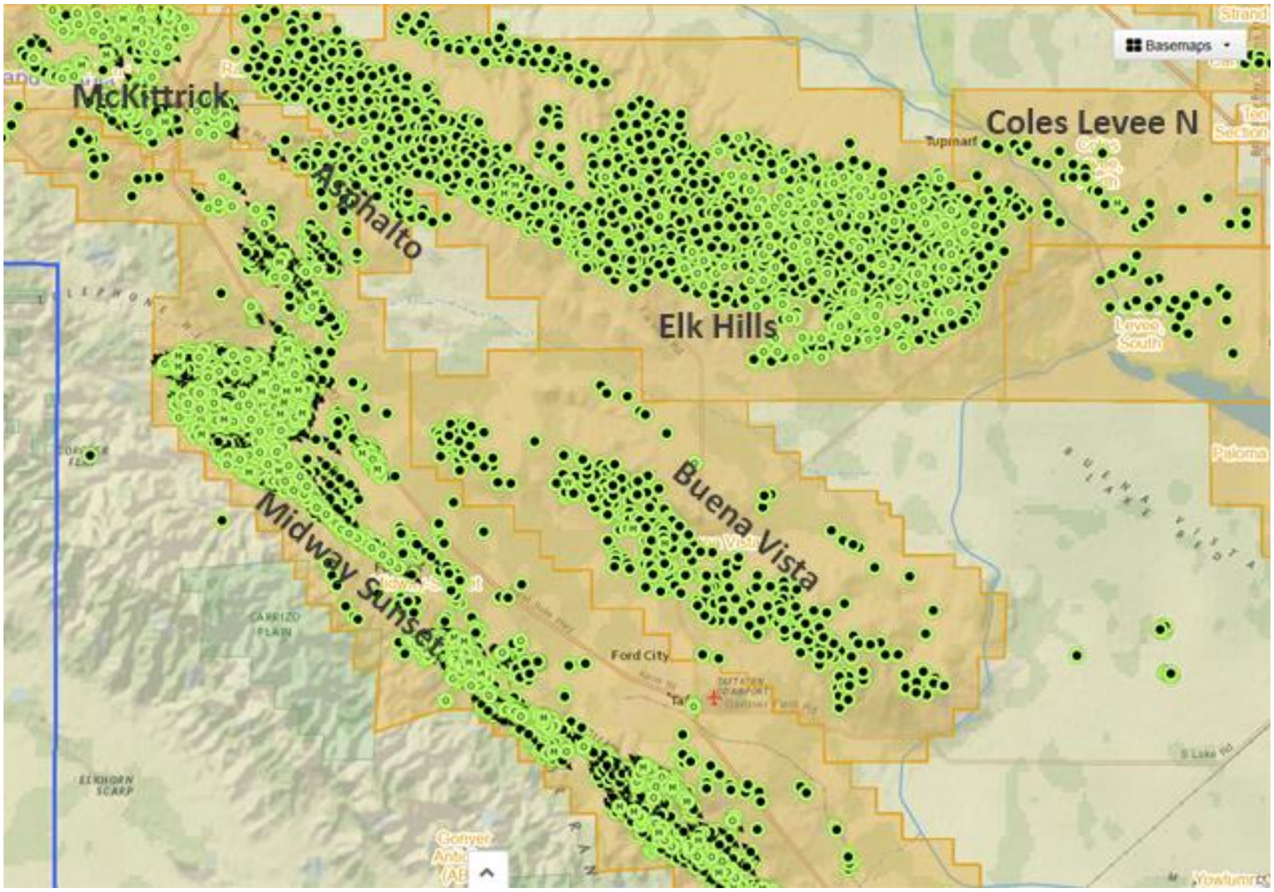

Figure 22. Overview of the Elk Hills, Buena Vista, Midway Sunset, Coles Levee, McKittrick and Asphalto fields with active oil and gas wells. Markers with arrows are cyclic steam. DOC Cal Gem Well Finder, 2021.

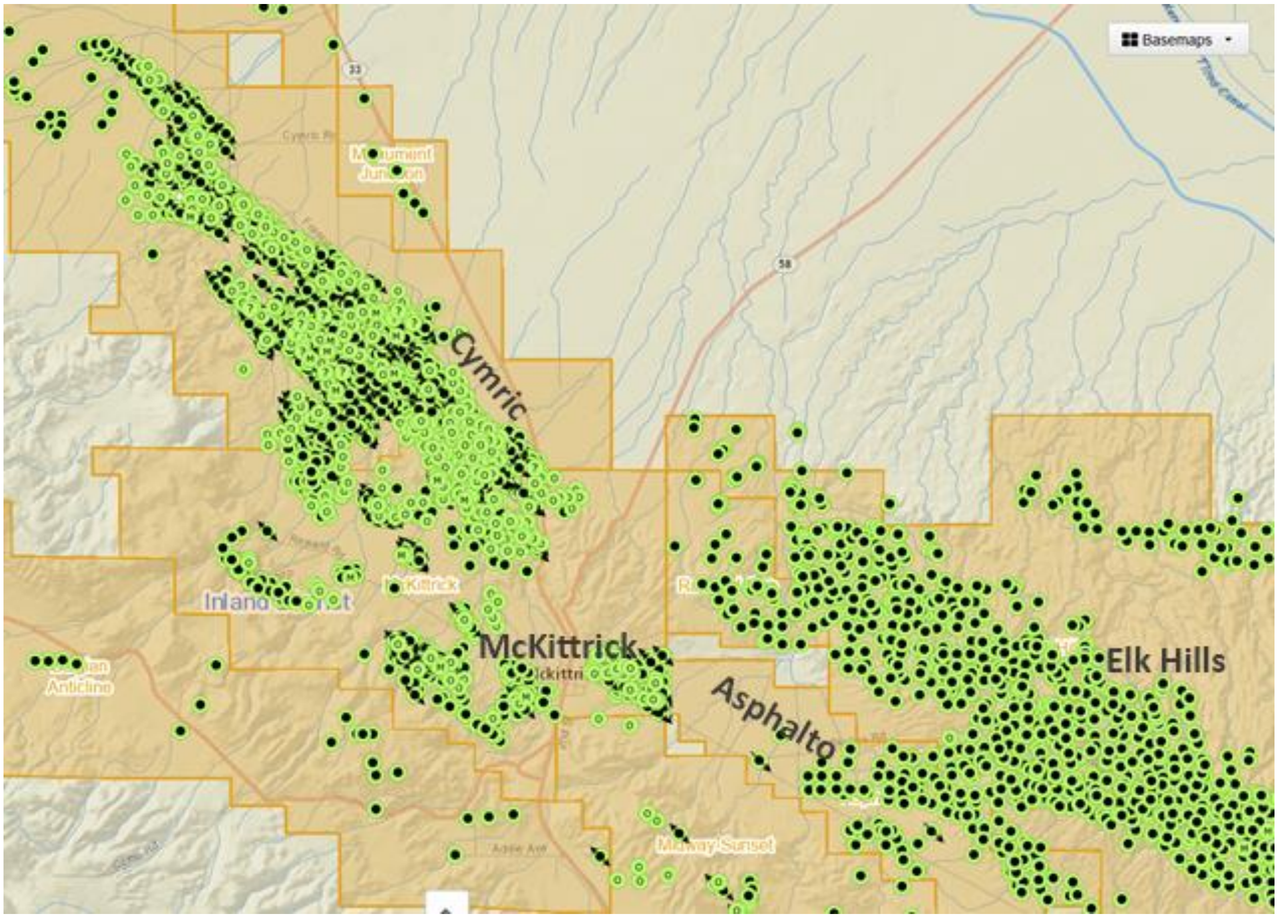

Figure 23. Overview of the Elk Hills, Asphalto, McKittrick and Cymric fields with active oil and gas wells according DOC Cal Gem Well Finder, 2021.

2.6 Plume Dispersion Modeling

In order to investigate the spreading of emitted gases in surrounding communities, a plume dispersion model was applied to a few cases in the San Joaquin Valley. The dispersion model is based on the Weather Research and Forecasting (WRF) model (Skamarock, 2019, 2021) with some source code modification to allow emission and tracking of inert tracer gases. Initialization and boundary conditions for WRF were taken from the High-Resolution Rapid Refresh (HRRR) model (Benjamin, 2016), for which a data archive from University of Utah was used (Blaylock, 2017a). WRF has an accompanying Chemical Transport Model, WRF-CHEM (Grell., 2005), but using WRF-CHEM would slow down simulations considerably for no clear benefit, since only short-range transport is of interest, for which little chemistry is expected. Instead, passive inert tracers were introduced in the basic WRF model as previously applied in (Blaylock, 2017a) and (Bhimireddy, 2018). The WRF source code modifications needed for this are detailed in (https://home.chpc.utah.edu/~u0553130/Brian_Blaylock/tracer.html). Small additional source code modifications were applied to ensure constant rate emissions.

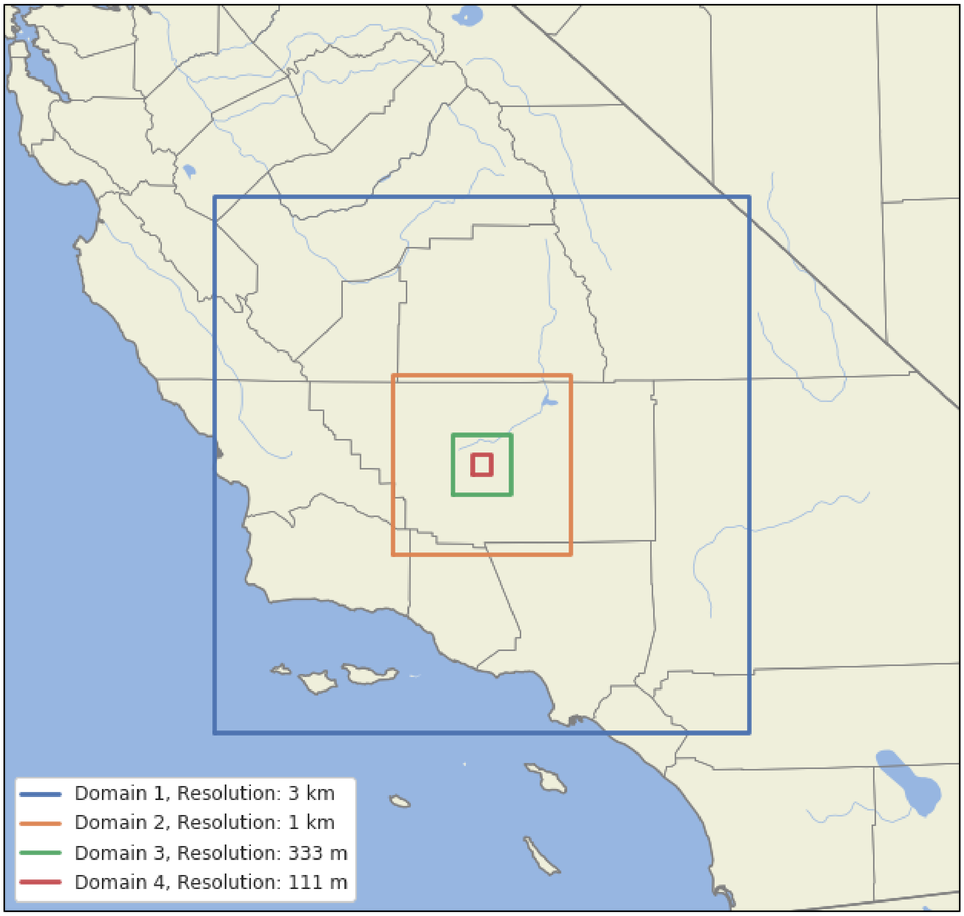

Figure 24 Map showing extent of nested domains for the plume dispersion simulations for the Kern Oil emissions sources.

The model was set up with 4 nested domains, each with 3 times higher resolution than its parent, all centered around the location of the emission sources of interest. All four domains consisted of 40 vertical layers with 120x120 cells in each. An example of the domain structure for the simulations for the Kern Oil sources is shown in Figure 24. Emissions were released for a number of sources in Domain 4 according to where emissions had been observed in SOF measurements. For each source, 1 kg/h was emitted in the model, and the resulting model concentrations were later rescaled according to the actual emissions measured with SOF. Concentrations scale linearly with the magnitude of the emission rates since there is no chemistry in the model. The model was run for 3-5 days for each simulation, covering a period when measurements were performed in the area.

3 RESULTS

The results of the project are presented in separate sections for emission measurements, pollutant dispersion measurements, concentration mapping in support of community monitoring and pollutant dispersion modeling. Emissions measurements that were more observational in nature i.e. too few measurements to satisfy statistical criteria, but pertinent to the goals and implementation of this study, are included in a separate section. Emission results are presented according to the geographical areas SJV and South Coast and source types (oil and gas fields; oil and gas treatment facilities and refineries).

3.1 Emissions - oil and gas fields

Oil and gas fields and associated in-field facilities are the dominant emission sources for alkanes within the survey. In the San Joaquin Valley most of the major fields in Kern County were measured, and within the South Coast Air Basin, measurements were made in one field in Los Angeles County. A summary of results is presented for fields with sufficient measurements (at least 4 valid SOF transects, see CEN 2021) in Table 6 and Table 7 and Figure 25. Complete results of emission measurements are presented in each site-specific section.

Table 6. Summary of SOF alkane results from the 2019 and 2021 measurement surveys for Oil & Gas fields . D=number of measurement days. N=number of measurements. SD = 1 σ standard deviation. CI = confidence interval. Note: only oil fields with sufficient statistics (>3 valid measurements) are presented here.

		Counts		Emission	Emission	Emission
Region	**Oil & Gas field, survey year**	**D**	**N**	**Average [kg/h]**	**SD [kg/h]**	**CI-95% [kg/h]**
SJV	Lost Hills, 2019	2	5	522	69	86
	Lost Hills 2021	3	7	452	131	121
	Cymric & McKittrick, 2019	3	10	1377	373	267
	Cymric & McKittrick, 2021	4	9	1209	438	336
	Cymric & McKittrick & Belridge, 2019	2	7	2968	873	807
	Cymric 2021	2	4	841	238	378
	McKittrick, 2021	2	4	242	127	203
	Elk Hills, 2021	4	11	2246	865	581
	Coles Levee - North, 2021	2	7	226	79	73
	Kern Front, 2021	3	7	143	34	32
	Kern River, 2021	2	7	243	70	65
	Kern Front & Kern River, 2021	3	5	385	102	126
	Edison & Mountain View, 2021	4	6	112	32	33
South Coast	Inglewood, 2021	3	7	101	21	19

Table 7. Summary of BTEX, benzene and methane emission results from the 2019 and 2021 measurement surveys for Oil & Gas fields . N=number of measurements. Mass fractions correspond to the median of the observations. BDL = concentration of target species Below Detection Limit for valid Alkane plume from the same source. *Aggregated methane ratio from Lost Hills - North and – South regions. • Ratios from Kern River. ǂ Ethylbenzene concentrations had a higher uncertainty and were excluded from BTEX sum (for Inglewood). Note: only oil fields with sufficient statistics (>3 valid SOF measurements) are presented here. NM – not measured. Note that individual field measurements and combined field measurements may differ in time and number of measurements and therefore may not add up entirely.

Region	Oil & Gas field, survey year	Alkanes (SOF)			BTEX/ Alkane	BTEX	Benzene /Alkane	Benzene		CH_4/ Alkane	CH_4
		N	[kg/h]	N	[%]	[kg/h]	[%]	[kg/h]	N	[%]	[kg/h]
SJV	Lost Hills, 2019	5	522		BDL	BDL	BDL	BDL	11	43*	224
	Lost Hills, 2021	7	452	3	5.0	23	1.5	6.7	5	100	453
	Cymric & McKittrick, 2019	10	1377		BDL	BDL	BDL	BDL	10	177	2433
	Cymric & McKittrick, 2021	9	1209		BDL	BDL	BDL	BDL	7	181	2184
	Cymric & McKittrick & Belridge, 2019	7	2968		NM	NM	NM	NM		NM	NM
	Cymric Field, 2021	4	841		BDL	BDL	BDL	BDL	12	97	819
	McKittrick, 2021	4	242		BDL	BDL	BDL	BDL	2	722	1749
	Elk Hills, 2021	11	2246		BDL	BDL	BDL	BDL	12	197	4432
	Coles Levee - North, 2021	7	226		BDL	BDL	BDL	BDL	5	43	98
	Kern Front, 2021	7	143		BDL	BDL	BDL	BDL	8	350	501
	Kern River, 2021	7	243	9	4.7	11	0.6	1.5	13	294	714
	Kern Front & Kern River, 2021	5	385	9	4.7•	18	0.6•	2.4	13	294	1133
	Edison & Mountain View, 2021	6	112		BDL	BDL	BDL	BDL	2	93	104
South Coast	Inglewood, 2021	7	101	14	16.1ǂ	16.2	7.7	7.7	8	121	121

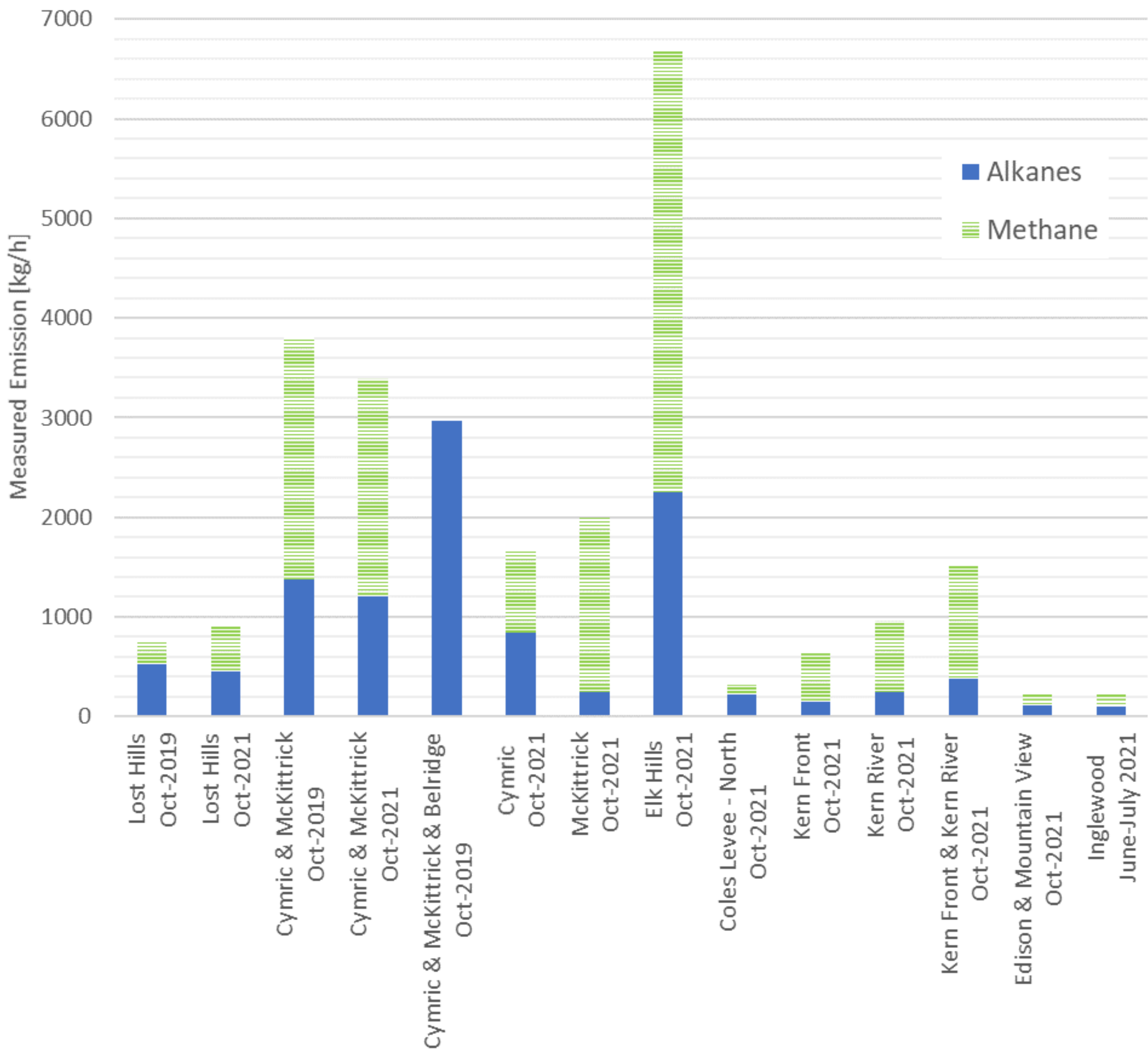

Figure 25. Summary of measured emissions of alkane and methane from Oil & Gas fields . All fields are located in San Joaquin Valley except for Inglewood which belong to the South Coast region. Note: only oil fields with sufficient statistics (>3 valid measurements) are presented here.

3.1.1 Lost Hills

The Lost Hills oil and gas field was the main target for the project survey in September-October 2019, with both in-field emission measurements and concentration mapping (section 0 and 3.2.1), fenceline emission quantification (this section), plume tracing with distance from the field (section 3.5.1) and concentration mapping in the nearby Lost Hills town (3.6.1.1). Application of a site-specific dispersion model was applied, centered to the location of one of the largest emission source areas identified within the Lost Hills field (section 3.7.2).

The Lost Hills field was revisited in the October 2021 survey for follow-up measurements of the total and part field emissions and concentration mapping in the Lost Hills town. An alkane emission measurement of the Lost Hills north oil field from 10 October 2021 at noon is seen in Figure 26, and a measurement from the Lost Hills south field from 17 October 2021 at 10:25 is shown in Figure 27.

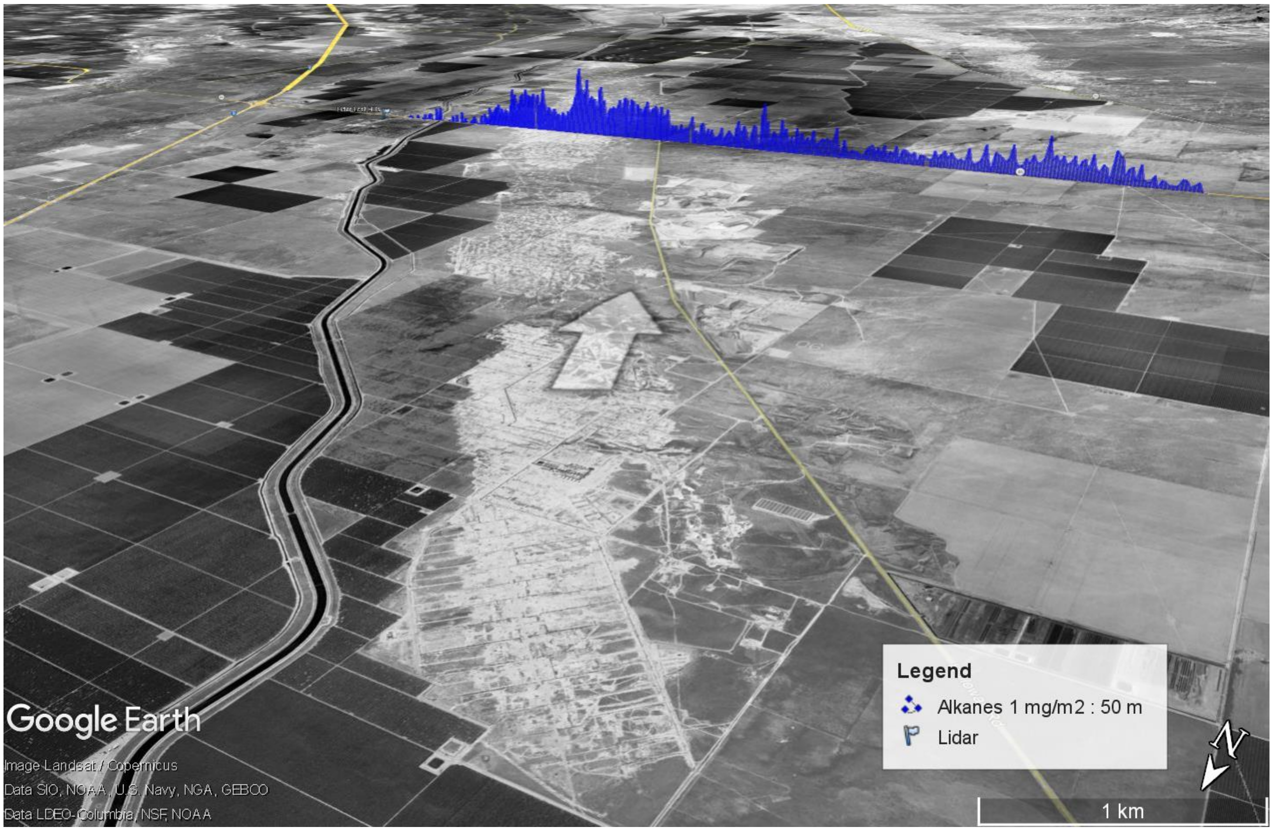

Figure 26. Alkane emission measurement of the north portion of the Lost Hills oil field 10 October 2021 , 12:50. The height of the blue contour corresponds to the measured column of alkanes where 50 m equals 1 mg/m^2. The white arrow indicates the average wind direction during the measurement. Map from Google Earth™, 2021.

The October 2021 measurements yielded total alkane emissions of 452 kg/h (95% CI 330-573 kg/h) as summarized in Table 9. The methane to alkane mass concentration ratio obtained from measurements in the overall Lost Hills emission plume was 100% for the 2021 survey (Table 11) which, when combined with the measured alkane emissions, results in a methane emission estimate of 453 kg/h.

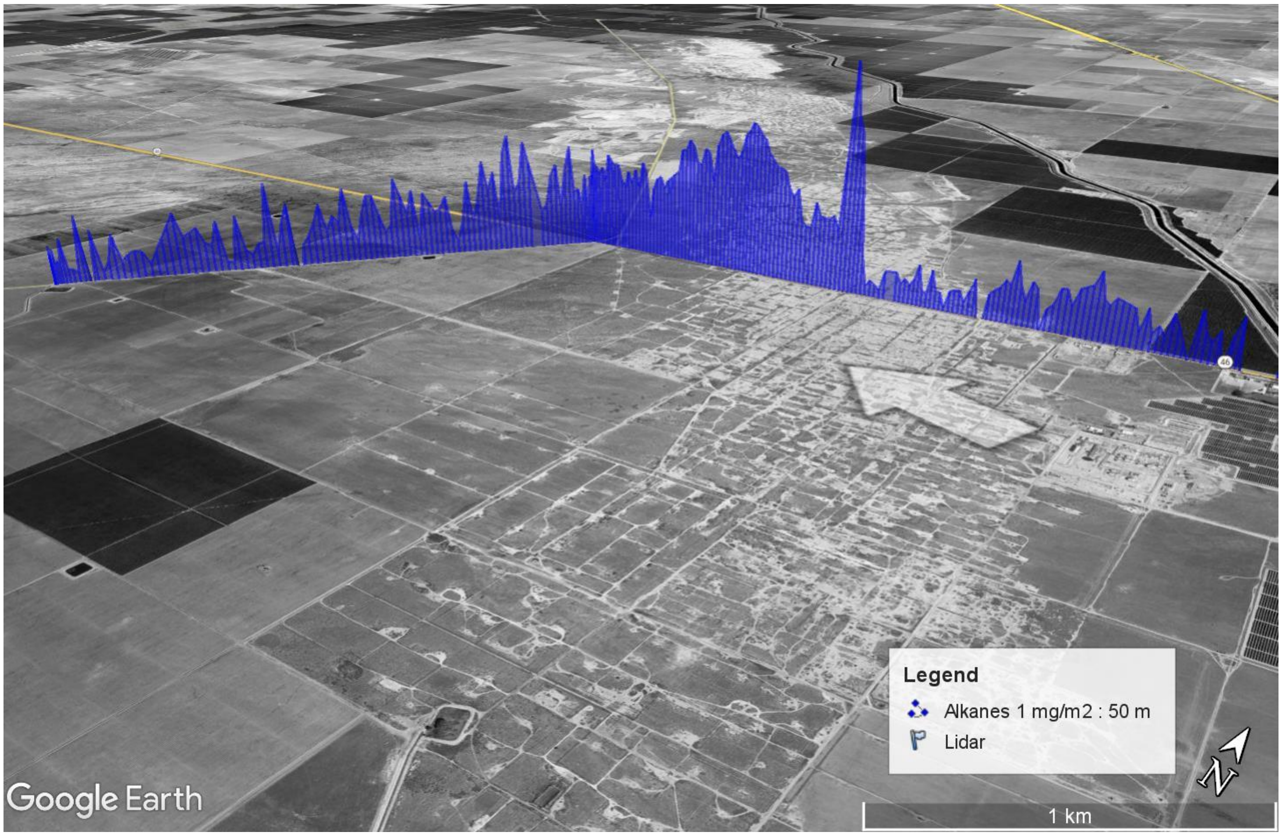

Figure 27. Alkane emission measurement of the Lost Hills south oil field 17 October 2021 , 10:25. The height of the blue contour corresponds to the measured column of alkanes where 50 m equals 1 mg/m^2. The white arrow indicates the average wind direction during the measurement. Map from Google Earth™, 2021.

In the 2019 survey, five measurements on two days during first half of October showed alkane emissions of 522 kg/h (95% CI 435-608 kg/h) (Table 10). More measurements were done separately on the north and south sections of the Lost Hill fields than for the aggregate field in 2019, and methane emissions were thus obtained from adding the north and south contributions to an overall emission of 224 kg/h (Table 7).

BTEX and benzene fenceline plume concentration measurements were near or below detection limit for measurements both in the 2019 and 2021 measurements. Table 12 and Table 13 show October 2021 results indicative of BTEX and benzene mass fractions of around 5% and 1.5% respectively. This would imply emissions at the order of 23 kg/h BTEX and 6.7 kg/h benzene.

In terms of active oil and gas wells in the Lost Hills field, the CalGEM database reports about 3930 active wells in October 2019 and 2410 active wells in October 2021. When comparing emissions to these numbers, it should be noted that that there could also be emissions from new, idle or plugged wells not included in the active well number, as well as significant contribution from other processing/storage sites and facilities. Still, normalizing observed emissions to the reported number of active wells, would give a number of 0.13 kg/h/well head and 0.19 kg/h/well head for the production in October 2019 and October 2021, respectively.

Specific measurements of the north and south part of the Lost Hills oil field, (Lost Hills – North and Lost Hills – South) are presented in the two subsections below. A summary of alkane and methane emissions from the two parts compared to the aggregate Lost Hills field measurements are presented in Table 8.

The average emission of alkanes from the north part was 178 kg/h in 2021 (Table 14) and 210 kg/h in 2019 (Table 15). The corresponding emissions from the south part was 201 kg/h in 2021 (Table 20) and 214 kg/h in 2019 (Table 21). Measured methane, benzene and BTEX ratios are found in Table 16 to Table 19 and Table 22 to Table 24, respectively.

Table 8. Summary of measured alkane and methane emissions from the Lost Hills oil field, 2019 and 2021. Measurements of individual parts (bottom-up approach) are compared to total measurements where both are measured simultaneously (top-down approach).

	Alkanes					CH_4		
Lost Hills Oil & Gas field, survey year	Counts D	Counts N	Emission Average [kg/h]	Emission SD [kg/h]	Emission CI-95% [kg/h]	Counts N	Ratio %	Emission [kg/h]
Lost Hills North, 2019	*3*	*14*	*210*	*85*	*49*	*6*	*29*	*61*
Lost Hills South, 2019	*3*	*3*	*214*	*NA*	*NA*	*6*	*76*	*163*
Sum (bottom-up)	3	14	424	NA	NA	NA	NA	224
Lost Hills (top-down), 2019	**2**	**5**	**522**	**69**	**86**	**1**	**47**	**244**
Lost Hills North, 2021	*2*	*13*	*178*	*93*	*56*	*12*	*123*	*220*
Lost Hills South, 2021	*2*	*4*	*201*	*71*	*112*	*6*	*134*	*270*
Sum (bottom-up)	2	17	379	65	126	NA	NA	489
Lost Hills (top-down) 2021	**3**	**7**	**452**	**131**	**121**	**5**	**100**	**453**

Table 9. Measurements of alkane emissions from the Lost Hills oil and gas field, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211005	*132004-144454*	*2*	*600*	N/A	*3.7-4.1*	*293-300*
211010	*151209-162446*	*2*	*417*	N/A	*2.7-3.4*	*0-333*
211011	*111154-135959*	*3*	*375*	N/A	*4.4-9.8*	*319-334*
Total # of Meas.		**7**				
Median			**492.4**			
IQR			**330.4 - 552.7**			
Mean			**451.7**			
SD			**130.9**			
CI 95%			**330.6 - 572.8**			

Table 10. Measurements of Alkane emissions from Lost Hills oil field, October 2019.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
191001	*151839-155657*	*1*	*446*	N/A	*2.8-2.8*	*350-350*
191015	121110-165351	4	540	439.6 - 641.4	1.6-2.5	2-360
Total # of Meas.		**5**				
Median			**503.8**			
IQR			**478.3 - 558.5**			
Mean			**521.5**			
SD			**69.3**			
CI 95%			**435.5 - 607.6**			

Table 11. Measurements of CH_4/alkane ratios for Lost Hills oil field, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211010	*111055-171418*	*3*	*94.8*	*1.5-3.4*	*3-356*
211017	*110350-110839*	*1*	*102*	*2.1-2.1*	*136-136*
211021	*142807-144425*	*1*	*152*	*1.7-1.7*	*83-83*
Total # of Meas.		**5**			
Median			**100.3**		
IQR			**96.0 - 102.0**		

Table 12. Measurements of BTEX/alkane ratios for Lost Hills oil field, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211010	*150640-171418*	*2*	*4.7*	*2.4-2.8*	*2-356*
211021	*142807-144425*	*1*	*5.0*	*1.6-1.6*	*58-58*
Total # of Meas.		**3**			
Median			**5.0**		
IQR			**4.6 - 5.1**		

Table 13. Measurements of benzene/alkane ratios for Lost Hills, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211010	*150640-171418*	*2*	*1.6*	*2.4-2.8*	*2-356*
211021	*142807-144425*	*1*	*1.0*	*1.6-1.6*	*58-58*
Total # of Meas.		**3**			
Median			**1.5**		
IQR			**1.2 – 1.6**		

3.1.1.1 *Lost Hills – North (Northern portion of Lost Hills oil field)*

Table 14. Measurements of Alkane emissions from Lost Hills - North, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211007	114647-134003	7	208	104.2 - 312.6	1.6-2.6	11-301
211010	112833-144703	6	143	86.7 - 199.2	1.5-2.9	15-355
Total # of Meas.		**13**				
Median			**159.7**			
IQR			**121.8 - 216.6**			
Mean			**178.2**			
SD			**93.3**			
CI 95%			**121.8 - 234.6**			

Table 15. Measurements of Alkane emissions from Lost Hills - North, October 2019.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
190930	123248-154234	5	174	103.8 - 243.4	2.2-3.2	16-339
191001	095714-164459	6	245	133.6 - 357.4	2.1-3.4	2-360
191005	*132303-161818*	*3*	*200*	N/A	*2.3-2.8*	*334-357*
Total # of Meas.		**14**				
Median			**204.1**			
IQR			**134.6 - 245.5**			
Mean			**210.2**			
SD			**84.5**			
CI 95%			**161.3 - 259.0**			

Table 16. Measurements of CH_4/alkane ratios for Lost Hills - North, October 2021

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211005	*185414-191008*	*2*	*123*	*3.9-4.2*	*36-38*
211007	*115605-121002*	*1*	*127*	*1.6-1.6*	*69-69*
211010	120531-143628	6	128	1.2-3.8	11-360
211017	*101444-103211*	*2*	*123*	*1.5-2.2*	*18-346*
211021	*135923-141526*	*1*	*107*	*1.2-1.2*	*58-58*
Total # of Meas.		**12**			
Median			**123.3**		
IQR			**108.7 - 136.0**		

Table 17. Measurements of CH_4/alkane ratios for Lost Hills - North, September-October 2019

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
190930	*150134-151945*	*1*	*27.8*	*2.4-2.4*	*343-343*
191001	*140851-163039*	*2*	*34.8*	*1.8-4.0*	*12-323*
191005	*144715-164050*	*2*	*29.6*	*1.3-1.9*	*313-345*
191007	*144737-145922*	*1*	*16.2*	*2.3-2.3*	*328-328*
Total # of Meas.		**6**			
Median			**29.1**		
IQR			**23.8 - 35.2**		

Table 18. Measurements of BTEX/alkane ratios for Lost Hills - North, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211005	*185105-185826*	*1*	*4.9*	*3.8-3.8*	*39-39*
211007	*115753-121002*	*1*	*6.2*	*1.8-1.8*	*63-63*
211017	*101444-103153*	*2*	*5.8*	*1.5-2.1*	*18-346*
211021	*140411-141526*	*1*	*4.5*	*1.2-1.2*	*43-43*
Total # of Meas.		**5**			
Median			**5.6**		
IQR			**4.9 - 5.9**		

Table 19. Measurements of benzene/alkane ratios for Lost Hills - North, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211005	*185105-191008*	*2*	*0.32*	*3.8-4.2*	*36-39*
211007	*115605-121002*	*1*	*0.26*	*1.8-1.8*	*61-61*
211017	*101444-103153*	*2*	*0.96*	*1.5-2.1*	*16-346*
211021	*135923-141526*	*1*	*0.91*	*1.2-1.2*	*38-38*
Total # of Meas.		**6**			
Median			**0.5**		
IQR			**0.3 - 0.9**		

3.1.1.2 Lost Hills – South (Southern portion of Lost Hills oil field)

Table 20. Measurements of Alkane emissions from Lost Hills South, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211017	*095831-110112*	*3*	*174*	N/A	*1.6-3.3*	*91-125*
211021	*143539-144752*	*1*	*283*	N/A	*1.7-1.7*	*102-102*
Total # of Meas.		**4**				
Median			**205.5**			
IQR			**178.5 - 228.1**			
Mean			**201.2**			
SD			**70.6**			
CI 95%			**88.9 - 313.5**			

Table 21. Measurements of Alkane emissions from Lost Hills South, September-October 2019

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
190930	*154616-163412*	*1*	*409*	N/A	*2.9-2.9*	*355-355*
191005	*135236-144610*	*1*	*55.0*	N/A	*2.1-2.1*	*340-340*
191015	*113525-130945*	*1*	*177*	N/A	*1.5-1.5*	*7-7*
Total # of Meas.		**3**				
Median			**177.0**			
IQR			**116.0 - 292.9**			
Mean			**213.6**			
SD			**179.7**			
CI 95%			**0 - 660.0**			

Table 22. Measurements of CH_4/alkane ratios for Lost Hills South, October 2021

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211017	*170710-171436*	*2*	*78.9*	*7.2-10.5*	*199-200*
211021	192213-203624	4	146	1.9-3.7	188-250
Total # of Meas.		**6**			
Median			**134.0**		
IQR			**91.3 - 150.6**		

Table 23. Measurements of CH_4/alkane ratios for Lost Hills South, October 2019.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
191001	*115953-121050*	*1*	*74.4*	*3.7-3.7*	*290-290*
191005	*172126-173705*	*2*	*19.9*	*2.8-3.0*	*240-275*
191007	*221144-222049*	*1*	*78.1*	*3.9-3.9*	*279-279*
191015	*203938-210827*	*2*	*206*	*0.7-0.8*	*227-238*
Total # of Meas.		**6**			
Median			**76.2**		
IQR			**43.6 - 147.2**		

Table 24. Measurements of benzene/alkane ratios for Lost Hills South, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211017	*170710-171436*	*1*	*0.68*	*10.5-10.5*	*200-200*
211021	*192213-203334*	*3*	*0.64*	*1.9-3.7*	*213-250*
Total # of Meas.		**4**			
Median			**0.6**		
IQR			**0.5 - 0.8**		

3.1.2 Belridge, North and South

The Belridge fields were not a prioritized target for the surveys in 2019 and 2021, but emissions were sampled directly in a few measurements and in combined measurements of the joint Cymric, McKittrick and Belridge field emissions (section 3.1.6). Some measurements were made of Belridge, North separately but too few to be have statistical certainty. Belridge, South is a much larger field.

Table 25 shows two measurements of the Belridge alkane emissions of around 1170 kg/h. The number of measurements were too few for a quantitative statistical analysis in the 2021 survey, hence the average alkane emission in Table 25 should be considered indicative only and the result is omitted from the summary in Table 6 and Table 7. Comparing the aggregate Belridge, Cymric and McKittrick emissions of 2968 kg/h from October 2019 (as reported in section 3.1.6) with the Cymric and McKittrick combined alkane emissions of 1377 kg/h imply an emission of around 1590 kg/h for Belridge in October 2019.

A methane to alkane mass fraction of 89% was measured in the Belridge plume (Table 26) October 2021 and 53% October 2019 (Table 27), whereas BTEX (Table 28) and benzene (Table 29) mass fractions were low and at detection limit in the 2021 measurements. Applying the 2021 methane mass fraction to the Belridge alkane emission estimate above, gives methane emission of around 1400 kg/h.

Table 25. Measurements of Alkane emissions from Belridge, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211011	*124616-132736*	*2*	*1171*	N/A	*4.6-6.2*	*315-321*

Table 26. Measurements of CH_4/alkane ratios for Belridge, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211004	*211207-215000*	*2*	*146*	*2.7-4.9*	*225-243*
211005	*212608-214356*	*2*	*34.7*	*4.3-6.3*	*253-272*
211007	*163904-164639*	*1*	*30.4*	*2.3-2.3*	*51-51*
211011	124835-160825	4	105	4.2-15.2	318-337
Total # of Meas.		**9**			
Median			**88.9**		
IQR			**37.2 - 120.8**		

Table 27. Measurements of CH_4/alkane ratios for Belridge, October 2019.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
191006	*111100-130630*	*3*	*60.8*	*1.5-1.7*	*1-345*
191007	*223300-224513*	*1*	*26.6*	*3.9-3.9*	*277-277*
Total # of Meas.		**4**			
Median			**52.7**		
IQR			**37.9 - 67.1**		

Table 28. Measurements of BTEX/alkane ratios for Belridge oil field, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211005	*213236-214356*	*1*	*4.4*	*6.3-6.3*	*253-253*
211007	*163904-165816*	*2*	*1.3*	*3.8-4.5*	*307-310*
Total # of Meas.		**3**			
Median			**3.3**		
IQR			**1.3 - 3.8**		

Table 29. Measurements of benzene/alkane ratios for Belridge oil field, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211005	*213236-214356*	*1*	*0.32*	*6.3-6.3*	*253-253*
211007	*163904-164639*	*1*	*0.73*	*2.3-2.3*	*51-51*
Total # of Meas.		**2**			
Median			**0.5**		
IQR			**0.4 - 0.6**		

3.1.3 Cymric

The alkane emissions from the Cymric field in west San Joaquin Valley were measured on the two last days of September 2021. Four measurements showed alkane emissions of 841 kg/h (95% CI 462-1220 kg/h), Table 30. Figure 28 shows a SOF measurement of the alkane emissions from the Cymric field on 30 September 2021.

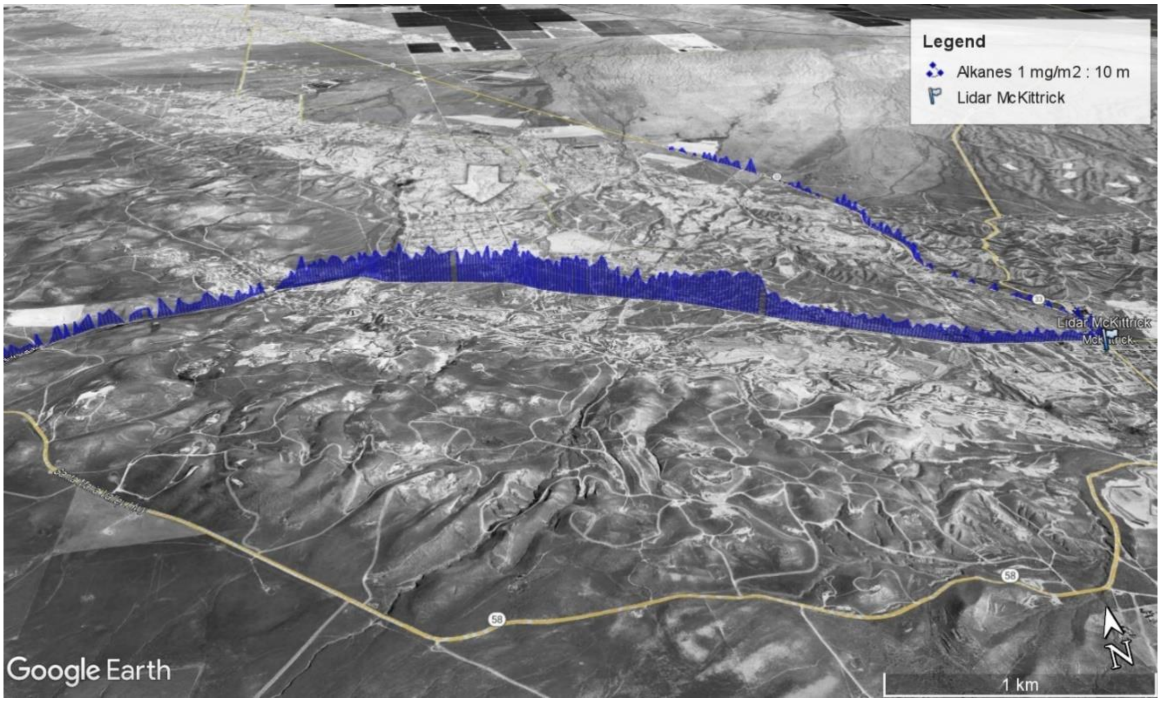

Figure 28. Alkane emission measurement of the Cymric field on 30 September 2021 , 14:20. Wind was blowing from north as indicated by the enclosed white arrow. The blue curve marks measured alkane column, where the height is scaled with the column having 1 mg/m^2 correspond to 10 m height above ground. Map from Google Earth™, 2021.

Methane and alkane plume concentration measurements were done both during daytime and evenings on six days in September-October, with a median methane to alkane mass fraction of 97% (Table 31). This gives a methane emission estimate of 819 kg/h (Table 7) for the Cymric field.

The aggregate plume of the Cymric and McKittrick fields were measured with more repeats and provide a better confined emission estimate for both alkanes and methane, see section 3.1.5.

BTEX measurements were done on four days during the 2021 survey (28 Sep, 30 Sep, 4 Oct, 11 Oct) but the current concentrations were below the detection limits.

Table 30. Measurements of Alkane emissions from Cymric oil field, September 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210929	*135910-150810*	*2*	*636*	N/A	*3.4-4.0*	*338-353*
210930	*133433-144235*	*2*	*1046*	N/A	*2.5-3.2*	*9-12*
Total # of Meas.		**4**				
Median			**833.9**			
IQR			**644.3 - 1030.6**			
Mean			**841.0**			
SD			**237.8**			
CI 95%			**462.5 - 1219.4**			

Table 31. Measurements of CH_4/alkane ratios for Cymric oil field, September-October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210927	*184136-185230*	*1*	*93.0*	*1.3-1.3*	*6-6*
210929	140108-170238	4	99.3	3.2-3.8	325-353
210930	*134227-183611*	*3*	*61.6*	*2.5-2.8*	*16-133*
211004	*192202-211156*	*2*	*350*	*4.0-4.9*	*25-216*
211011	*160552-164428*	*2*	*357*	*15.3-16.2*	*321-329*
Total # of Meas.		**12**			
Median			**97.4**		
IQR			**68.6 - 279.3**		

3.1.4 McKittrick

The McKittrick field alkane emissions were assessed on 2 days in late September 2021. Four measurements showed an emission of 242 kg/h (Table 32). The few and variable observations results in a comparably wide confidence interval (95% CI 39-445 kg/h) and more observations would help to improve certainty. Methane to alkane mass ratio measurements for the McKittrick field in isolation were also few, indicating a ratio of 720% (Table 33). Figure 29 shows an alkane emission measurement of the McKittrick field on 29 September 2021, 14:05, with the Cymric field upwind.

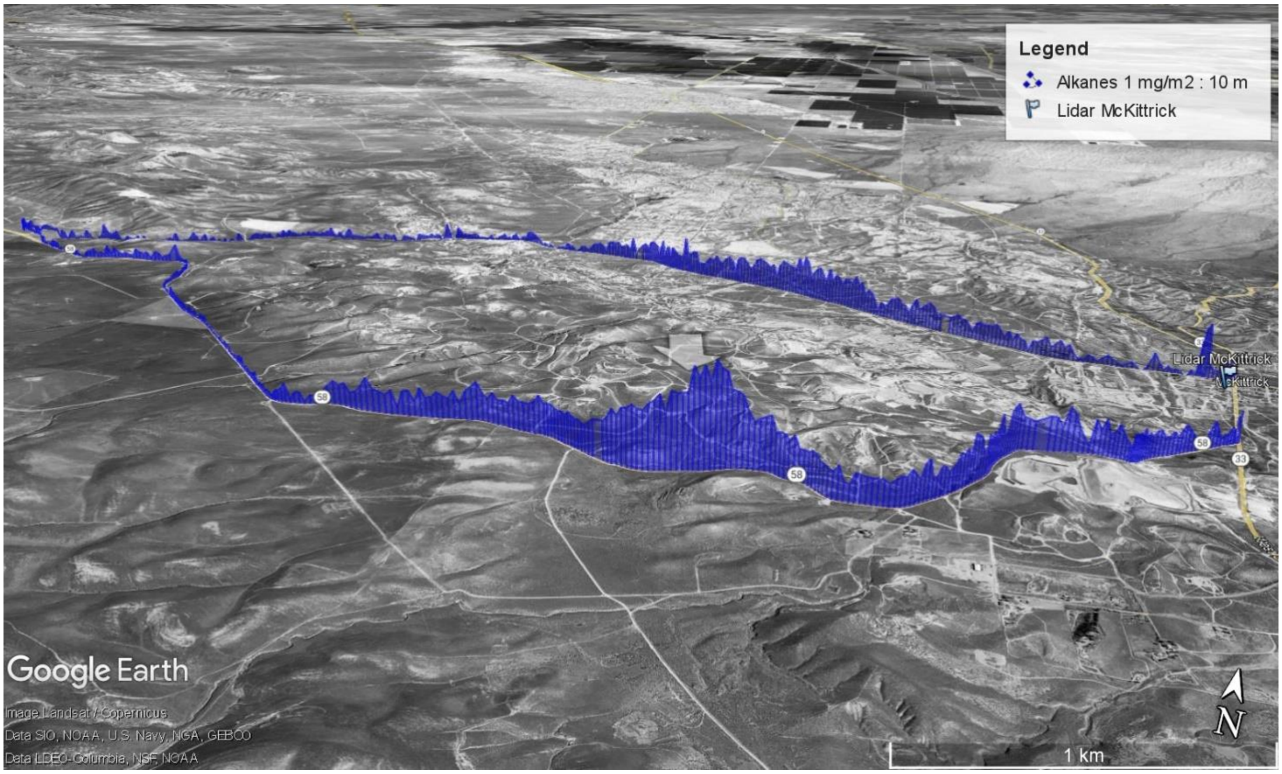

Figure 29. Alkane emission measurement of the McKittrick field on 29 September 2021 , 14:05, with the Cymric field upwind. Wind was blowing from north-northwest as indicated by the enclosed white arrow. The blue curve marks measured alkane column, where the height is scaled with the column having 1 mg/m^2 correspond to 10 m height above ground. Map from Google Earth™, 2021.

As decided by the layout of accessible roads versus oil field borders, it should be noted that the enclosed measurement of the McKittrick field does not include McKittrick wells/areas east of Hwy 33 and north of Reward Rd. These will instead go into the field measurements of Elk Hills and Cymric, respectively.

The combined plume of the Cymric and McKittrick fields were measured with more repeats and provide a better confined emission estimate for both alkanes and methane, see section 3.1.5.

BTEX measurements were made on two days during the 2021 survey (28 Sep and 30 Sep) with resulting concentrations below the detection limit for indirect emission quantifications.

Table 32. Measurements of Alkane emissions from McKittrick oil field, September 2021 . Note that the enclosed measurement of the McKittrick field does not include McKittrick wells/areas east of Hwy 33 and north of Reward Rd.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210929	*140413-152531*	*2*	*288*	N/A	*3.4-4.1*	*335-348*
210930	*134212-151113*	*2*	*197*	N/A	*2.6-3.4*	*9-24*
Total # of Meas.		**4**				
Median			**287.6**			
IQR			**199.9 - 329.8**			
Mean			**242.1**			
SD			**127.5**			
CI 95%			**39.2 - 445.0**			

Table 33. Measurements of CH_4/alkane ratios for McKittrick oil field, September-October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Mass Ratio 95% CI [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210927	*190949-193059*	*1*	*1025*	N/A	*1.0-1.0*	*126-126*
211004	*205334-210050*	*1*	*420*	N/A	*4.2-4.2*	*206-206*
Total # of Meas.		**2**				
Median			**722.5**			
IQR			**571.1 - 873.9**			

3.1.5 Cymric and McKittrick

The overall emissions from the Cymric and McKittrick oil and gas fields in SJV were measured in both fall campaigns of 2019 and 2021. The 2021 measurements showed alkane emissions of 1209 kg/h (95% CI 872-1546 kg/h) (Table 34). This is at a comparable level to the 2019 result of 1377 kg/h (95% CI 1110-1644 kg/h) (Table 35). Figure 30 shows an alkane emission measurement of the Cymric and McKittrick field on the 11 October 2021 at noon. It should be noted that the measurements of the McKittrick field do not include the McKittrick wells/areas east of Hwy 33.

Methane emissions were also in line comparing the 2019 and 2021 measurements. The methane to alkane mass fraction in 2019 was measured to be 177% (Table 37) compared to 181% (Table 36) in the 2021 survey measurements, which along with the alkane emission measurements implies methane emissions of 2430 kg/h in October 2019 and 2180 kg/h in October 2021 (Table 7).

Benzene and BTEX measurements were made on two days during the 2021 survey (29 Sep and 5 Oct), but the concentrations were below the detection limit for indirect emission quantifications. The same applies to the 2019 benzene and BTEX observations here as well.

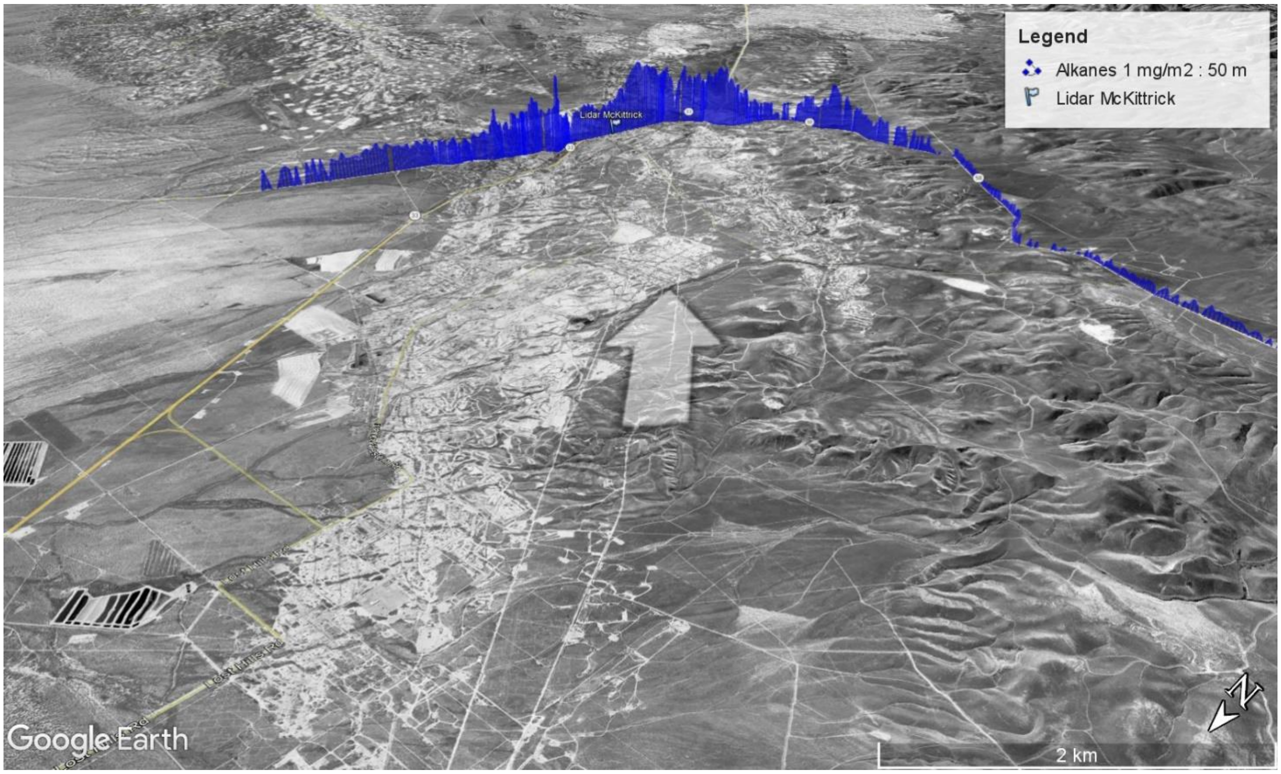

Figure 30. Alkane emission measurement of the Cymric & McKittrick combined oil fields on 11 October 2021 12:05. The height of the blue contour corresponds to the measured column of alkanes where 50 m equals 1 mg/m^2. The white arrow indicates the average wind direction during the measurement. Map from Google Earth™, 2021.

Table 34. Measurements of Alkane emissions from Cymric-McKittrick, September-October 2021 . Note that the enclosed measurements of the McKittrick field does not include McKittrick wells/areas east of Hwy 33.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210929	123842-152913	4	833	630.3 - 1035.3	2.4-4.1	10-354
210930	*135557-152022*	*2*	*1249*	N/A	*2.9-3.4*	*8-21*
211007	*161022-163720*	*1*	*1703*	N/A	*2.7-2.7*	*230-230*
211011	*120410-162913*	*2*	*1676*	N/A	*8.0-12.7*	*328-342*
Total # of Meas.		**9**				
Median			**934.8**			
IQR			**925.9 - 1567.6**			
Mean			**1209.3**			
SD			**437.7**			
CI 95%			**872.8 - 1545.7**			

Table 35. Measurements of Alkane emissions from Cymric-McKittrick, October 2019 . Note that the enclosed measurements of the McKittrick field does not include McKittrick wells/areas east of Hwy 33.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
191006	115747-162159	6	1360	900.5 - 1819.7	1.9-2.6	10-359
191013	*151955-155628*	*1*	*1834*	N/A	*2.5-2.5*	*337-337*
191018	*143502-153414*	*3*	*1258*	N/A	*3.8-4.2*	*315-321*
Total # of Meas.		**10**				
Median			**1340.4**			
IQR			**1173.9 - 1478.2**			
Mean			**1376.8**			
SD			**372.6**			
CI 95%			**1110.2 - 1643.3**			

Table 36. Measurements of CH_4/alkane ratios for Cymric-McKittrick, September-October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210929	*133341-144212*	*2*	*166*	*4.0-4.3*	*351-355*
210930	*135548-151149*	*2*	*84.9*	*2.7-2.8*	*30-359*
211005	*214356-215438*	*1*	*343*	*6.3-6.3*	*242-242*
211011	*113744-114743*	*1*	*194*	*10.6-10.6*	*334-334*
211014	*132529-133116*	*1*	*182*	*3.5-3.5*	*343-343*
Total # of Meas.		**7**			
Median			**180.6**		
IQR			**141.8 - 187.7**		

Table 37. Measurements of CH_4/alkane ratios for Cymric-McKittrick, October 2019.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
191006	120311-184432	7	195	1.2-2.2	13-359
191013	*125409-141534*	*2*	*164*	*2.0-2.1*	*19-358*
191017	*212224-212853*	*1*	*501*	*3.4-3.4*	*348-348*
Total # of Meas.		**10**			
Median			**176.7**		
IQR			**139.4 - 213.6**		

3.1.6 Cymric, McKittrick and Belridge

The alkane emissions from the combined plume of the Cymric, McKittrick and Belridge fields were assessed on two days in 7 measurements in October 2019. An overall alkane emission of 2970 kg/h (95% CI 2160-3775 kg/h) was measured (Table 39). Comparing this to the Cymric & McKittrick field emissions of 1377 kg/h (95% CI 1110-1644 kg/h) indicates that the Belridge field also had a significant alkane emissions, on the order of 1590 kg/h in the October 2019 survey. This is somewhat consistent with emission rate of 1171 kg/h measured from Belridge in October 2021, see Table 25. It should be noted that the enclosed measurements of the Cymric, McKittrick and Belridge field do not include McKittrick wells/areas east of Hwy 33.

Methane and BTEX to alkane mass fraction measurements for the combined plume of all three fields were omitted due to the heterogenous mass ratios in the different fields and risk of biasing the estimate towards a specific field due to variable source proximity.

Two alkane emission measurements on 11 October 2021 showed emissions on the order of 2560 kg/h (Table 38). In lack of statistical certainty, this result is more of observational character and the result is therefore omitted from the summaries in Table 6 and Table 7. In comparison to the Cymric and McKittrick aggregate emissions of 1210 kg/h in October 2021 (Table 34) and weighing in the two measurements on the Belridge field as a sole entity (1170 kg/h) (Table 25), implies that Belridge alkane emissions were also significant in October 2021.

Table 38. Measurements of alkane emissions from Cymric, McKittrick and Belridge, October 2021. Note that the enclosed measurements of the Cymric, McKittrick and Belridge field do not include McKittrick wells/areas east of Hwy 33.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211011	*112433-123915*	*2*	*2564*	N/A	*7.9-9.7*	*312-330*

Table 39. Measurements of alkane emissions from Cymric, McKittrick and Belridge, October 2019. Note that the measurements of the Cymric, McKittrick and Belridge fields don't include McKittrick wells/areas east of Hwy 33.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
191013	125522-151920	5	3157	2102.1 - 4211.2	1.9-2.7	14-357
191018	*120901-132650*	*2*	*2496*	N/A	*4.0-4.8*	*6-353*
Total # of Meas.		**7**				
Median			**2858.4**			
IQR			**2436.7 - 3582.5**			
Mean			**2967.8**			
SD			**872.6**			
CI 95%			**2160.7 - 3774.8**			

3.1.7 Elk Hills

The alkane emissions from the Elk Hills oil and gas field were measured on 4 days and 11 occasions, with an average emission of 2246 kg/h (95% CI 1665-2828) (Table 40). The methane to alkane mass fraction through the cross section of the emission plume was measured to 197% (Table 41) based on 12 observations, which leads to a methane emission estimate of 4430 kg/h (Table 7). Figure 31 shows an alkane emission measurement from the Elk Hills field on 17 October 2021, 14:10.

BTEX and benzene measurements were made on two days during the 2021 survey, with resulting concentrations below the detection limit and not used for emission quantification.

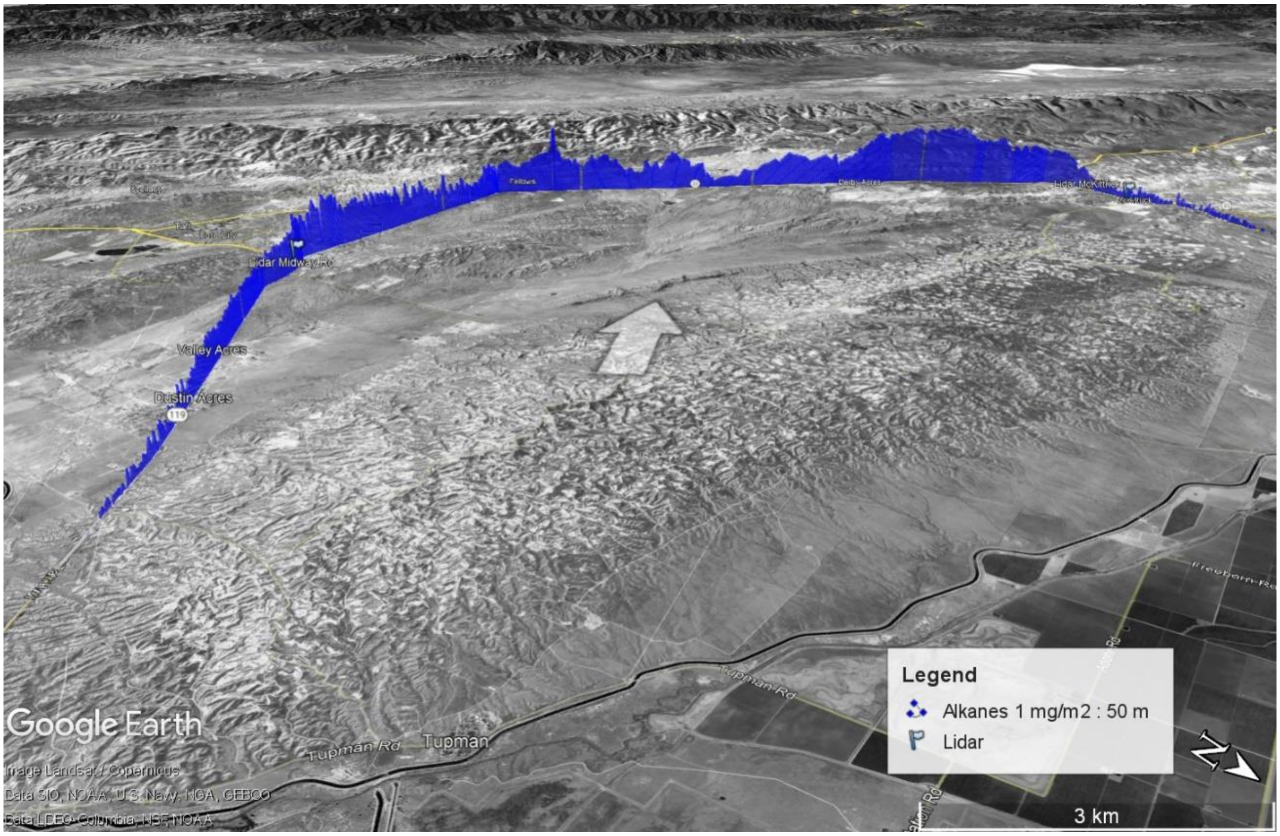

Figure 31. Alkane emission measurement of the Elk Hills field on 17 October 2021 , 14:10. Wind was blowing from north-east as indicated by the enclosed white arrow. The blue curve marks measured alkane column, where the height is scaled with the column having 1 mg/m^2 correspond to 50 m height above ground. Map from Google Earth™, 2021.

As decided by the layout of accessible roads versus oil field borders, it should be noted that the enclosed measurement of the Elk Hills field also include the Asphalto field, some McKittrick wells/areas east of Hwy 33, the Midway Sunset area north of Hwy 33 and the Buena Vista areas north of Midway Rd and Hwy 119.

Table 40. Measurements of Alkane emissions from Elk Hills, September-October 2021 . Note that the enclosed measurement of the Elk Hills field also include the Asphalto field, some McKittrick wells/areas east of Hwy 33, the Midway Sunset area north of Hwy 33 and the Buena Vista areas north of Midway Rd and Hwy 119.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210930	*153108-170844*	*1*	*4391*	N/A	*2.5-2.5*	*50-50*
211006	*125935-163721*	*2*	*2227*	N/A	*2.5-2.7*	*87-97*
211014	102705-161130	5	1910	1452.5 - 2367.3	2.4-3.6	0-27
211017	*112748-144958*	*3*	*2106*	N/A	*2.5-3.5*	*59-69*
Total # of Meas.		**11**				
Median			**1870.7**			
IQR			**1727.1 - 2582.0**			
Mean			**2246.5**			
SD			**864.8**			
CI 95%			**1665.5 - 2827.4**			

Table 41. Measurements of CH_4/alkane ratios for Elk Hills, September-October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210930	*122322-162212*	*2*	*133*	*2.2-2.4*	*8-50*
211006	*114359-133603*	*2*	*292*	*1.1-2.3*	*114-342*
211014	115736-154736	4	179	2.4-4.5	0-341
211017	112837-144649	4	254	2.4-3.5	54-72
Total # of Meas.		**12**			
Median			**197.3**		
IQR			**152.3 - 243.5**		

3.1.8 Midway Sunset

During the 2021 survey, winds were rarely westerly on the western edge of Kern County, but on the 17 October measurements of the alkane emissions were completed for a portion of Midway Sunset field. Due to the north-south extent of the field (McKittrick to south of Maricopa), these measurements do not encompass the entire field. Also, because of their limited number the measurements are observational in nature and the result from this site is therefore omitted from the summaries in Table 6 and Table 7. The measurements on 17 October showed alkane emissions on the order of 100 kg/h Maricopa to Taft and on the order of 1000 kg/h from Taft to McKittrick.

The methane to alkane mass fraction in the Midway Sunset plume as probed on six evenings, showed a median fraction of 424% (Table 42). This would suggest partial field methane emissions on the order of 4600 kg/h. Given the potential strength in emissions here, more measurements of the alkane emissions would be beneficial to narrow down uncertainties.

Benzene and BTEX fractions were below detection limit, indicative of mass contributions less than a percent or a few percent, respectively.

Table 42. Measurements of CH_4/alkane ratios for Midway-Sunset, September-October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210927	*195233-201259*	*1*	*601*	*3.9-3.9*	*234-234*
211004	*194301-205911*	*2*	*424*	*4.2-5.2*	*201-205*
211005	*215422-221826*	*1*	*673*	*6.2-6.2*	*233-233*
211006	*181222-183514*	*1*	*708*	*0.6-0.6*	*284-284*
211007	*173231-174734*	*1*	*130*	*8.0-8.0*	*243-243*
211017	*155033-200640*	*2*	*226*	*3.8-9.1*	*221-263*
Total # of Meas.		**8**			
Median			**423.8**		
IQR			**236.9 - 619.3**		

3.1.9 Coles Levee – North

The Coles Levee North field is comprised of 10+ active wells and a comparably large processing facility. Seven alkane emission measurements from two days yielded 226 kg/h (95% CI 152-299 kg/h) (Table 43). Figure 32 shows an alkane emission measurement from 14 October 2021, 11:40.

A methane to alkane mass fraction of 43% (Table 44) brings the methane emission estimate for Coles Levee North to 98 kg/h. BTEX and benzene measurements were done on three days during the 2021 survey (27, 30 September and 6 October) but the concentrations were below the detection limit and could not be used for indirect emission quantifications.

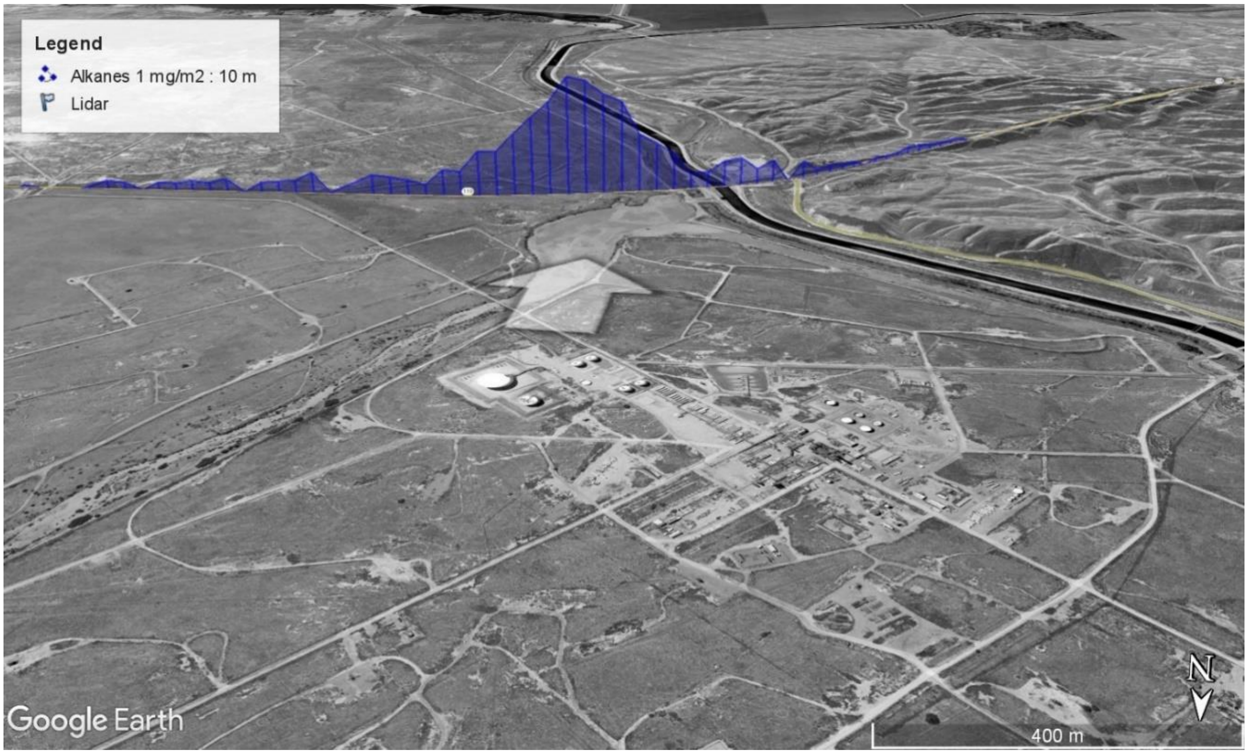

Figure 32. Alkane emission measurement of the Coles Levee North field on 14 October 2021 , 11:40. Wind was blowing from north as indicated by the enclosed white arrow. The blue curve marks measured alkane column, where the height is scaled with the column having 1 mg/m^2 correspond to 10 m height above ground. Map from Google Earth™, 2021.

Table 43. Measurements of Alkane emissions from Coles Levee N, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211014	101949-152218	5	236	156.3 - 315.0	2.5-4.2	12-351
211017	*133233-151537*	*2*	*201*	N/A	*2.8-3.2*	*21-46*
Total # of Meas.		**7**				
Median			**203.9**			
IQR			**187.7 - 283.6**			
Mean			**225.6**			
SD			**79.4**			
CI 95%			**152.2 - 299.0**			

Table 44. Measurements of CH_4/alkane ratios for Coles Levee N, September-October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210927	*151020-151150*	*1*	*19.2*	*5.8-5.8*	*27-27*
211014	114142-152339	4	55.7	2.3-4.6	5-359
Total # of Meas.		**5**			
Median			**43.4**		
IQR			**19.2 - 43.6**		

3.1.10 Kern Front

The Kern Front field, located in between the Kern River and Poso Creek fields, north of Bakersfield, was measured to have an alkane emission of 143 kg/h (95% CI 111-176 kg/h) (Table 45) based on 7 observations on three days. Figure 33 shows an alkane emission measurement of both the Kern Front field and the aggregate plume of the Kern Front and Kern River fields at noon on the 15 October 2021.

The methane emission was indirectly determined to be 501 kg/h (Table 7) based on a methane to alkane mass fraction of 350% (Table 46). BTEX and benzene measurements were done on two days during the 2021 survey (2 and 20 October), but the concentrations were below the detection limit and could not be used for emission quantifications.

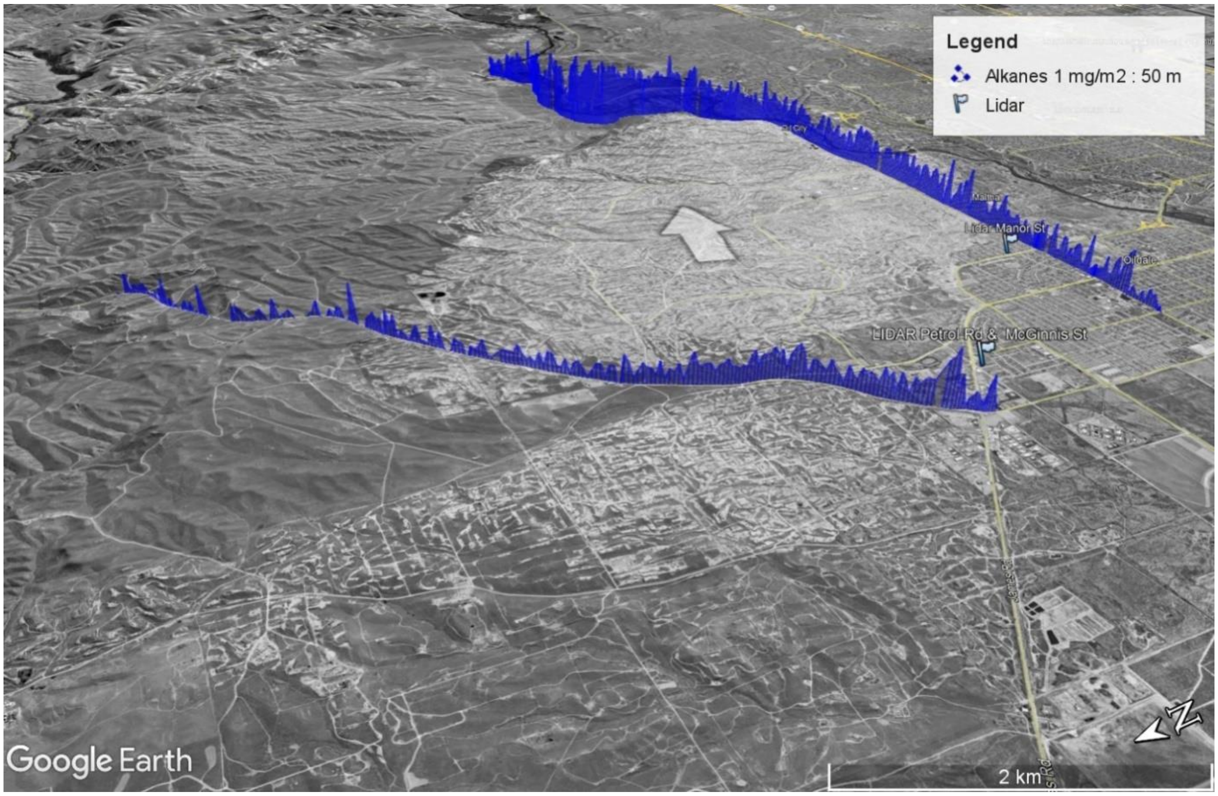

Figure 33. Alkane emission measurement of the Kern Front field (foreground) and the combined Kern Front + Kern River field emission plume (back end) on 15 October 2021, 13-14. Wind was blowing from west-northwest as indicated by the enclosed white arrow. The blue curve marks measured alkane column, where the height is scaled with the column having 1 mg/m^2 correspond to 50 m height above ground. Map from Google Earth™, 2021.

Table 45. Measurements of Alkane emissions from Kern Front, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211015	140110-153006	4	136	96.5 - 176.3	2.8-4.1	256-305
211016	*124120-155434*	*2*	*125*	N/A	*2.7-3.4*	*317-359*
211020	*153444-154953*	*1*	*207*	N/A	*3.7-3.7*	*325-325*
Total # of Meas.		**7**				
Median			**138.2**			
IQR			**123.7 - 152.7**			
Mean			**143.3**			
SD			**34.5**			
CI 95%			**111.4 - 175.2**			

Table 46. Measurements of CH_4/alkane ratios for Kern Front, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211002	*125651-165650*	*3*	*471*	*3.0-6.3*	*1-335*
211015	*140307-152908*	*3*	*354*	*3.2-4.7*	*272-300*
211016	*124150-124549*	*1*	*440*	*2.0-2.0*	*313-313*
211020	*152454-153821*	*1*	*33.9*	*4.4-4.4*	*328-328*
Total # of Meas.		**8**			
Median			**349.5**		
IQR			**134.5 - 382.7**		

3.1.11 Kern River

Alkane emissions from the Kern River field, located just north of Bakersfield and the Kern River, was measured on two days in October 2021. Table 47 summarizes the results, with an average emission of 243 kg/h (95% CI 178-308 kg/h) based on seven measurement transects. Figure 34 shows an alkane emission measurement of the Kern River field on October 16, 2021, 15:10.

The methane to alkane mass fraction at the Kern River field was measured on six days and the 13 plume integrations showed a median methane fraction of 294%, Table 48. The resulting methane emission estimate was 714 kg/h (Table 7). Benzene (Table 50) and BTEX (Table 49) concentrations were near detection limit, indicating emissions around/less than 1.5 kg/h and 11 kg/h respectively.

Table 47. Measurements of Alkane emissions from Kern River, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211002	*154409-163038*	*2*	*331*	N/A	*3.5-4.0*	*6-357*
211016	132742-154025	5	208	167.0 - 249.0	2.5-3.4	280-355
Total # of Meas.		**7**				
Median			**204.1**			
IQR			**195.7 - 276.0**			
Mean			**243.0**			
SD			**70.1**			
CI 95%			**178.2 - 307.9**			

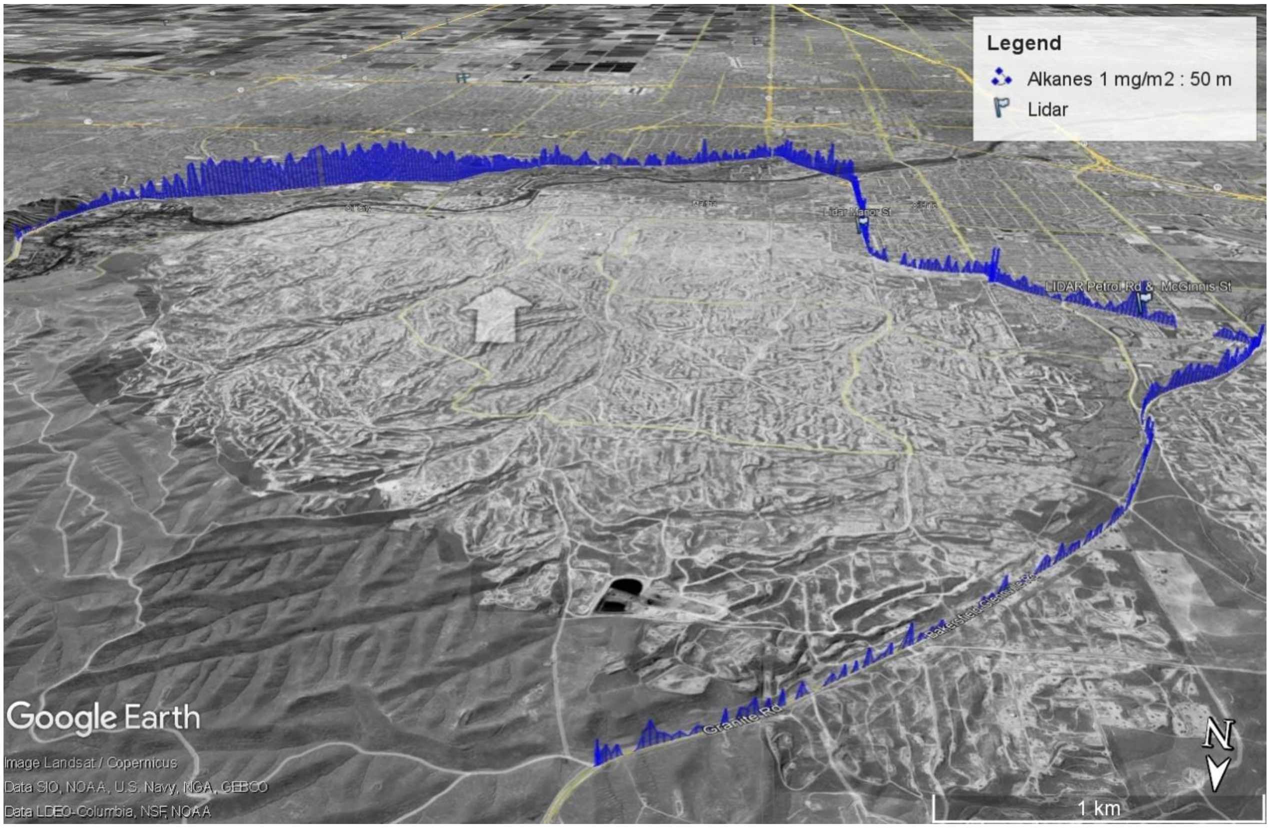

Figure 34. Alkane emission measurement by SOF of the Kern River oil field 16 October 2021 , 15:10. The height of the blue contour corresponds to the measured column of alkanes where 50 m equals 1 mg/m². The white arrow indicates the average wind direction during the measurement (e.g. northerly wind here). Map from Google Earth™, 2021.

Table 48. Measurements of CH_4/alkane ratios for Kern River, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211002	*154336-190513*	*3*	*322*	*1.5-4.4*	*1-19*
211013	*144544-145028*	*2*	*293*	*2.5-2.9*	*322-333*
211014	*201502-202209*	*1*	*441*	*1.3-1.3*	*61-61*
211015	124421-181251	4	316	1.4-6.2	2-352
211016	*132904-133620*	*1*	*599*	*2.9-2.9*	*323-323*
211020	*145011-151550*	*2*	*58.5*	*3.3-3.7*	*315-330*
Total # of Meas.		**13**			
Median			**293.8**		
IQR			**198.9 - 440.6**		

Table 49. Measurements of BTEX/alkane ratios for Kern River, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211002	*154743-163815*	*2*	*7.1*	*4.1-4.4*	*1-7*
211012	*221854-222653*	*1*	*2.0*	*2.0-2.0*	*119-119*
211014	*201506-202711*	*1*	*3.8*	*1.0-1.0*	*88-88*
211015	*170752-172328*	*1*	*2.6*	*3.6-3.6*	*350-350*
211020	*145454-150323*	*1*	*8.8*	*3.5-3.5*	*321-321*
Total # of Meas.		**6**			
Median			**4.7**		
IQR			**2.9 - 7.9**		

Table 50. Measurements of benzene/alkane ratios for Kern River, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211002	*154743-163815*	*2*	*6.4*	*4.1-4.5*	*1-5*
211012	*221854-222653*	*1*	*0.29*	*2.0-2.0*	*119-119*
211014	*201506-202711*	*1*	*0.62*	*0.7-0.7*	*82-82*
211015	*170752-172328*	*1*	*1.3*	*3.6-3.6*	*350-350*
Total # of Meas.		**5**			
Median			**0.6**		
IQR			**0.3 - 1.3**		

3.1.12 Kern Front and Kern River

During north-west wind conditions, the aggregate plume from the Kern Front and Kern River fields was measured in 5 transects on 3 days. The alkane emission of 385 kg/h (95% CI 259-512 kg/h) (Table 51) shows good agreement with the separate field measurements of Kern Front (143 kg/h) and Kern River (243 kg/h) totaling 386 kg/h.

For the aggregate Kern Front and Kern River results, the methane/alkane, BTEX/alkane and benzene/alkane mass fraction ratios from the Kern River measurements (Table 48, Table 49 and Table 50) have been used as the emission measurements were done in closer proximity to the Kern River area with Kern Front upwind. Benzene and BTEX mass fractions were near detection limit, indicating emission levels of 2.5 and 11 kg/h, respectively.

Table 51. Measurements of Alkane emissions from Kern Front-Kern River, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211015	*124149-131523*	*2*	*314*	N/A	*2.5-3.0*	*282-285*
211016	*141722-142943*	*1*	*377*	N/A	*3.4-3.4*	*318-318*
211020	*145118-151614*	*2*	*462*	N/A	*4.1-4.2*	*316-330*
Total # of Meas.		**5**				
Median			**409.8**			
IQR			**376.6 - 441.9**			
Mean			**385.5**			
SD			**101.7**			
CI 95%			**259.2 - 511.7**			

3.1.13 Edison and Mountain View

Compared to the Kern Front and Kern River fields, the Edison and Mountain View fields are less densely populated with wells and interspersed with communities (Lamont, Arvin) and agriculture. The combined plume of these two fields were measured on four days in six measurements resulting in an alkane emission of 112 kg/h (95% CI 78.3-145.2 kg/h) (Table 52).

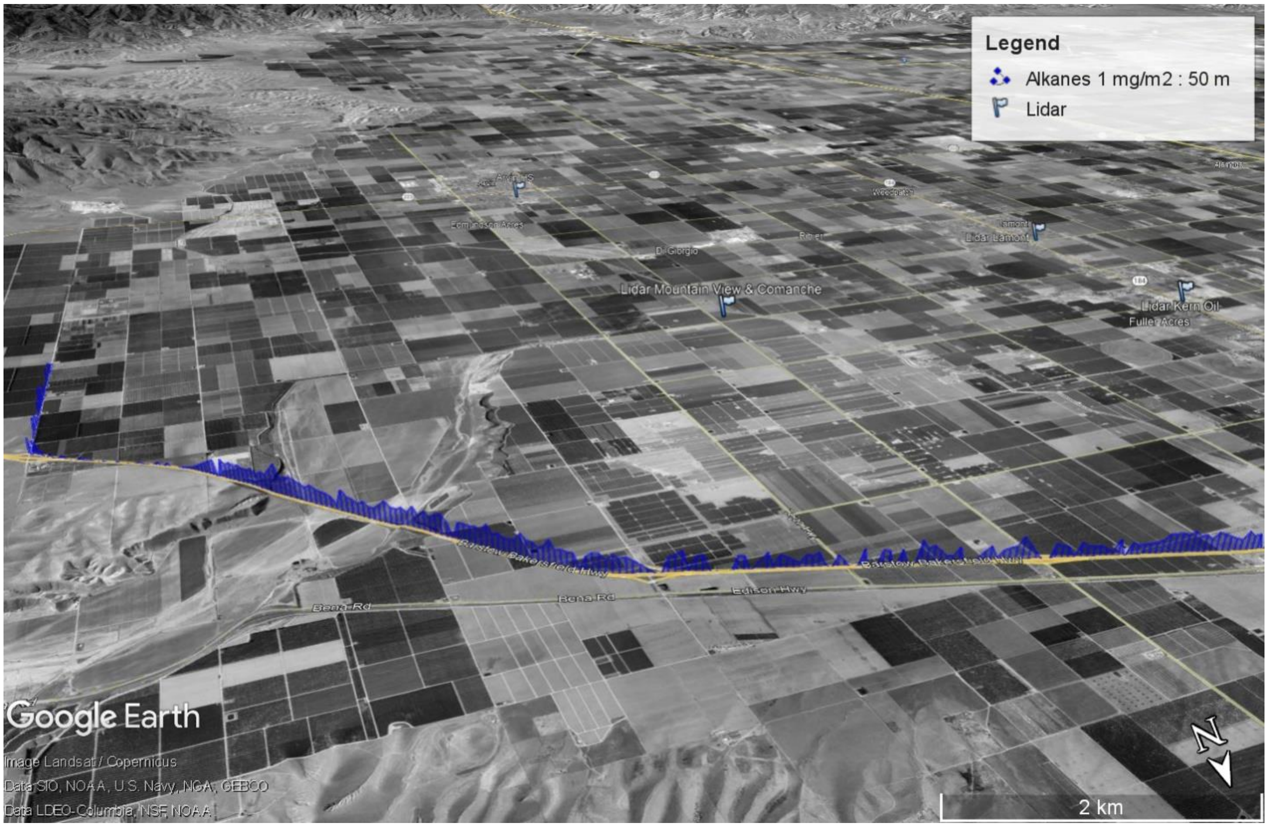

Figure 35. Alkane emission measurement by SOF of the Edison and Mountain View oil fields 13 October 2021 , 11:50. The height of the blue contour corresponds to the measured column of alkanes where 50 m equals 1 mg/m^2. The white arrow indicates the average wind direction during the measurement (e.g. south-westerly wind here). Map from Google Earth™, 2021.

The large-scale plume measurements of the methane to alkane mass fractions here could potentially be biased high in methane from contribution of CAFOs and agricultural activities in the southwest part of the area, but the methane mass fraction of 93% (Table 53) does not immediately suggest that when compared to other field ratios.

BTEX and benzene measurements were done on four days during the 2021 survey (1 ,12, 20, and 21 October) but the concentrations were below detection limit and could not be used for indirect emission quantification.

Table 52. Measurements of Alkane emissions from Edison - Mountain View, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211012	*135441-144810*	*1*	*92.6*	N/A	*2.1-2.1*	*181-181*
211013	*104352-121328*	*3*	*122*	N/A	*1.8-2.1*	*207-235*
211020	*115508-121033*	*1*	*86.7*	N/A	*2.1-2.1*	*242-242*
211021	*115424-121147*	*1*	*124*	N/A	*2.0-2.0*	*266-266*
Total # of Meas.		**6**				
Median			**105.8**			
IQR			**88.2 - 123.1**			
Mean			**111.8**			
SD			**31.9**			
CI 95%			**78.3 - 145.2**			

Table 53. Measurements of CH_4/alkane ratios for Edison - Mountain View, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211001	*154314-160000*	*1*	*80.3*	*1.9-1.9*	*277-277*
211021	*115919-120817*	*1*	*106*	*1.9-1.9*	*297-297*
Total # of Meas.		**2**			
Median			**93.4**		
IQR			**86.8 - 99.9**		

3.1.14 Inglewood Oil Field

The Inglewood oilfield in Baldwin Hills in the South Coast Basin has around 417 active oil and gas wells and several production/Processing Sites (Figure 11) located in close proximity to residential neighborhoods. During all measurements in this survey (June-July 2021) winds were blowing from the west to southwest, pushing emissions towards communities east and northeast of the fields.

Alkane emissions from the aggregate Inglewood field averaged 101 kg/h (95% CI 81-120 kg/h) over 7 measurements and 3 days in the first week of July 2021 (Table 54). The oilfield is bisected by La Cienega Blvd going south to north, allowing for the western half of the oilfield to be measured with westerly winds. Over six days and 12 measurements alkane emissions from the western half of the field averaged 61 kg/h (95% CI 50-71 kg/h), Table 55. A typical SOF measurement is found in Figure 36.

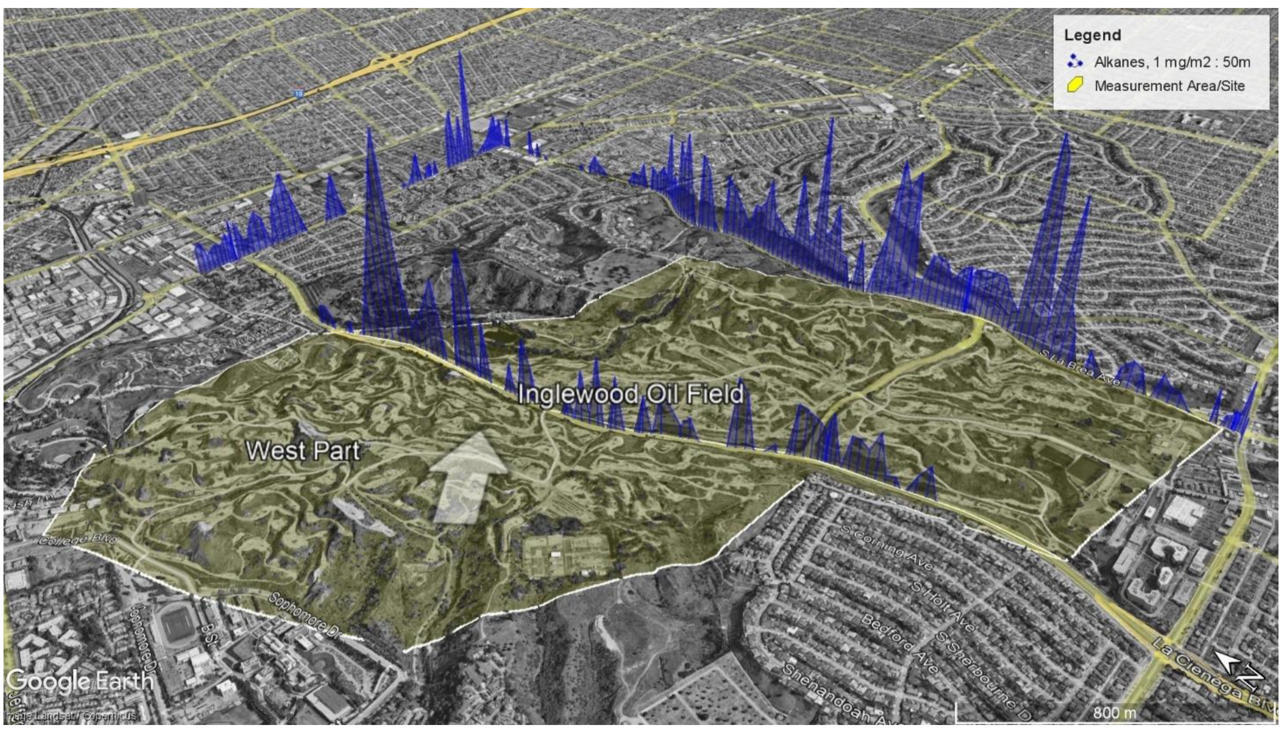

Figure 36. Typical SOF Alkanes measurement of the Inglewood oil field (Total and West Part) site 1 July 2021 at 12:00-12:30. The height of the blue contour corresponds to the measured column of alkanes where 50 m equals 1 mg/m^2. The white arrow indicates the average wind direction during the measurement. Map from Google Earth™, 2021.

The methane to alkane mass fraction in the cross section of the Inglewood field plume was 120% as obtained from 8 measurements on 4 days (Table 56), giving a methane emission estimate of 121 kg/h.

For the aromatic concentration measurements at Inglewood, ethylbenzene was below detection limit and omitted from the mass ratio analysis, instead reporting the BTX/alkane fraction. Concentrations were near detection limit for the benzene and BTX measurements, but indicating mass fractions of around 16% and 7.7%, respectively. This implies benzene and BTX emissions at the order of 8 and 16 kg/h, respectively.

The CalGEM data base reports 417 active oil, gas and multipurpose wells for the Inglewood field in July 2021. It should be noted that apart from active wells, emission contributions might also come from new, idle or plugged wells as well as other production/treatment facilities in the field. Still, normalizing the observed alkane emissions to the number of active well heads results in an estimate of 0.23 kg/h/well for the Inglewood field production for the July 2021 measurements.

Several potential monitoring locations for the SNAPS program are located in proximity to the Inglewood oil field. Concentrations were monitored at some of these locations within this project as further described in section 3.6.2.3.

Table 54. Emission measurements of Alkanes for Inglewood Oilfield (Baldwin Hills), July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210701	*123301-140457*	*3*	*114*	N/A	*4.7-6.0*	*252-256*
210705	*123954-152318*	*3*	*99.4*	N/A	*4.0-5.7*	*243-254*
210707	*144712-145307*	*1*	*62.7*	N/A	*4.2-4.2*	*245-245*
Total # of Meas.		**7**				
Median			**104.1**			
IQR			**94.2 - 109.9**			
Mean			**100.5**			
SD			**20.7**			
CI 95%			**81.4 - 119.6**			

Table 55. Emission measurements of Alkane for Inglewood Oilfield- West, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210626	*125748-131440*	*2*	*55.8*	N/A	*5.5-5.6*	*246-254*
210629	*164540-164927*	*1*	*65.4*	N/A	*5.3-5.3*	*257-257*
210630	*150215-154653*	*2*	*66.4*	N/A	*5.2-5.6*	*237-247*
210701	110946-115748	5	67.7	46.6 - 88.7	3.3-4.1	238-253
210705	*122858-123307*	*1*	*41.0*	N/A	*3.8-3.8*	*235-235*
210707	*150808-151814*	*1*	*41.7*	N/A	*5.2-5.2*	*250-250*
Total # of Meas.		**12**				
Median			**60.0**			
IQR			**48.1 - 71.0**			
Mean			**60.9**			
SD			**15.8**			
CI 95%			**50.9 - 70.9**			

Table 56. Measurements of CH_4/alkane ratios for Inglewood Oilfield, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210619	*114751-115137*	*1*	*107*	*4.6-4.6*	*254-254*
210701	*123838-133954*	*2*	*170*	*4.7-5.4*	*255-261*
210705	*000130-223419*	*2*	*88.7*	*1.8-3.1*	*208-245*
210707	*141248-161121*	*3*	*131*	*5.3-6.1*	*242-248*
Total # of Meas.		**8**			
Median			**120.5**		
IQR			**104.3 - 139.2**		

Table 57. Emission measurements of BTX/alkane ratios for Inglewood Oilfield, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210619	*101915-103809*	*2*	*13.4*	*3.4-4.4*	*233-252*
210623	*145108-150028*	*1*	*17.4*	*6.9-6.9*	*257-257*
210626	*145534-145856*	*1*	*14.3*	*4.8-4.8*	*247-247*
210629	*114804-122542*	*3*	*21.6*	*3.6-4.4*	*246-251*
210701	*114545-133858*	*2*	*15.2*	*3.8-5.3*	*244-261*
210705	*211247-231535*	*3*	*14.5*	*1.8-2.7*	*208-247*
210707	*144338-163119*	*2*	*15.9*	*4.6-5.2*	*238-243*
Total # of Meas.		**14**			
Median			**16.1**		

Table 58. Measurements of benzene/alkane ratios from Inglewood Oilfield, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210619	*101956-103809*	*2*	*7.8*	*3.4-4.3*	*231-252*
210623	*145108-150028*	*1*	*11.2*	*6.9-6.9*	*257-257*
210626	*145534-145856*	*1*	*7.5*	*4.8-4.8*	*247-247*
210629	*114804-122542*	*3*	*12.0*	*3.6-4.4*	*246-251*
210701	*114545-133858*	*2*	*5.4*	*3.8-5.3*	*244-261*
210705	*211247-231535*	*3*	*6.9*	*1.8-2.7*	*208-247*
210707	*144338-163119*	*2*	*6.7*	*4.6-5.2*	*238-243*
Total # of Meas.		**14**			
Median			**7.7**		
IQR			**5.9 - 10.2**		

3.2 Emissions – refineries, processing facilities and well sites

Emissions from individual refineries and Processing Sites in San Joaquin Valley (2019 and 2021 surveys) and South Coast Air Basin (2021 survey) are presented here. A summary of results is presented for sites with sufficient measurements (at least 4 valid SOF transects) in Table 59-Table 60 and Table 19. Complete results of emission measurements are presented in each site-specific section.

Table 59. Summary of SOF alkane results from the 2019 and 2021 measurement surveys for Refineries & Processing Sites . D=number of measurement days. N=number of measurements. SD = 1σ standard deviation. CI = confidence interval. Note: only sites with sufficient statistics (>3 valid measurements) are presented here.

		Counts		Emission	Emission	Emission
Region	**Site, survey year**	**D**	**N**	**Average [kg/h]**	**SD [kg/h]**	**CI-95% [kg/h]**
SJV	Lost Hills - Processing 1, 2019	8	27	54	37	14
	Lost Hills - Processing 1, 2021	3	6	58	14	15
	Kern Oil Refinery - Main Area, 2021	4	23	75	64	28
	Kern Oil Refinery - East Tank Park, 2021	3	7	13	11	10
	Buena Vista - Processing Site, 2021	5	11	153	91	61
	Asphalto - Facility Skyline Rd	2	11	13	4.3	2.9
South Coast	Las Cienegas - St. James Lease, 2021	2	5	0.5	0.3	0.3
	Las Cienegas - Jefferson, 2021	3	27	2.2	1.6	0.6
	Las Cienegas - Murphy, 2021	4	16	3.3	2.3	1.2
	Playa Del Rey - Gas Storage, 2021	2	6	12	4.0	4.2
	Honor Rancho - Gas Storage, 2021	1	5	13	3.3	4.1

Table 60. Summary of BTEX and CH_4 emission results from the 2019 and 2021 measurement surveys for Refineries & Processing Sites. N=number of measurements. BDL = Concentration Below the Detection Limit for valid alkane plume from same source. Note: only sites with sufficient statistics (>3 valid SOF measurements) are presented here. Mass fractions are the median value of the observations. [a]Ethylbenzene not included in BTEX measurements for LA

Site, survey year	Alkanes N	Alkanes [kg/h]	N	BTEX/ Alkane [%]	BTEX [kg/h]	Benzene/ Alkane [%]	Benzene [kg/h]	N	CH_4/ Alkane [%]	CH_4 [kg/h]
Lost Hills - Processing 1, 2019	27	54	1	3.7	2.0	0.3	0.2	13	33	18
Lost Hills - Processing 1, 2021	6	58	4	2.7	1.6	0.5	0.3	3	71	41
Kern Oil Refinery - Main Area, 2021	23	75	17	8.4	6.3	1.4	1.0	22	26	19
Kern Oil Refinery - East Tank Park, 2021	7	13	7	2.1	0.3	1.3	0.2	5	22	2.9
Buena Vista - Processing Site, 2021	11	153	8	2.6	4.0	1.7	2.6	11	162	248
Asphalto - Facility Skyline Rd	11	13	28	3.9	0.5	1.1	0.1	24	26	3.5
Las Cienegas - St. James Lease, 2021	5	0.5	12	6.5 [a]	0.03	BDL	BDL	13	152	0.7
Las Cienegas - Jefferson, 2021	27	2.2	51	5.0 [a]	0.1	2.2	0.05	38	131	2.9
Las Cienegas - Murphy, 2021	16	3.3	20	9.2 [a]	0.3	BDL	BDL	6	66	2.2
Playa Del Rey - Gas Storage, 2021	6	12	9	6.9 [a]	0.8	1.9	0.2	5	135	15
Honor Rancho - Gas Storage, 2021	5	13	5	3.5 [a]	0.4	2.3	0.3	11	704	92

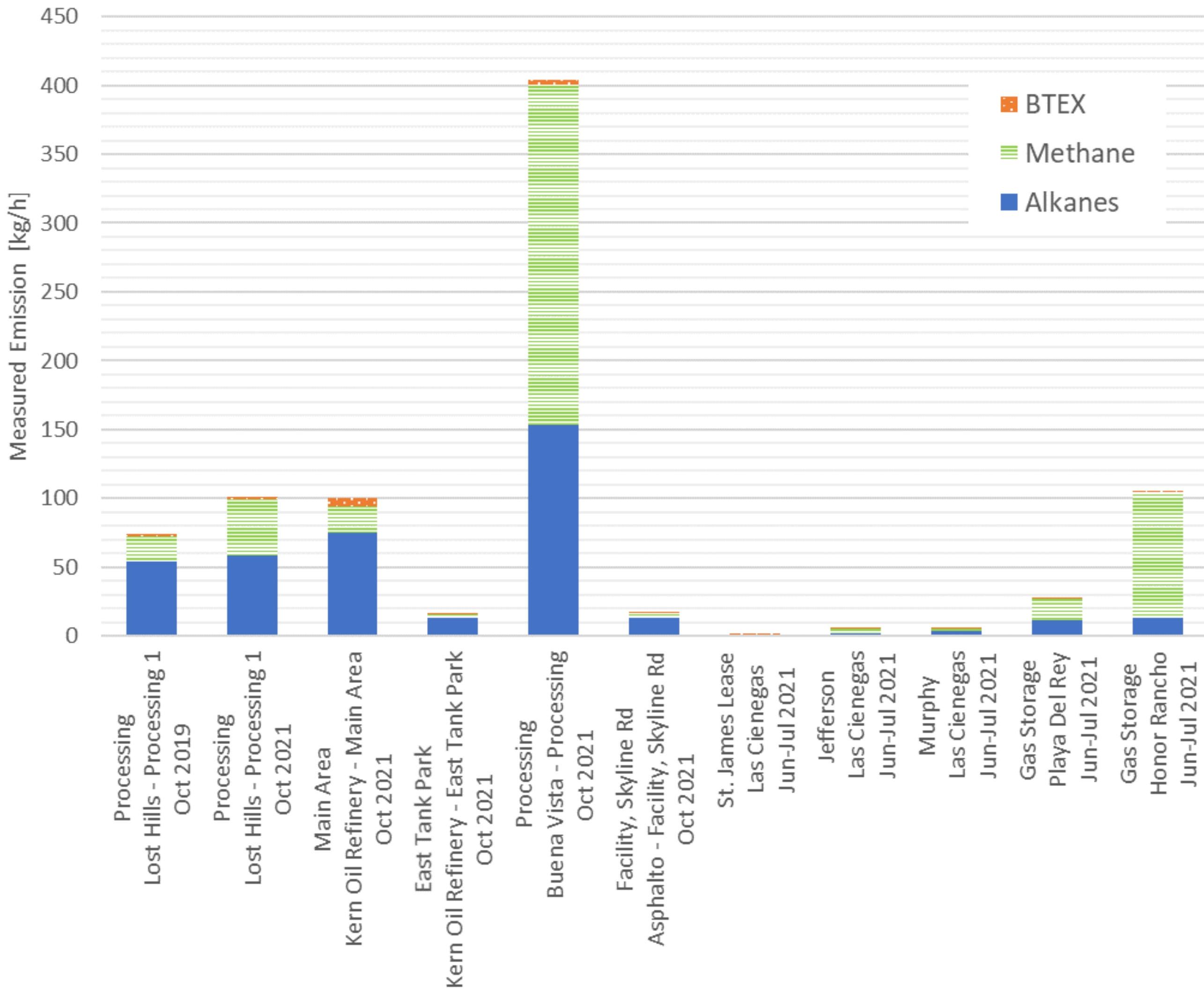

Figure 37. Summary of measured alkane, methane and BTEX emissions from refineries & processing sites during the CARB 2 surveys. Note: only sites with sufficient statistics (>3 valid SOF measurements) are presented here.

3.2.1 Lost Hills - Processing 1

Emissions from the Lost Hills – Processing 1 were measured during eight days in October 2019 and during three days in October 2021.

Alkane emissions averaged 54 kg/h (95% CI 40-69 kg/h) over 27 measurements in 2019 (see Table 61) and 32 kg/h (17- 49 95% CI) in 2021 based on 6 measurements, see Table 64. The methane mass ratio in the plume was 33% in 2019 and 70% in 2021 which translates to an indirect emission of 18 kg/h in 2019 and 41 kg/h in 2021 (Table 62 and Table 65, respectively). BTEX emissions were 2.0 kg/h in 2019 and 1.6 kg/h in 2021. Benzene emissions were 0.2 kg/h and 0.3 kg/h in 2019 and 2021, respectively.

Alkanes emissions from the water treatment area within the facility averaged 32 kg/h over 11 measurements and four days in 2019, see Table 63.

Table 61. Measurements of Alkane emissions from Lost Hills Processing 1, October 2019.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
191002	112817-162519	6	64.9	0.7 - 129.0	1.9-2.8	5-356
191003	125807-161938	4	41.6	0 - 90.5	2.4-3.0	9-352
191004	*103525-112450*	*3*	*59.9*	N/A	*3.0-3.3*	*341-341*
191005	*122512-164644*	*2*	*69.5*	N/A	*2.3-2.8*	*321-356*
191007	112458-165708	6	40.4	31.1 - 49.8	1.3-2.8	4-343
191008	*123342-132709*	*3*	*34.3*	N/A	*1.4-1.6*	*104-250*
191009	*150725-153722*	*2*	*54.5*	N/A	*6.3-6.5*	*352-353*
191010	*144046-145016*	*1*	*139*	N/A	*2.3-2.3*	*360-360*
Total # of Meas.		**27**				
Median			**48.4**			
IQR			**32.1 - 61.6**			
Mean			**54.4**			
SD			**36.6**			
CI 95%			**39.9 - 68.9**			

Table 62. Measurements of CH_4/alkane ratios for Lost Hills Processing 1, October 2019.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
191002	*163726-164010*	*1*	*32.9*	*1.6-1.6*	*36-36*
191004	*103944-183707*	*3*	*91.6*	*2.5-2.9*	*326-344*
191005	*164249-164656*	*1*	*12.9*	*1.5-1.5*	*279-279*
191007	112803-201906	6	85.5	0.6-3.1	5-327
191008	*131217-131747*	*1*	*16.0*	*0.4-0.4*	*268-268*
191010	*144415-144943*	*1*	*6.2*	*2.5-2.5*	*24-24*
Total # of Meas.		**13**			
Median			**32.9**		
IQR			**14.0 - 73.7**		

Table 63. Measurements of Alkane emissions from Lost Hills Processing 1 - Water Treatment part, October 2019.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
191002	114544-121206	6	20.7	11.5 - 30.0	1.2-1.9	12-357
191003	*130737-131156*	*1*	*16.1*	N/A	*2.1-2.1*	*324-324*
191004	*110025-110655*	*1*	*6.8*	N/A	*2.3-2.3*	*36-36*
191008	*113140-131726*	*3*	*67.2*	N/A	*1.0-1.7*	*85-109*
Total # of Meas.		**11**				
Median			**25.6**			
IQR			**13.4 - 35.2**			
Mean			**31.7**			
SD			**26.1**			
CI 95%			**14.2 - 49.2**			

Table 64. Measurements of Alkane emissions from Lost Hills Processing 1, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% C.I. [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211005	*154413-160044*	*2*	*59.0*	N/A	*2.1-2.3*	*299-321*
211007	*135042-140347*	*2*	*62.2*	N/A	*2.2-2.5*	*309-321*
211010	*151859-160800*	*2*	*53.4*	N/A	*2.9-4.3*	*328-335*
Total # of Meas.		**6**				
Median			**60.8**			
IQR			**46.3 - 67.9**			
Mean			**58.2**			
SD			**14.0**			
C.I. 95%			**43.5 - 72.9**			

Table 65. Measurements of CH_4/alkane ratios for Lost Hills Processing 1, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211021	*184104-192639*	*3*	*97.4*	*0.9-3.5*	*156-236*
Total # of Meas.		**3**			
Median			**70.5**		
IQR			**69.1 - 112.3**		

3.2.2 Kern Oil Refinery

The Kern Oil Refinery area was divided into three emission source areas: a western section with apparent loading to rail tankers (Train Loading Area), the centrally located refinery process section, and a tank park and truck loading area (East Tank Park) to the east of Weedpatch Highway (Main St), see Figure 18. Most often the measurements were carried out on Panama Lane or on Weedpatch Highway immediately at the facility fenceline. In the following, the *Main area* denotes the combined refinery process section and the rail loading area, all located west of Main St. The results are presented in the separate sections of the proceeding.

An alkane emission measurement (by SOF) of the entire facility is shown in Figure 38 where plumes from all three emission source areas can be seen.

Figure 38. Typical SOF Alkanes measurement of the Kern Oil Refinery. The height of the blue contour corresponds to the measured column of alkanes where 10 m equals 1 mg/m^2. The white arrow indicates the average wind direction during the measurement. Map from Google Earth™, 2021.

The overall alkane emissions were measured to 88 kg/h. Corresponding total site methane, BTEX and benzene emissions were 22 kg/h, 7 kg/h and 1 kg/h, respectively.

3.2.2.1 Main Area

Emissions from the Kern Oil Refinery was measured during four days in October 2021. The alkane emissions from the *Main Area* (process area and rail loading area, all located west of Main St.) averaged 75 kg/h (95% CI 47-103 kg/h) based on 23 measurements (Table 66). The methane to alkane mass ratio in the plume was 26% (Table 67) leading to a methane emission estimate of 18 kg/h (Table 60). The measured BTEX emission mass ratio was 8.4 % (Table 68) giving an emission rate of 6 kg/h, of which benzene constituted 1 kg/h based on a plume ratio of 1.4 %, (Table 69 and Table 60).

Table 66. Measurements of Alkane emissions from Kern Oil Refinery - Main Area, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% C.I. [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211012	093758-113629	9	49.1	31.3 - 66.8	1.5-4.8	217-289
211013	101801-140422	4	52.0	30.9 - 73.1	1.9-2.7	163-295
211019	115746-154553	5	68.3	50.1 - 86.6	1.4-3.2	214-285
211020	111454-133517	5	146	7.0 - 285.3	1.6-3.1	217-303
Total # of Meas.		**23**				
Median			**63.3**			
IQR			**41.5 - 79.6**			
Mean			**74.9**			
SD			**63.8**			
C.I. 95%			**47.3 - 102.5**			

Table 67. Measurements of CH_4/alkane ratios for Kern Oil Refinery - Main Area, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211001	*165118-165245*	*1*	*27.1*	*1.4-1.4*	*249-249*
211009	*180145-181457*	*2*	*32.2*	*2.2-2.3*	*241-247*
211012	093733-203325	11	24.7	0.8-4.4	183-355
211013	*131015-131800*	*2*	*29.7*	*1.7-1.7*	*268-268*
211014	*222715-222917*	*1*	*14.8*	*2.2-2.2*	*140-140*
211018	*205214-205502*	*1*	*28.6*	*2.1-2.1*	*120-120*
211019	*140540-154547*	*2*	*18.8*	*2.6-3.2*	*286-309*
211020	*111558-111952*	*2*	*24.3*	*0.1-0.5*	*231-236*
Total # of Meas.		**22**			
Median			**25.7**		
IQR			**16.6 - 27.4**		

Table 68. Measurements of BTEX/alkane ratios for Kern Oil Refinery - Main Area, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211001	*175512-175706*	*1*	*19.8*	*1.9-1.9*	*227-227*
211009	*180236-194313*	*3*	*8.4*	*1.5-3.8*	*185-249*
211012	093720-164100	7	8.5	1.4-4.4	213-289
211014	*222654-222903*	*1*	*4.7*	*2.2-2.2*	*140-140*
211015	*102930-103013*	*1*	*19.7*	*0.5-0.5*	*261-261*
211018	*205310-205456*	*1*	*2.0*	*2.2-2.2*	*117-117*
211019	*154434-154547*	*1*	*5.6*	*3.2-3.2*	*286-286*
211020	*111558-111952*	*2*	*5.9*	*0.1-0.5*	*231-236*
Total # of Meas.		**17**			
Median			**8.4**		
IQR			**5.6 - 9.4**		

Table 69. Measurements of benzene/alkane ratios for Kern Oil Refinery - Main Area, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211001	*175512-175706*	*1*	*1.5*	*1.9-1.9*	*227-227*
211009	*180236-194313*	*3*	*1.4*	*1.5-3.8*	*185-249*
211012	093720-203325	11	1.6	1.1-4.4	171-295
211015	*102930-103013*	*1*	*1.6*	*0.5-0.5*	*261-261*
211020	*111558-111648*	*1*	*0.87*	*0.1-0.1*	*231-231*
Total # of Meas.		**17**			
Median			**1.4**		
IQR			**1.0 - 1.8**		

Emissions from the Train Loading Area within the Kern Oil Refinery - Main Area was measured during three days in October 2021. The alkane emissions were 17 kg/h (6-29 95% CI) based on 8 valid measurements, see Table 70. The plume methane mass ratio was 17% (Table 71), the BTEX ratio 11 % (Table 72) and the Benzene ratio 1 % (Table 73).

Table 70. Measurements of Alkane emissions from Kern Oil Refinery – Train Loading area, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211012	094003-105107	5	18.3	0 - 40.6	2.6-3.9	217-246
211013	*101801-101905*	*1*	*15.5*	N/A	*1.8-1.8*	*163-163*
211020	*111454-112037*	*2*	*16.3*	N/A	*2.6-3.1*	*215-235*
Total # of Meas.		**8**				
Median			**14.2**			
IQR			**10.8 - 16.3**			
Mean			**17.4**			
SD			**13.7**			
CI 95%			**6.0 - 28.9**			

Table 71. Measurements of CH_4/alkane ratios for Kern Oil Refinery– Train Loading area, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211009	*180147-181406*	*2*	*23.6*	*3.9-4.0*	*184-189*
211012	093918-193853	5	11.6	0.8-3.4	168-258
211020	*111458-111531*	*1*	*14.6*	*0.0-0.0*	*229-229*
Total # of Meas.		**8**			
Median			**16.5**		
IQR			**10.2 - 20.2**		

Table 72. Measurements of BTEX/alkane ratios for Kern Oil Refinery – Train Loading area, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211009	*180147-194555*	*3*	*12.3*	*1.4-3.9*	*184-244*
211012	100832-193925	4	11.2	1.5-3.4	90-258
211015	*102845-102930*	*1*	*5.7*	*0.5-0.5*	*257-257*
211020	*111458-111545*	*1*	*11.3*	*0.0-0.0*	*230-230*
Total # of Meas.		**9**			
Median			**11.3**		
IQR			**5.7 - 12.4**		

Table 73. Measurements of benzene/alkane ratios for Kern Oil Refinery– Train Loading area, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211009	*180147-194555*	*3*	*1.4*	*1.4-4.0*	*184-244*
211012	093958-193925	5	0.98	1.5-3.4	168-310
211015	*102845-102930*	*1*	*2.2*	*0.5-0.5*	*257-257*
211020	*111458-111531*	*1*	*2.7*	*0.0-0.0*	*229-229*
Total # of Meas.		**10**			
Median			**1.0**		
IQR			**0.8 - 2.0**		

3.2.2.2 East Tank Park

Emissions from the Kern Oil Refinery - East Tank Park area was measured during three days in October 2021. The alkane emissions averaged to 13 kg/h (95% CI 3 – 23 kg/h) based on 7 measurements, see Table 74. The methane to alkane mass ratio in the plume was 22% (Table 75), the BTEX to alkane ratio 2 % (Table 76) and the benzene to alkane mass ratio around 1% (Table 77). The sampled mass ratios combined with the alkane emission rate results in methane, BTEX and benzene emission estimates of 3.3 kg/h, 1.1 kg/h and 0.2 kg/h, respectively.

Table 74. Measurements of Alkane emissions from Kern Oil Refinery – East Tank Park, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211012	093622-103208	4	17.3	0 - 36.4	2.6-3.4	218-230
211013	*102016-102113*	*1*	*3.3*	N/A	*1.9-1.9*	*164-164*
211020	*111642-111900*	*2*	*8.8*	N/A	*2.8-2.9*	*223-228*
Total # of Meas.		**7**				
Median			**13.2**			
IQR			**4.6 - 15.4**			
Mean			**12.9**			
SD			**10.7**			
CI 95%			**3.0 - 22.8**			

Table 75. Daily Measurements of CH_4/alkane ratios for Kern Oil Refinery– East Tank Park, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211009	*181456-181551*	*1*	*15.5*	*2.3-2.3*	*247-247*
211012	*093631-202248*	*2*	*16.8*	*2.4-2.9*	*174-240*
211015	*103011-103103*	*1*	*26.9*	*1.1-1.1*	*230-230*
211018	*210228-210329*	*1*	*28.6*	*1.2-1.2*	*127-127*
Total # of Meas.		**5**			
Median			**22.1**		
IQR			**15.5 - 26.9**		

Table 76. Measurements of BTEX/alkane ratios for Kern Oil Refinery– East Tank Park, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211012	093631-203325	5	0.32	2.0-2.3	47-243
211015	*103011-103103*	*1*	*14.1*	*0.6-0.6*	*265-265*
211018	*210228-210329*	*1*	*7.3*	*1.2-1.2*	*127-127*
Total # of Meas.		**7**			
Median			**2.0**		
IQR			**1.5 - 6.1**		

Table 77. Measurements of benzene/alkane ratios for Kern Oil Refinery– East Tank Park, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
211012	*093631-202247*	*2*	*0.97*	*2.2-2.4*	*243-355*
211015	*103011-103103*	*1*	*1.4*	*0.6-0.6*	*265-265*
Total # of Meas.		**3**			
Median			**1.3**		
IQR			**1.0 - 1.4**		

3.2.3 La Paloma Generating Facility

The number of valid SOF measurements were too few (<4) for a quantitative statistical analysis, hence the average alkane emission in Table 78 should be considered indicative only. The result from this site is therefore omitted from the summary tables Table 59 and Table 60.

Table 78. Measurements of Alkane emissions from La Paloma Generating Facility, September 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210929	*154545-162844*	*3*	*21.2*	N/A	*3.4-4.4*	*325-345*

Table 79. Measurements of CH_4/alkane ratios for La Paloma Generating Facility, September-October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210929	*154614-161736*	*3*	*224*	*2.6-3.5*	*330-346*
210930	*181444-181614*	*1*	*87.7*	*3.0-3.0*	*39-39*
211021	*151602-154214*	*2*	*388*	*1.8-3.0*	*86-349*
Total # of Meas.		**6**			
Median			**246.0**		
IQR			**195.0 - 276.1**		

3.2.4 Buena Vista - Processing Site

Emissions from the Buena Vista Processing Site, located immediately northwest of the Midway Rd & Taft Hwy junction, was monitored during five days in September and October 2021.

The measured alkane emissions were 153 kg/h on average (92-214 95% CI) based on 11 valid measurements, see Table 80. Figure 39 show an alkane emission measurement of the site from October 14, 2021, at noon.

Methane was the dominating gas in the emission plume with a mass ratio to alkanes of 162%, see Table 81. This gave an emission of 248 kg/h methane from this site which makes it the largest emitter of all refinery and Processing Sites in this survey, see Table 60. The BTEX emissions were quantified to 4 kg/h based on a plume mass ratio of 2.6 %, see Table 82. Benzene constituted 2.6 kg/h of the BTEX emissions based on a measured benzene ratio of 1.7%, see Table 83.

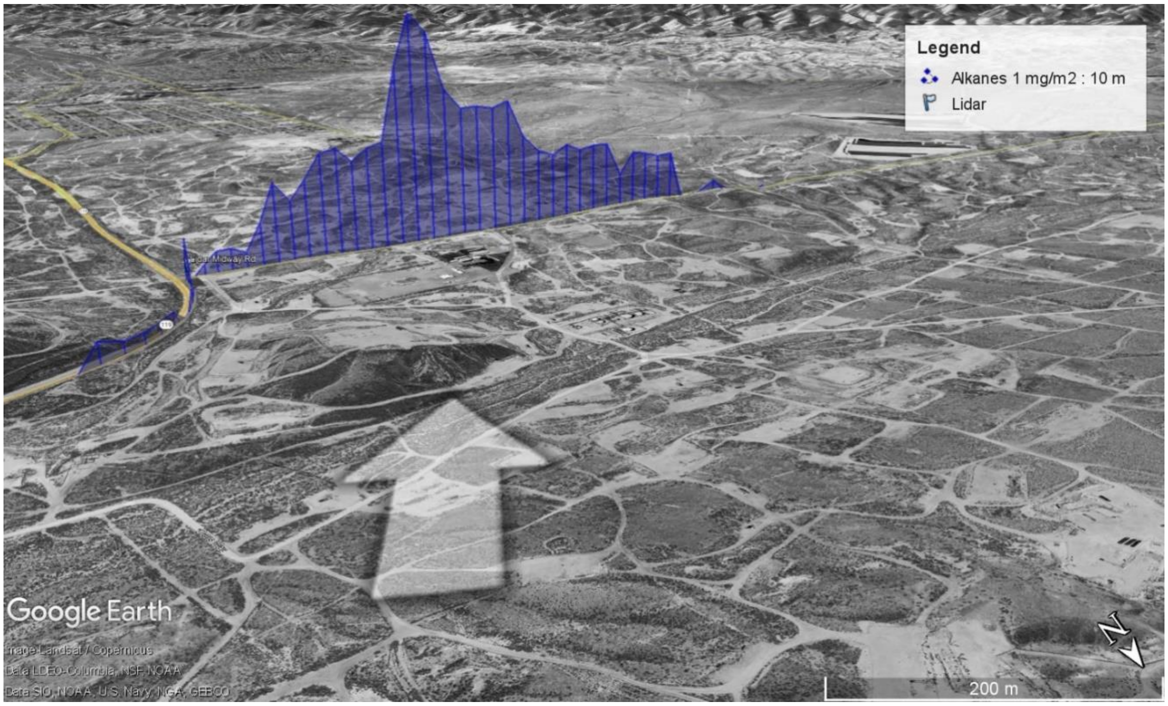

Figure 39. Alkane emission measurement by SOF of the Buena Vista Processing Site on October 14 2021 , 11:55. The height of the blue contour corresponds to the measured column of alkanes where 10 m equals 1 mg/m². The white arrow indicates the average wind direction during the measurement (e.g. north-east here). Map from Google Earth™, 2021.

Table 80. Measurements of Alkane emissions from Buena Vista - Processing Site, October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% C.I. [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210927	*153725-153915*	*1*	*46.1*	N/A	*1.7-1.7*	*49-49*
210930	*123212-123618*	*1*	*90.7*	N/A	*2.5-2.5*	*350-350*
211006	*120748-120946*	*1*	*286*	N/A	*2.9-2.9*	*31-31*
211014	103914-153634	6	182	94.5 - 269.2	1.8-4.3	4-356
211017	*143711-152707*	*2*	*84.1*	N/A	*1.6-2.5*	*42-291*
Total # of Meas.		**11**				
Median			**98.9**			
IQR			**90.8 - 214.5**			
Mean			**152.9**			
SD			**90.8**			
C.I. 95%			**91.9 - 213.9**			

Table 81. Measurements of CH_4/alkane ratios for Buena Vista - Processing Site, September-October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210927	*153804-154000*	*1*	*36.7*	*1.3-1.3*	*65-65*
210930	*160531-160855*	*1*	*26.9*	*2.2-2.2*	*44-44*
211006	*153021-153120*	*1*	*7.7*	*3.0-3.0*	*271-271*
211007	*174841-175128*	*1*	*248*	*8.1-8.1*	*242-242*
211014	115525-153606	4	189	3.3-4.2	17-323
211017	*115340-143930*	*3*	*177*	*1.3-2.9*	*62-81*
Total # of Meas.		**11**			
Median			**161.9**		
IQR			**91.2 - 207.7**		

Table 82. Measurements of BTEX/alkane ratios for Buena Vista - Processing Site, September-October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210930	*160419-161134*	*1*	*2.4*	*2.2-2.2*	*43-43*
211006	*153021-153120*	*1*	*18.2*	*3.0-3.0*	*271-271*
211014	115525-153549	4	1.9	3.4-4.2	17-323
211017	*115410-131830*	*2*	*11.3*	*2.6-3.0*	*74-75*
Total # of Meas.		**8**			
Median			**2.6**		
IQR			**2.2 - 9.9**		

Table 83. Measurements of benzene/alkane ratios for Buena Vista - Processing Site, September-October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210930	*160419-161134*	*1*	*1.1*	*2.2-2.2*	*43-43*
211006	*153021-153120*	*1*	*1.7*	*3.0-3.0*	*271-271*
211014	*115525-153535*	*3*	*2.6*	*3.3-4.2*	*17-29*
211017	*115429-115501*	*1*	*1.6*	*3.0-3.0*	*75-75*
Total # of Meas.		**6**			
Median			**1.7**		
IQR			**1.6 - 1.9**		

3.2.5 Asphalto - Facility Skyline Rd

Emissions from the SkyLine Rd Facility in Asphalto gas field in SJV was measured during two days in September and October 2021. The alkane emissions averaged 13 kg/h (0.1.-0.8 95% CI) based on 11 valid measurements, see Table 84. Only one valid measurement was made on October 21, so this daily value is indicative only. The methane mass ratio in the plume was 26% which translates to an indirect emission of 3.5 kg/h, see Table 85. The large variance in methane ratios is likely due to not being able to exclude upwind oilfield sources. BTEX emissions were quantified to 0.5 kg/h based on a plume mass ratio of 3.9 %, see Table 86. Benzene emissions were 0.1 kg/h with a plume mass ratio of 1.1 %.

Table 84. Measurements of Alkane emissions from Asphalto - Facility Skyline Rd, September-October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210929	155111-162441	10	13.0	9.9 - 16.1	3.7-4.3	1-360
211021	*154340-154512*	*1*	*17.0*	N/A	*2.0-2.0*	*359-359*
Total # of Meas.		**11**				
Median			**12.2**			
IQR			**9.8 - 16.5**			
Mean			**13.4**			
SD			**4.3**			
CI 95%			**10.5 - 16.3**			

Table 85. Measurements of CH_4/alkane ratios for Asphalto - Facility Skyline Rd, September-October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210928	195243-202231	4	145	0.8-3.9	169-346
210929	155116-162442	12	24.1	2.0-3.4	6-354
210930	181016-181413	6	55.5	1.3-3.0	0-77
211021	*151858-152050*	*2*	*250*	*2.4-2.4*	*76-76*
Total # of Meas.		**24**			
Median			**26.0**		
IQR			**23.7 - 119.4**		

Table 86. Measurements of BTEX/alkane ratios for Asphalto - Facility Skyline Rd, September 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210928	195243-202231	6	4.0	0.8-3.9	169-347
210929	155116-162438	14	4.7	2.0-4.0	6-352
210930	181016-183332	8	4.4	1.3-6.4	64-133
Total # of Meas.		**28**			
Median			**3.9**		
IQR			**2.6 - 5.5**		

Table 87. Measurements of Benzene/alkane ratios for Asphalto - Facility Skyline Rd, September-October 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210928	195243-202231	3	1.4	0.5-1.5	169-209
210929	155116-162433	5	1.1	2.0-3.4	6-352
210930	181016-181413	3	2.1	1.3-3.0	0-77
211021	151437-151535	1	3.9	3.3-3.3	90-90
Total # of Meas.		**12**			
Median			**1.1**		
IQR			**0.5 - 2.3**		

3.2.6 Mountain View - Arvin well sites

Two specific well sites in Arvin were investigated for emissons, Well Site A, south of Bear Mountain Blvd., and Well Site B, just south of Arvin High School. Well Site A was discovered to be a point source of interest in concentration mapping and warranted a revisit for emissions quantification. Well Site B was of interest due to proximity to the high school, but was difficult to isolate from upwind emissions. The SOF measurements were made on only one ocassion and were the basis for this determination (Figure 40). The number of valid SOF measurements were too few (<4) for a quantitative statistical analysis. The result from this area is therefore omitted from the summary tables Table 59 and Table 60.

Figure 40. Two alkane emission measurements by SOF of the Mountain View Arvin well sites on October 12 2021 , 15:00. Note there are other active wells and many plugged wells in this area not indicated on the image. The height of the blue contour corresponds to the measured column of alkanes where 10 m equals 1 mg/m^2. The white arrows indicate the average wind direction during the measurements. Map from Google Earth™, 2021.

3.2.7 Las Cienegas - St. James Lease

All the wells at the St. James Lease site were currently idle or plugged. Alkane emissions from the Las Cienegas – St. James Lease site were measured during two days in June and July 2021. The alkane emissions were barely detectable and averaged 0.5 kg/h (0.1.-0.8 95% CI) based on 5 valid measurements, see Table 88. Methane was the dominating species and the methane to alkane mass ratio in the plume was 152% which gave an indirect methane emission estimate of 0.7 kg/h, see Table 89. The BTX emissions were close to the detection limit and estimated to 0.03 kg/h. see Table 90 (note that ethylbenzene was below detection limit for the MeDOAS system and only BTX sum reported here). Benzene emissions from the site could not be quantified.

Table 88. Measurements of Alkane emissions from Las Cienegas - St. James Lease, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210625	*122330-124358*	*3*	*0.34*	N/A	*2.9-4.2*	*240-264*
210702	*131828-140214*	*2*	*0.61*	N/A	*2.9-3.8*	*251-264*
Total # of Meas.		**5**				
Median			**0.3**			
IQR			**0.2 - 0.6**			
Mean			**0.5**			
SD			**0.3**			
CI 95%			**0.1 - 0.8**			

Table 89. Measurements of CH_4/alkane ratios for Las Cienegas - St. James Lease, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210624	*155524-163858*	*3*	*151*	*4.7-5.8*	*237-253*
210625	*121516-124419*	*2*	*106*	*4.9-5.1*	*239-257*
210702	*132602-133142*	*1*	*65.3*	*3.9-3.9*	*254-254*
210707	222514-231436	7	145	0.4-0.9	225-268
Total # of Meas.		**13**			
Median			**151.9**		
IQR			**73.6 - 161.5**		

Table 90. Emission measurements of BTX/alkane ratios for Las Cienegas - St. James Lease, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210624	*161025-162706*	*3*	*10.6*	*5.1-5.6*	*243-260*
210625	*121516-121604*	*1*	*4.2*	*5.2-5.2*	*240-240*
210702	*125712-134418*	*3*	*7.0*	*3.9-4.0*	*252-262*
210707	222514-225725	5	4.0	1.0-1.5	184-239
Total # of Meas.		**12**			
Median			**6.5**		
IQR			1.7 **- 8.4**		

3.2.8 Las Cienegas - Fourth Avenue

The Las Cienegas – Fourth Avenue site has only plugged or abandoned wells. The SOF measurements of the alkane emissions showed very low emissions, if any, and observations were at the detection limit. Also, the fenceline concentration measurements on 23 and 26 June of alkane, methane, benzene and BTEX showed concentrations near detection limit, supporting low emissions. The number of valid SOF measurements were too few (<3) for a quantitative statistical analysis, hence the average alkane emission in Table 91 should be considered indicative only. The result from this site is therefore omitted from the summary tables Table 59 and Table 60.

Table 91. Measurements of Alkane emissions from Las Cienegas - Fourth Avenue, June 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210625	*145120-145740*	*2*	*0.29*	*3.3-3.9*	*258-258*

3.2.9 Las Cienegas – Jefferson

The Jefferson Site had currently active wells and facilities. Emission measurements of the Las Cienegas – Jefferson site were conducted during three days in June and July 2021. The average alkane emissions were 2.2 kg/h (1.6.-2.8 95% CI) based on 27 valid measurements, see Table 92. The methane mass ratio in the plume was 131% which gave an indirect methane emission of 2.9 kg/h, Table 93. The BTX emissions were close to the detection limit and estimated to 0.1 kg/h of which 0.05 kg/h in the form of benzene, see Table 94 and Table 95 (note that ethylbenzene was below detection limit for the MeDOAS system and only BTX sum reported here). An example of a SOF alkane measurement of the site is shown in Figure 41.

Table 92. Measurements of Alkane emissions from Las Cienegas - Jefferson, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210624	151154-154215	6	4.7	3.7 - 5.6	3.9-4.4	229-246
210625	131718-134304	7	1.9	1.3 - 2.4	3.2-4.3	227-252
210702	110036-161753	14	1.4	0.8 - 1.9	1.9-4.5	198-278
Total # of Meas.		**27**				
Median			**1.8**			
IQR			**1.0 - 3.1**			
Mean			**2.2**			
SD			**1.6**			
CI 95%			**1.6 - 2.8**			

Figure 41. Typical SOF Alkanes measurement of the La Cienegas – Jefferson site 2 July 2021 at 16:10. The height of the blue contour corresponds to the measured column of alkanes where 10 m equals 1 mg/m^2. The white arrow indicates the average wind direction during the measurement. Map from Google Earth™, 2021.

Table 93. Measurements of CH_4/alkane ratios for Las Cienegas - Jefferson, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210623	170931-173419	5	132	4.9-6.8	256-260
210624	151803-154243	5	132	5.0-5.7	231-243
210625	131709-143050	9	118	4.0-5.4	226-244
210702	111615-164531	9	113	2.8-4.2	230-259
210707	204935-220911	10	152	1.5-3.6	250-278
Total # of Meas.		**38**			
Median			**130.8**		
IQR			**112.9 - 149.4**		

Table 94. Emission measurements of BTX/alkane ratios for Las Cienegas - Jefferson, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210623	170943-173403	6	6.1	4.9-6.8	256-262
210624	150516-154243	6	5.4	5.0-5.7	231-245
210625	131709-143050	9	7.8	1.1-5.4	225-244
210702	110051-164531	17	5.9	2.0-4.6	197-278
210707	204935-220911	13	3.1	1.0-1.8	244-303
Total # of Meas.		**51**			
Median			**5.0**		
IQR			**2.7 - 7.3**		

Table 95. Summary of daily and survey Measurements of benzene/alkane ratios for Las Cienegas - Jefferson, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210623	170943-173403	6	2.4	4.9-6.8	256-262
210624	150516-154243	6	2.7	5.0-5.7	231-245
210625	131709-143050	9	1.9	1.1-5.4	225-244
210702	110051-164531	17	2.4	2.0-4.6	197-278
210707	204935-220911	13	1.6	1.0-1.8	244-303
Total # of Meas.		**51**			
Median			**2.2**		
IQR			**1.4 - 2.7**		

3.2.10 Las Cienegas - Murphy

Like Jefferson, the Las Cienegas – Murphy site had currently active wells and facilities. Measurements of emissions from the Las Cienegas – Murphy site were conducted during four days in June and July 2021. An example measurement is shown in Alkane emissions were close to the detection limit and averaged 3.3 kg/h (2.1-4.5.0 95% CI), see Table 96. The methane mass ratio was 66% which translates to an emission of 2 kg/h, Table 97. The BTX emissions were very close to the detection limit and was estimated to 0.3 kg/h, see Table 98 (note that ethylbenzene was below detection limit for the MeDOAS system and only BTX sum reported here). Benzene/alkane ratios were under the detection limit.

Figure 42 SOF Alkane measurement of the La Cienegas – Murphy site 25 June 2021 at 11:36 showing complete box measurement. Emissions were near the detection limit as seen in the upwind measurement here (to the southwest of the area). The height of the blue contour corresponds to the measured column of alkanes where 10 m is equivalent to 1 mg/m^2. The white arrow indicates the average wind direction during the measurement. Map from Google Earth™, 2021.

Table 96. Measurements of Alkane emissions from Las Cienegas - Murphy, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210623	*155201-155403*	*1*	*2.2*	N/A	*5.7-5.7*	*256-256*
210624	*165638-171858*	*3*	*1.0*	N/A	*4.1-4.5*	*242-245*
210625	111013-115828	7	5.1	3.6 - 6.7	2.9-3.7	220-242
210702	143659-154358	5	2.3	0.0 - 4.6	3.6-4.5	231-255
Total # of Meas.		**16**				
Median			**2.9**			
IQR			**1.6 - 4.5**			
Mean			**3.3**			
SD			**2.3**			
CI 95%			**2.1 - 4.5**			

Table 97. Measurements of CH_4/alkane ratios for Murphy, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210623	*152532-154735*	*2*	*47.2*	*6.2-6.6*	*252-259*
210624	*171818-172050*	*1*	*75.6*	*5.3-5.3*	*250-250*
210625	*114802-114929*	*1*	*92.8*	*5.3-5.3*	*250-250*
210702	*153540-154419*	*2*	*51.6*	*1.1-4.2*	*260-271*
Total # of Meas.		**6**			
Median			**65.5**		
IQR			**49.7 - 80.5**		

Table 98. Emission measurements of BTX/alkane ratios for Las Cienegas - Murphy, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210623	153658-160104	4	13.0	5.7-6.2	244-259
210624	*171137-172017*	*2*	*19.7*	*5.3-6.0*	*250-251*
210625	111039-120436	5	7.3	3.2-5.3	228-263
210702	143708-155102	9	6.7	3.9-5.6	256-281
Total # of Meas.		**20**			
Median			**9.2**		
IQR			**4.7 - 12.8**		

3.2.11 Playa Del Rey - Gas Storage

Alkane emissions from the Playa Del Rey Area was measured on two days in July 2021. Besides the Gas Storage facility the area includes a number of active oil & gas wells. Six measurements averaged an emission of 11.5 kg/h (7.3-15.7 kg/h 95% CI), Table 99. Plume concentration ratio measurements versus alkanes were done on two days for methane (Table 100) and seven days for BTX (Table 101) (note that Ethylbenzene was below detection limit for the MeDOAS system and only BTX sum reported here). The median methane/alkane mass ratio of 135% yields a methane emission estimate of 15 kg/h, whereas BTX was near detection limit and less than 2 kg/h. Benzene concentrations were also near detection limit and gave an indirect emission of 0.2 kg/h.

Figure 43 SOF Alkane measurement of Playa Del Rey Gas Storage Site 25 June 2021 at 11:36. The height of the blue contour corresponds to the measured column of alkanes where 10 m is equivalent to 1 mg/m^2. The white arrow indicates the average wind direction during the measurement. Map from Google Earth™, 2021.

Table 99. Emission measurements of Alkane emission from Playa Del Rey - gas storage, July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210701	152148-165025	4	10.4	3.9 - 16.8	6.9-8.0	254-272
210707	*112410-125513*	*2*	*13.8*	N/A	*4.2-4.3*	*237-250*
Total # of Meas.		**6**				
Median			**10.8**			
IQR			**8.8 - 14.7**			
Mean			**11.5**			
SD			**4.0**			
CI 95%			**7.3 - 15.7**			

Table 100. Measurements of CH_4/alkane ratios for Playa Del Rey gas storage, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210626	*185322-185646*	*1*	*135*	*3.2-3.2*	*260-260*
210707	110004-125641	4	133	3.5-3.8	253-262
Total # of Meas.		**5**			
Median			**134.6**		
IQR			**117.7 - 138.2**		

Table 101. Emission measurements of BTX/alkane ratios for Playa Del Rey gas storage, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210624	185537-193231	4	12.0	7.1-7.4	222-226
210701	*152129-162848*	*2*	*2.7*	*4.3-6.0*	*252-271*
210707	*112301-125414*	*3*	*4.6*	*3.6-3.8*	*252-258*
Total # of Meas.		**9**			
Median			**6.9**		
IQR			**2.8 - 11.7**		

Table 102. Emission measurements of benzene/alkane ratios for Playa Del Rey gas storage, June-July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Mass Ratio 95% C.I. [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210624	185537-193231	4	3.0	1.8 - 4.1	7.1-7.4	222-226
210701	*152129-162848*	*2*	*1.9*	N/A	*4.3-6.0*	*252-271*
210707	*112301-125414*	*3*	*0.90*	N/A	*3.6-3.8*	*252-258*
Total # of Meas.		**9**				
Median			**1.9**			
IQR			**1.5 - 3.3**			

3.2.12 Honor Rancho - Gas Storage

The Honor Rancho gas storage site was measured on 3 July 2021. Emissions were dominated by methane, with a median methane/alkane mass concentration ratio of 704%, Table 104. Figure 44 shows an example measurement of the portion of the field containing the gas storage facilities which is defined as the measurement area. Due to lack of suitable perimeter roads the area could not be boxed in measurements. In some measurements it is evident that there are emissions at the northern end of the road. These possibly originate from the producing part of the field with active wells. For the area, alkane emissions averaged 13.0 kg/h (11.0-15.0 95% CI), Table 103. Combined with the methane mass ratio this result in a methane emission estimate of 92 kg/h. BTX and benzene to alkane mass concentration fractions were low and near detection limit, indicating BTX (Table 105) and benzene (Table 106) emissions less than 0.5 kg/h and 0.3 kg/h respectively (note that ethylbenzene was below detection limit for the MeDOAS system and only BTX sum reported here).

Figure 44 Example SOF Alkane measurement of Honor Rancho Oil Field 3 July 2021 at 11:13. The height of the blue contour corresponds to the measured column of alkanes where 10 m is equivalent to 1 mg/m^2. The white arrow indicates the average wind direction during the measurement. Map from Google Earth™, 2021.

Table 103. Measurements of Alkane emissions from Honor Rancho gas storage, July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210703	105224-175700	13	13.0	11.0 - 15.0	2.9-8.9	240-265
Total # of Meas.		**13**				
Median			**13.2**			
IQR			**10.3 - 15.5**			
Mean			**13.0**			
SD			**3.3**			
CI 95%			**11.0 - 15.0**			

Table 104. Measurements of CH_4/alkane ratios for Honor Rancho gas storage, July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210703	104856-180444	11	713	2.6-7.8	243-263
Total # of Meas.		**11**			
Median			**704.5**		
IQR			**671.5 - 776.7**		

Table 105. Measurements of BTX/alkane ratios for Honor Rancho gas storage, July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210703	110905-173427	5	3.7	3.0-7.4	246-263
Total # of Meas.		**5**			
Median			**3.5**		
IQR			**3.3 - 5.4**		

Table 106. Measurements of Benzene/alkane ratios for Honor Rancho gas storage, July 2021.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Mass Ratio avg [%]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
210703	110905-173427	5	2.4	3.0-7.4	246-263
Total # of Meas.		**5**			
Median			**2.3**		
IQR			**2.3 - 2.6**		

3.3 Emissions - oil and gas ponds

The Cymric/McKittrick oil and gas produced water ponds surveyed were small sources of alkane emissions and should be inconsequential for methane emissions. Because they are surrounded by typically larger sources, and other practical measurement issues (lack of perimeter roads) isolated emissions measurements with SOF were few. The Taft ponds and nearby vicinity showed evidence of emissions and high concentrations during times of low wind speeds. Only one day of measurements were made so it is unknown if these are typical emissions. The high percentages of methane in the plume may indicate additional sources than the ponds. Summary of results from pond measurements are found in Table 107 and individual results in the subsections below.

Table 107. Alkane and methane emission measurements of O&G produced water ponds . High methane percentages for Cymric and Taft may indicate interfering sources, October 2019. D=number of measurement days. N=number of measurements. SD = 1 σ standard deviation. CI = confidence interval. Entries in grey had fewer than the minimum number of measurements required for 30% certainty in emissions.

	Alkanes					CH_4		
Oil and Gas Ponds	Counts D	N	Emission **Average [kg/h]**	Emission **SD [kg/h]**	Emission **CI-95% [kg/h]**	Counts **N**	Ratio **%**	Emission **[kg/h]**
McKittrick 1-1 Pond	2	4	10	6.9	11	0	NM	NM
McKittrick 1 Pond	2	3	7.5	8.4	21	1	60	4.5
Taft Pond	1	4	18	6.8	11	7	241	44

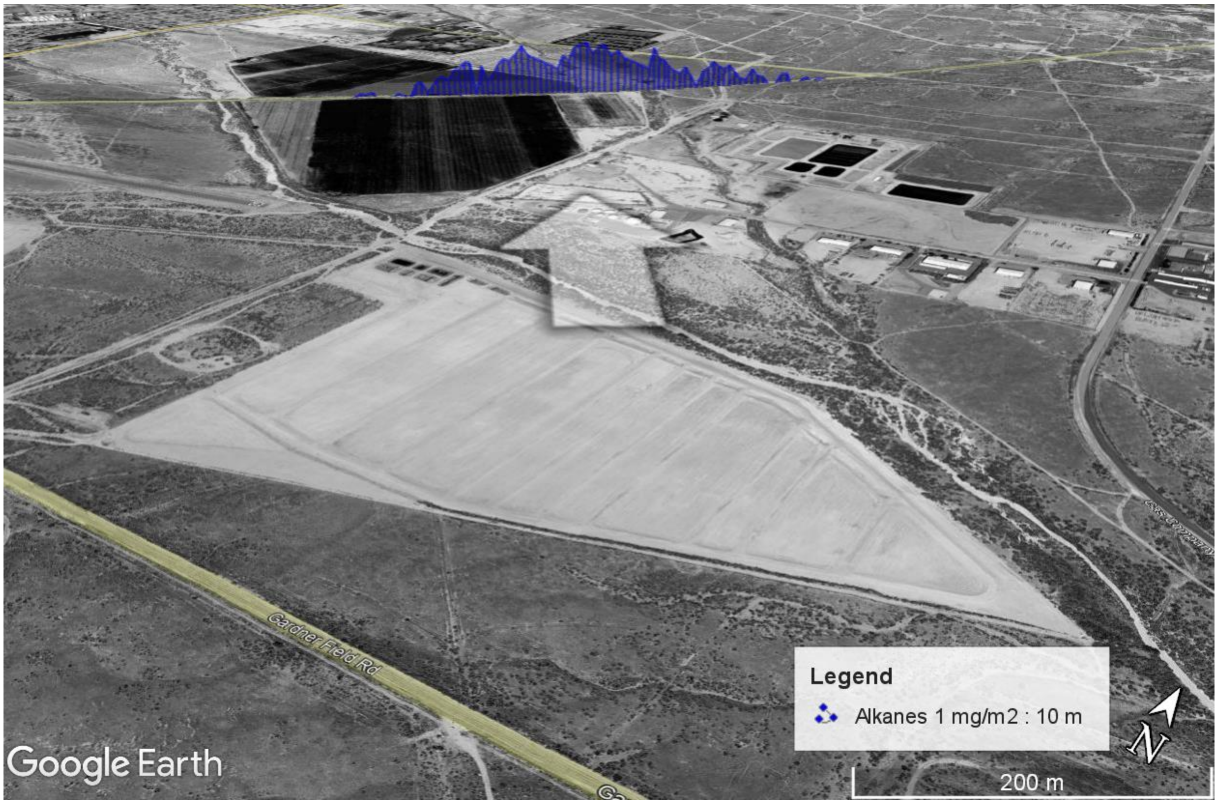

Figure 45. Alkane emission measurement from the Taft pond on 16 October 2019 , 12:50. The height of the blue contour corresponds to the measured column of alkanes where 10 m equals 1 mg/m^2. The white arrow indicates the average wind direction during the measurement. Map from Google Earth™, 2021.

Table 108. Measurements of Alkane emissions from McKittrick Pond 1-1, October 2019.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
191006	*114710-153104*	*3*	*7.3*	N/A	*2.1-2.6*	*59-344*
191018	*161137-161527*	*1*	*18.0*	N/A	*3.8-3.8*	*304-304*
Total # of Meas.		**4**				
Median			**9.3**			
IQR			**4.7 - 14.5**			
Mean			**9.9**			
SD			**6.9**			
CI 95%			**0 - 21.0**			

Table 109. Measurements of Alkane emissions from McKittrick Pond 1, October 2019.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
191006	*115935-120211*	*1*	*16.7*	N/A	*2.5-2.5*	*359-359*
191013	*162519-164133*	*2*	*2.9*	N/A	*2.5-2.8*	*314-325*
Total # of Meas.		**3**				
Median			**5.8**			
IQR			**2.9 - 11.2**			
Mean			**7.5**			
SD			**8.4**			
CI 95%			**0 - 28.5**			

Table 110. Measurements of Alkane emissions from Taft Pond, October 2019.

Day [yymmdd]	Time span [hhmmss-hhmmss]	N	Emission avg [kg/h]	Emission 95% CI [kg/h]	Wind Speed Min-Max [m/s]	Wind Dir Span [deg]
191016	121435-125423	4	18.1	7.3 - 28.9	0.7-1.7	106-192
Total # of Meas.		**4**				
Median			**15.3**			
IQR			**13.8 - 19.6**			
Mean			**18.1**			
SD			**6.8**			
CI 95%			**7.3 - 28.9**			

3.4 Emissions – Lost Hills local in-field sources

Seven days of in-field measurements were made within the boundaries of the Lost Hills field in the October 2019 survey. A large number of measurements were made of both individual wells and oil field sections managed by two different operators, as laid out in Figure 6 in the survey A setup section. According to the CalGEM database there was about 3930 active oil and gas wells in the Lost Hills field October 2019. It should be noted that there are also emissions from new, idle or plugged wells not included in this number, as well as from other production/treatment installations/facilities, and activities in the field.

Apart from the larger processing facilities, like the previously covered Lost Hills Processing 1, most of the larger emission sources were traced to activities: workover and other rigs, and vacuum trucks frequently encountered in the field. The large instantaneous emissions from these activities can make it more difficult to detect and locate smaller leaks in the proximity. The largest permanent sources were traced to various separators within the fields. These were not generally located on the fields of the operators for which we had authorization to measure which complicated identification since it was difficult to drive their perimeter. However, even well downwind their emissions could dominate quarter sections. Leak detection would have benefited from night-time measurements with less convection and better sensitivity to sources from a greater distance. Figure 46 shows an example of the type of digital data from the survey and its usefulness in identifying hotspots.

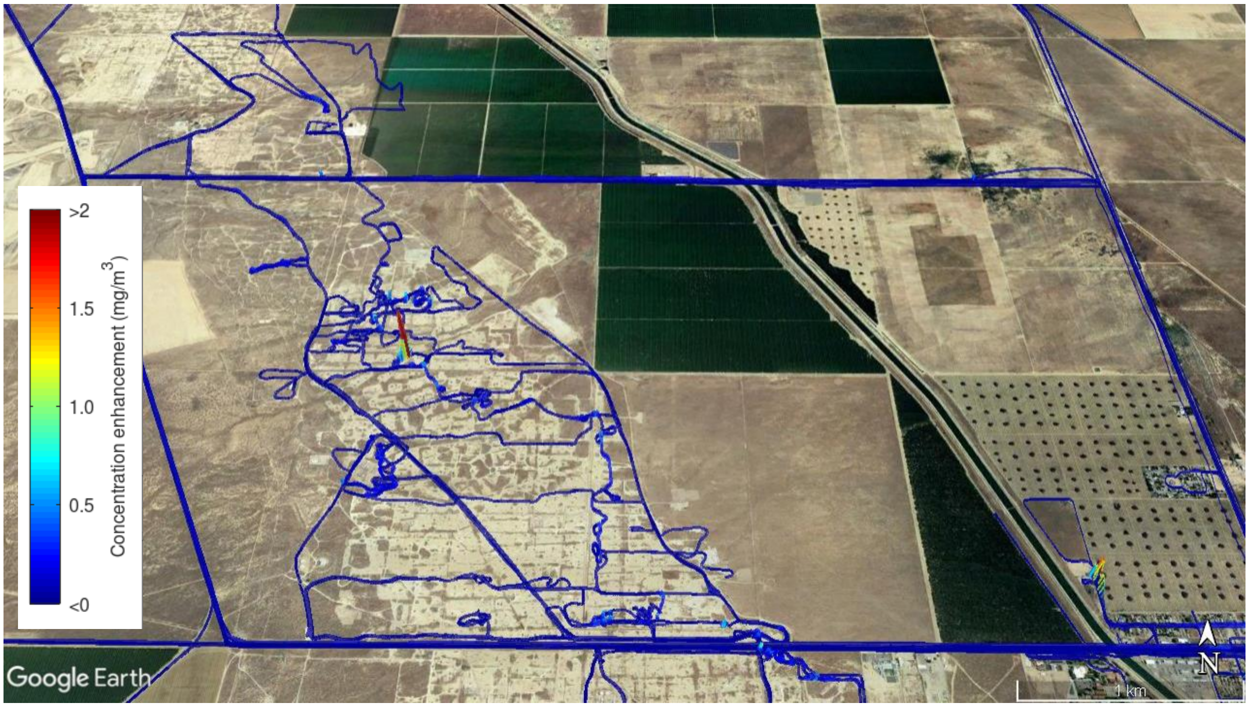

Figure 46 Concentration mapping of alkanes in Lost Hills - North area. Color and apparent height of curve (m) is proportional to concentration in mg/m^3 x 100. Map from Google Earth™, 2019.

Although a large number of well measurements were conducted, no large well head leaks were detected during the survey. The largest methane leak detected was instead traced to a buried pipeline that was later identified as belonging to a residential gas supplier and emissions averaged 4.5 kg/h methane. A smaller leak on a pipeline from a pumpjack was also identified through measurements and repaired by the operator.

Table 111 summarizes the results of section alkane emissions measurements where sections or groupings could be measured multiple times. The section emissions are often difficult to separate from one another and should be used merely as an indication of relative source strength.

For the two sectors with most measurement repeats, S5 and S24 in Table 111, the number of reported active wells in October 2019 was investigated in the CalGEM database. Sector 5 seemingly has mostly wells whereas sector 24 apart from wells also contain production/treatment facilities/installations. Attributing the observed alkane emissions of 12 kg/h in Sector 5 uniformly to the 196 active wells would give an average well emission of 0.06 kg/h. Corresponding approach for the 39 kg/h aggregate emission and 113 active wells in Sector 24 results in an average well head estimate of 0.35 kg/h but presumably this is biased high by contributions from the additional production/treatment facilities within this sector.

Table 111. Summary of alkane emissions measurements for sections and groupings of sections in the Lost Hills area made with SOF. Note that because measurements were made on different days individual section emissions do not necessarily sum to the whole of the group. Entries in grey had fewer than the minimum number of measurements required for 30% certainty in emissions. An underscore followed by a direction e.g. West, represents a half (West) or a quarter (NW) section.

Area	*Sections*	Days	N_{SOF}	Alkane [kg/h]	SD [kg/h]	CI -95% [kg/h]
Lost Hills – North	S13+18+19+24	2	2	126	NA	NA
	S19	2	2	21	NA	NA
	S24	3	6	39	21	22
	S32	3	3	30	NA	NA
Lost Hills - South	S3 - S10	1	2	135	NA	NA
	S4_West	1	2	13	NA	NA
	S4_North	2	3	10	NA	NA
	S5	2	5	12	7	9

Table 112 and Table 113 summarize unit (wellhead and aboveground equipment) and activity related emissions. Note that the unit and activity related emissions differ strongly from field measurements since they are biased to times of presumably higher emissions, i.e. a measurement is made when emissions were seen. For example, no measurements were made of vacuum trucks in the field that did not have obvious emissions. Because of time constraints these were ignored. Note that units identify an area rather than a specific pump jack, pipe, or other piece of equipment. Most units were measured only a single time but are included for completeness. Most of the well units are below the typically accepted quantification limit for SOF, 1 kg/h. Therefore, in addition to being biased to times of visible emissions, only one well unit had emissions significantly greater than 1 kg/h. This particular well was also within the vicinity of a vacuum truck which may have interfered, i.e. it was not possible to note the position of the vacuum truck in relation to the wind at all times. Normally SOF measurements are conducted with multiple repeats on each target in order to obtain statistics and improve certainty. For the measurements covered in

Table 63 focus was on targeting many sources in short time rather than a few with good statistics. In a total of 54 measurements, emissions from 21 units were targeted, and for the entirety of the well unit measurements alkane emissions averaged 0.66 kg/h.

Table 112 Summary of emissions measurements for well units (wellhead and aboveground equipment) in the Lost Hills area made with SOF. Entries in grey had fewer than the minimum number of measurements required for 30% certainty in emissions.

Units (Sequentially numbered for anonymization)	**Days**	**N_{SOF}**	**Alkane [kg/h]**
1	1	1	1.0
2	1	1	0.8
3	2	9	0.7
4	1	1	0.5
5	1	2	1.1
6	1	2	0.1
7	1	1	0.4
8	1	1	0.3
9	1	6	0.3
10	1	2	0.4
11	1	2	0.4
12	1	3	0.5
13	1	2	0.0
14	1	1	0.1
15	2	3	1.4
16	1	4	1.7
17	1	2	0.4
18	1	2	1.9
19	2	6	0.1
20	1	2	1.1
21	1	1	0.4
All		54	0.66

Table 113 Summary of emissions measurements for activity related and other equipment emissions in the Lost Hills area made with SOF. Entries in grey had fewer than the minimum number of measurements required for 30% certainty in emissions. An underscore followed by a direction e.g. West, represents a half (e.g. West) or a quarter e.g. (NW) section.

Approximate location and activity	**Days**	**N_{SOF}**	**Alkane [kg/h]**
S9_NW Vacuum Truck	1	3	2.0
Vacuum Truck Parking	1	3	1.7
S32 Drilling Fluid Container	1	1	0.3
S29 Workover rig & Vacuum Truck	1	2	1.4
S32 Workover	1	1	5.5
S4_SW Vacuum Truck	1	1	27.9
S4 Vacuum Truck	1	1	6.0
S5_SE Gathering	1	2	15.2

Additionally, emissions measurements of randomly selected wellheads and associated aboveground equipment were made using the tracer correlation technique. If a large number of wellheads can be measured in this manner, the technique can be used to scale up to field emissions. Due to access and time constraints only a few well units were measured in this fashion.

Six wells were initially randomly selected from wells that could be accessed from their entire perimeter. The selection was made by a CARB staff member. For the first 2 selections the exact well could not be located so the team measured the emissions from the well nearest the one identified in the selection process. Due to time constraints only 4 wellheads could be measured. Table 114 summarizes these measurements. Median emissions from these for alkane were 0.07 kg/h and for methane 0.06 kg/h.

Table 114 Summary of emissions measurements for wells in the Lost Hills area made with MeFTIR and tracer gas.

	Day [yymmdd]	Timespan [HHMMSS - HHMMSS]	N	Alkane Emissions ±SD [kg/h]	Methane Emissions ±SD [kg/h]	Wind Speed [m/s]	Wind Dir [deg]
1	191008	135721 -142031	8	0.07±0.10	0.02±0.02	1.6-2.5	17-355
2	191008	144914 -151152	6	0.10±0.06	0.15±0.11	0.7-2.7	7-348
3	191008	153715 -154803	5	0.02±0.02	0.06±0.08	2.0-3.5	3-60
4	191008	161052 -161943	5	0.04±0.03	0.01±0.01	0.8-2.3	30-72

3.5 Plume tracing and dispersion

Pollutant dispersion was investigated for sources in both the SJV and South Coast surveys. This is possible with a single mobile instrument by observing a pollutant plume and traversing that same plume at successive distances downwind. To successfully measure pollutant dispersion parameters with this approach requires relatively isolated sources with passable roads at suitable distances downwind. Early evening, just after boundary layer collapse, afforded the best opportunity to study plume dispersion for several sites in Kern County and one in Los Angeles. The Kern County sources were one unidentified source in Oildale, the Lost Hills – Processing 1, Well Site A in Arvin, and an unidentified source in central Bakersfield. For these sites it was possible to follow the plumes more than a kilometer downwind. The studied source in the South Coast survey was Jefferson, and for this site it was not possible to follow the plume more than a few hundred meters owing to other interfering sources.

Daytime measurements of plume decay were not generally possible due to rapid plume rise and rapid vertical dispersion resulting in a lack of suitable measurement distances with concentrations above detection limits. Additionally, emissions measurements needed to be prioritized during the day. The exception to this was one morning measurement before the daytime boundary layer developed at the Arvin – Well Site. Source locations for the calculations were specified as points and distance from source determined as the distance from the source to the measurement. While the exact emission source or location may be unknown this should not have much effect on the relative distances between measurements.

Plume dispersion relationships are presented in boxplots for each site studied. These plots are based on at least three individual plume transects at varying distances and the plotted values are the concentration for each measurement within the plume, i.e. all measurements above the detection limit. The number of points in each plume transect depends on the distance downwind of the source. For most sites few plume transects were possible far downwind so the data are heavily weighted to near measurements. It should be noted that source emissions likely vary in time which, combined with the actual dispersion conditions and temporal extent of the measurements, impacts the variability in concentration observations at different plume transport distances.

3.5.1 San Joaquin Valley

3.5.1.1 Oildale, Bakersfield – Unidentified source

Just to the east of Manor Street in Oildale, Bakersfield, an emissions source with distinct BTEX and alkane plumes was observed on several evenings. BTEX and Alkane plumes are shown in Figure 47 and Figure 48. Both alkane and BTEX plumes were evident in the residential neighborhood to the northwest of the presumed source. Plume concentrations as a function of distance from source are shown in Figure 49. The nearest measurements on Manor Street just downwind of the presumed source had alkane concentrations over 1000 $\mu g/m^3$ (421 ppb, butane equivalent), averaging approximately 200 $\mu g/m^3$. Further afield, and into the residential neighborhoods (approximately 500 m), concentrations drop to less than 400 $\mu g/m^3$, averaging less than 100 $\mu g/m^3$. At a distance of 2000 m, concentrations are below 20 $\mu g/m^3$ but the plume was still apparent. In terms of air toxics, BTEX concentrations were decidedly lower, but clearly apparent, at the same distances downwind. In terms of dispersion, a factor of 2 reduction of median concentration ("half-distance") occurred after 750 m.

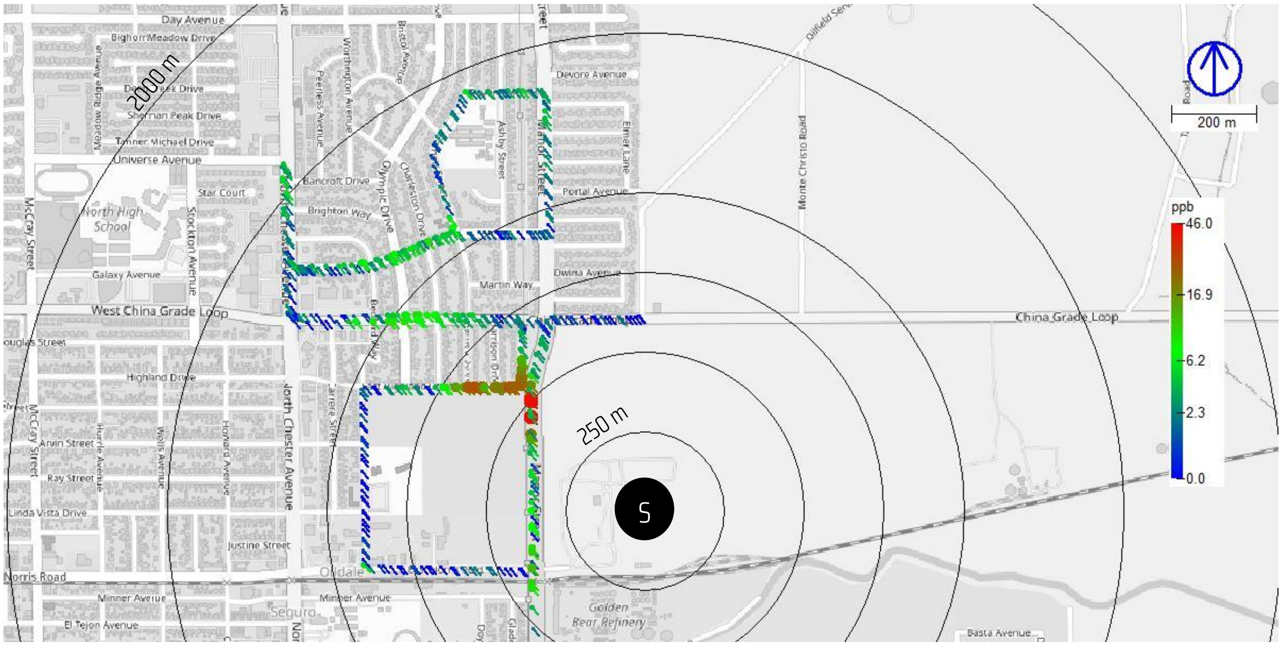

Figure 47 BTEX plume from source in Oildale, 20 October 2021, 18:58 – 19:21. Marker size and color scale are proportional to concentration (ppb). Color scale is logarithmic. Line from the mark points upwind in the direction of the source. Approximate location for plume distance calculation indicated with filled circle 'S'. Wind speed (KBFL) averaged 1.0 m/s. Arcs show the bin distances for the analysis.

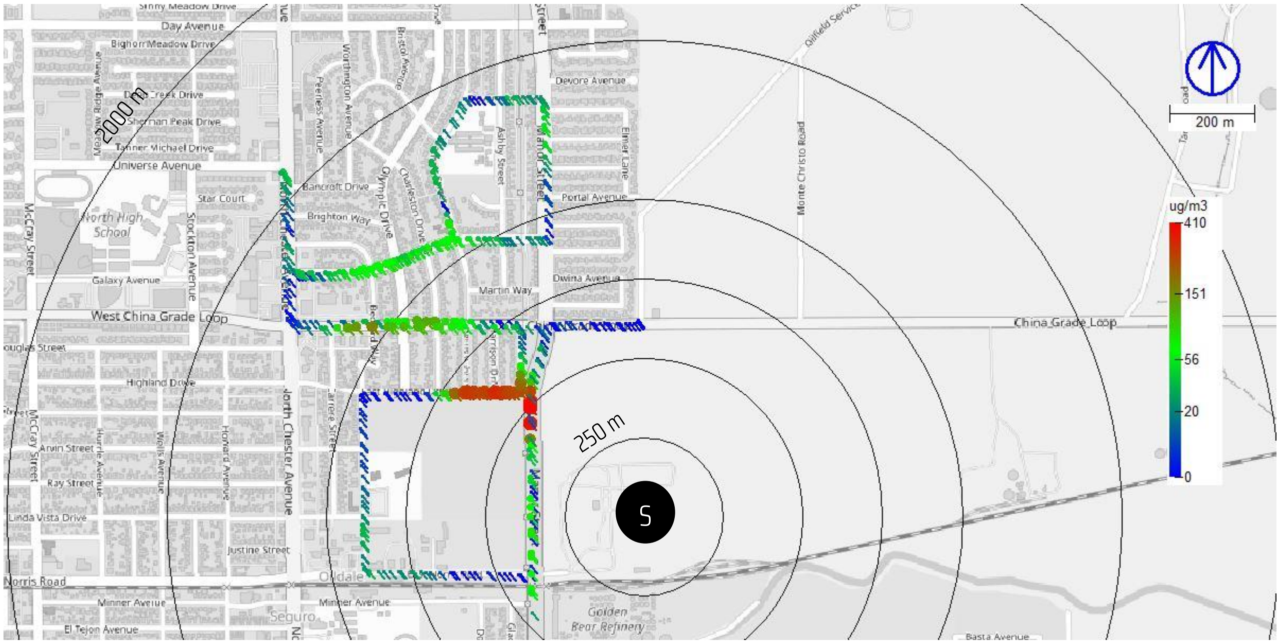

Figure 48 Alkane plume from source in Oildale, 20 October 2021 , 18:58 – 19:21. Marker size and color scale are proportional to concentration (µg/m^3). Color scale is logarithmic. Line from the marker points upwind in the direction of the source. Approximate location for plume distance calculation indicated with filled circle 'S'. Wind speed (Meadows Field KBFL) averaged 1.0 m/s. Arcs show the bin distances for the analysis.

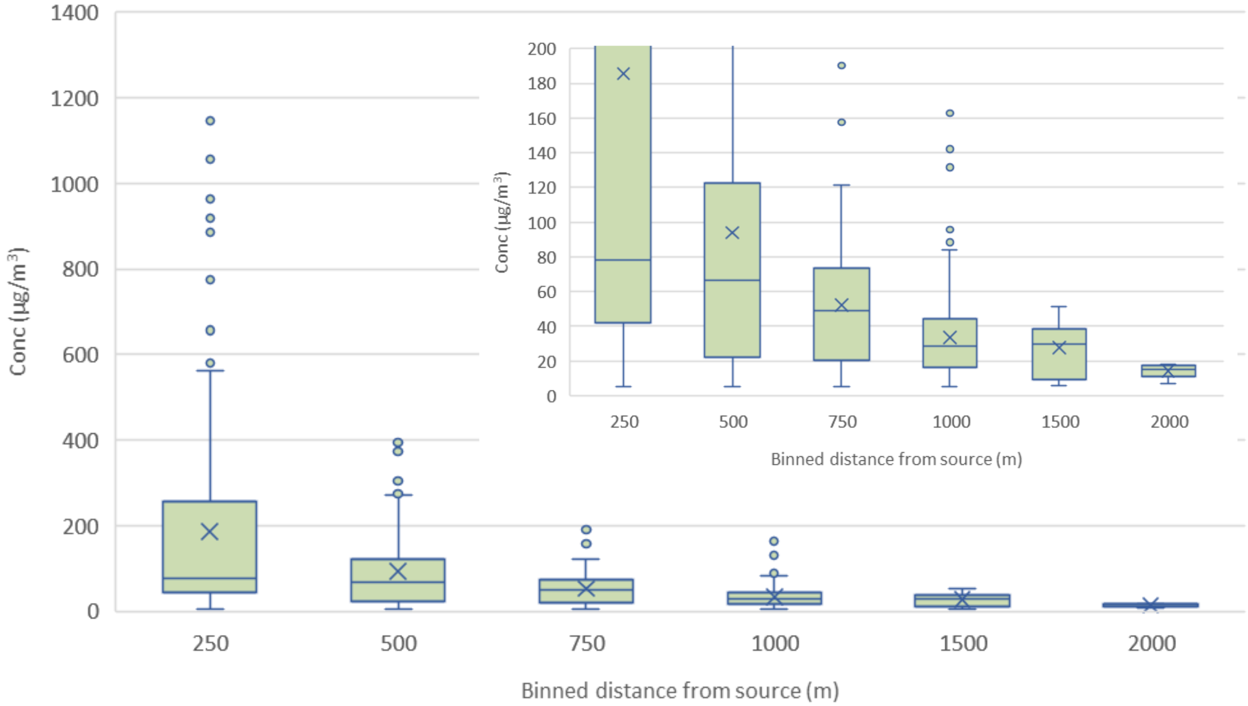

Figure 49 Alkane concentration as a function of distance from a point (presumed source location) in Oildale, October 2021 . All evening measurements binned by distance from source with bin minimum distance given. Inset: same data with concentration scale from 0 – 200 µg/m³. Box plots show interquartile range (shaded), median (line), mean (X), and outliers as point markers. Data are filtered out below the detection limit (5 µg/m³).

3.5.1.2 Lost Hills – Processing 1

Emissions from the facility to the southwest of Lost Hills (Processing 1) were measured during both 2019 and 2021 surveys, and given its proximity and isolation made a suitable source for plume tracing. The source area alkane emission was on average 54 kg/h and 58 kg/h for the 2019 and 2021 measurements, respectively. On two occasions during the 2021 survey, 17 and 20 October, winds were from the southwest allowing for plume tracing in the Lost Hills town. On 17 October, shown in Figure 50, winds were strong (6.5 m/s), and the plume showed little decrease in concentration with distance from the source (Figure 51). On the 20 October, shown in Figure 52, the plumes could be followed for a longer time with weak and shifting wind directions or multiple source areas. On this day there was a consistent decrease in concentration with distance from 1000 – 1750 m whereafter the concentration remained unchanged (Figure 53). It should be noted that the studied source is part of larger oil field, and the further away from the source the measurement is conducted, the more the source plume will merge into the overall plume from the field. Finally, the detection limit sets a fixed lower limit for the concentration measurement and plume detection. The “half-distance” for median concentration was on the order of 1250 m for the plume tracing displayed in Figure 52. Figure 54 shows how a BTEX plume from Lost Hills can be traced over to I5.

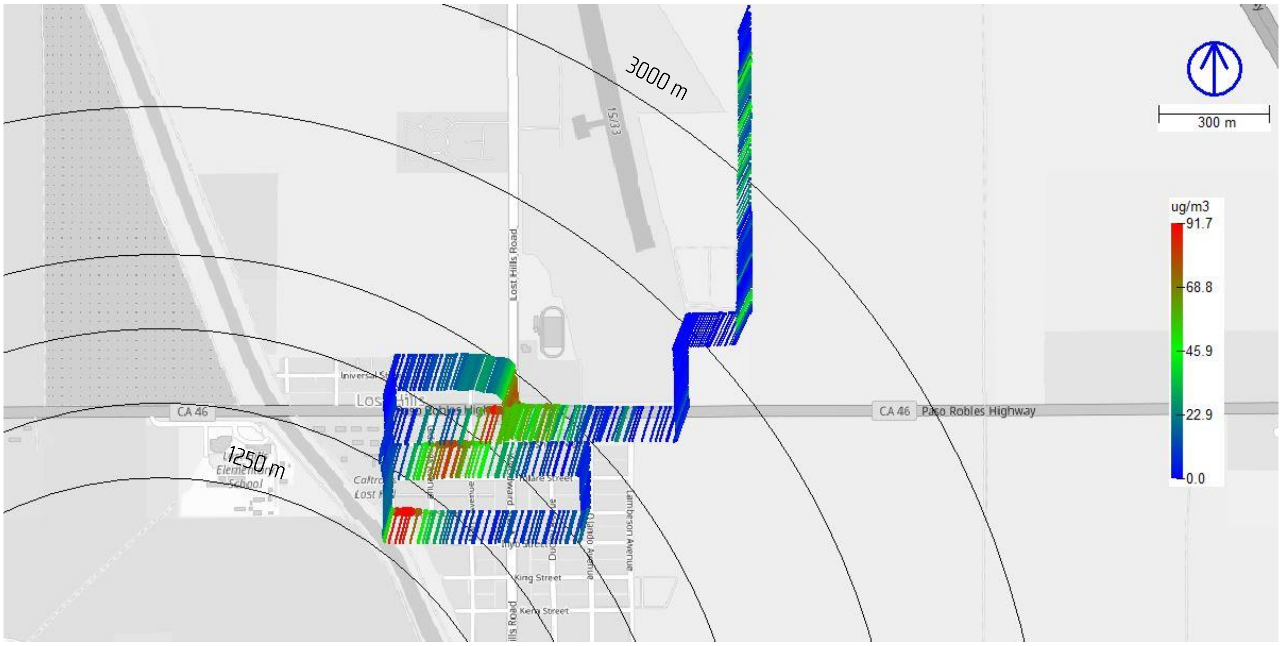

Figure 50 Alkane plume from sources in Lost Hills (Processing 1), 17 October 2021 , 18:18 – 18:47. Marker size and color scale are proportional to concentration (µg/m^3). Line from the marker points upwind in the direction of the source. Wind speeds averaged 6.5 m/s (range 6 – 7 m/s). Arcs show the bin distances for the analysis.

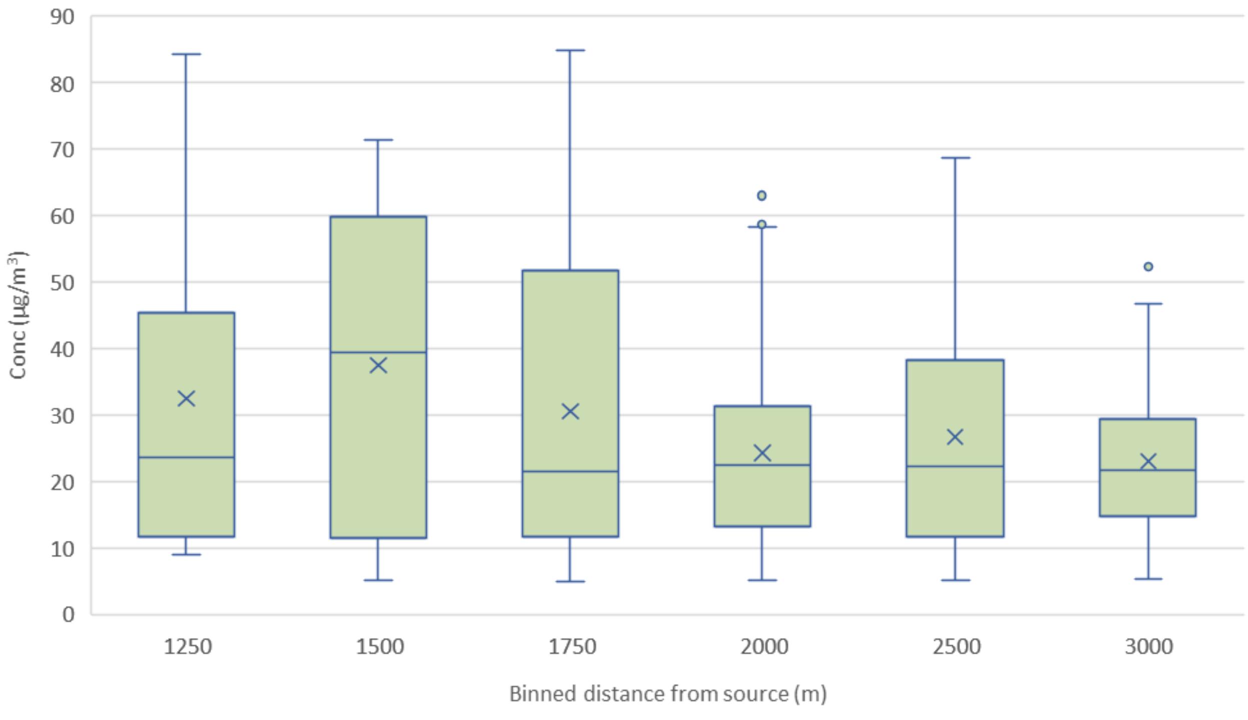

Figure 51 Alkane concentration as a function of distance from a point (Lost Hills – Processing 1), 17 October 2021 . Measurements binned by distance from source (not grouped by plume transect) with bin minimum distance given. Box plots show interquartile range (shaded), median (line), mean (X), and outliers as point markers. Data are filtered out below the detection limit (5 µg/m^3). Winds were strong during the measurements, 6.5 m/s on average.

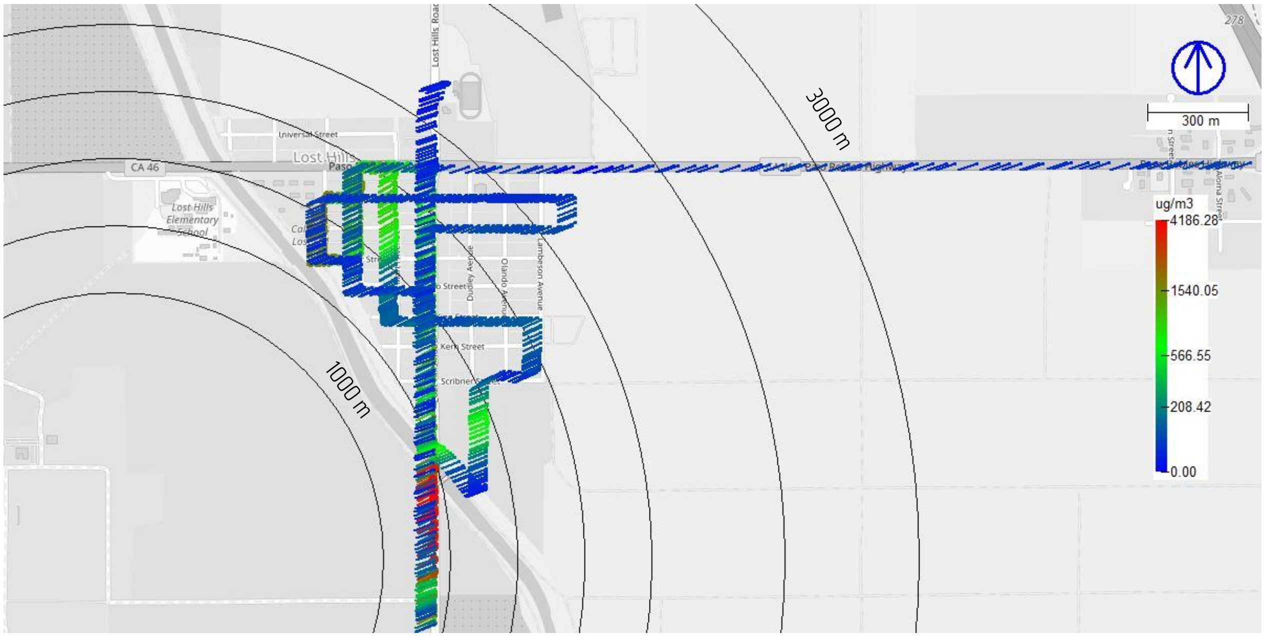

Figure 52 Alkane plumes from sources in Lost Hills (Processing 1), 20 October 2021 , 19:30 – 20:31. Marker size and color scale are proportional to concentration (μg/m^3). Color scale is logarithmic. Line from the marker points upwind in the direction of the source. Wind speeds averaged 2 m/s (range 1 – 4 m/s). Note the wind turned more westerly during the measurements. Arcs show the bin distances for the analysis.

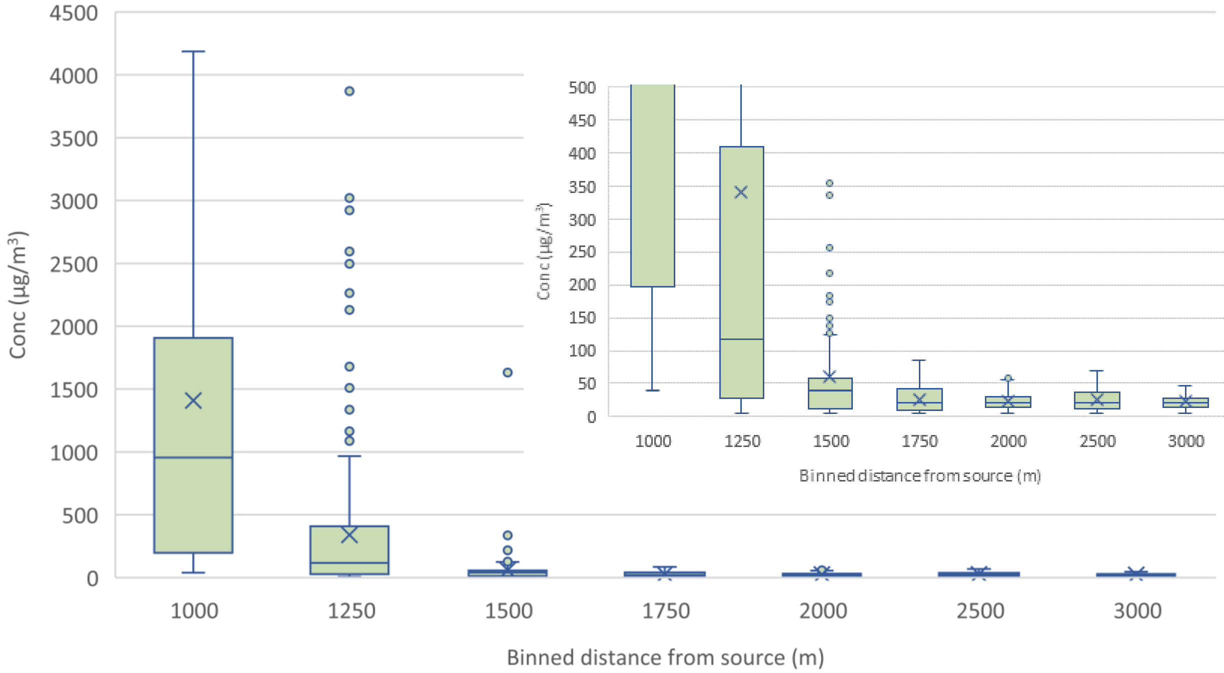

Figure 53 Alkane concentration as a function of distance from a point (Lost Hills – Processing 1), 20 October 2021. Measurements binned by distance from source with bin minimum distance given. Inset: same data with concentration scale from 0 – 500 µg/m^3. Box plots show interquartile range (shaded), median (line), mean (X), and outliers as point markers. Data are filtered out below the detection limit (5 µg/m^3). The bin 1750, (1750 – 2000 m) falls in the distance between 2 plumes and so captures only plume flank not the peak concentration in the plume.

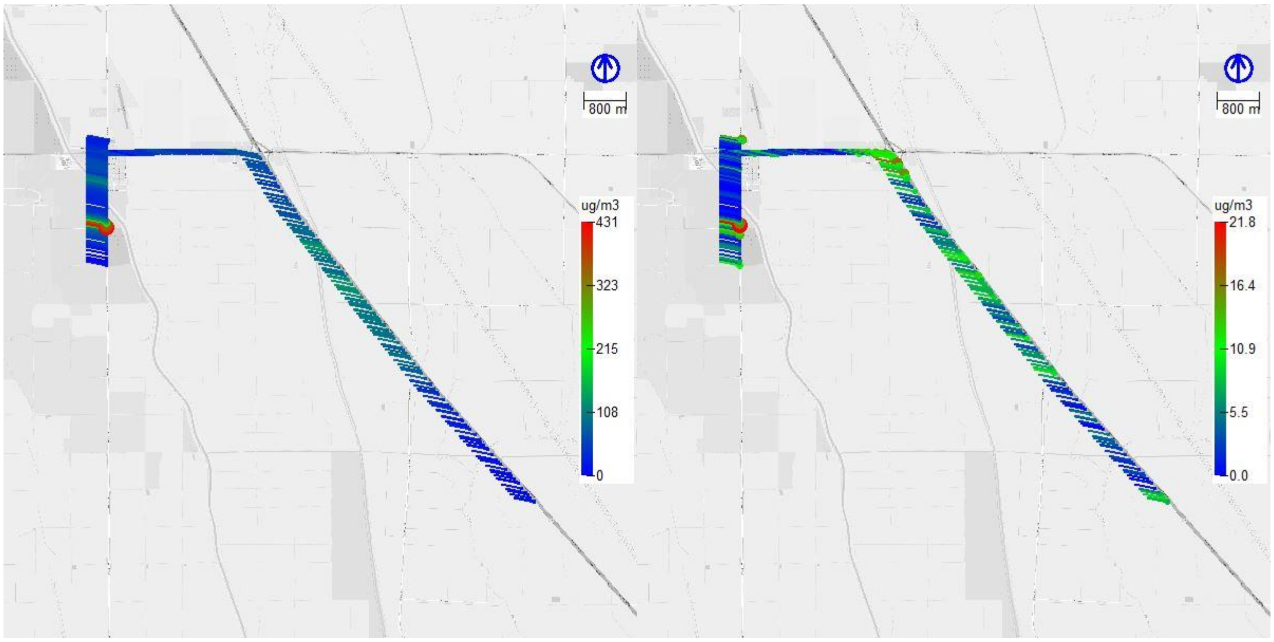

Figure 54 Alkane (left) and BTEX (right) plumes from sources in Lost Hills (Processing 1 and others), 20 October 2021 , 20:18 – 20:37. Marker size and color scale are proportional to concentration (µg/m^3). Note, BTEX at the junction of I5 and Highway 46 is from the fueling stations and associated facilities.

3.5.1.3 Arvin – Well Site A

Alkane and BTEX emissions from a well site near the intersection of Comanche and Bear Mountain Road (Arvin Site A) were observed on several occasions during concentration mapping in Arvin. Figure 55 shows measurements from the evening of 18 October with the source located between an apartment complex and a small housing subdivision. Because of light winds and shifting directions (NE – SE) on this evening the source location was not immediately known and could not be determined until later.

Additional measurements had been made on two prior evenings, and subsequently on one morning (19 October). Emissions of alkanes were measured from the site daytime, averaging 17.5 kg/h on 19 October, but may have included other sources, so these should only be considered observational. Figure 56 shows the concentrations in the plume with distance from the source. The irregular variation in concentration with distance is likely due to incomplete transects and shifting winds so a "half-distance" is not clear-cut but around 200 m.

It is possible that this source was observed even much further afield (on Malaga Road) at night however, we cannot rule out intervening sources so for plume dispersion purposes only plumes without suspect intervening sources were used. For Figure 56 only evening observations were used because of the large differences in nighttime and daytime concentrations.

Figure 55 Alkane plumes from sources in Arvin, 18 October 2021 , 21:40 – 22:38. Marker size and color scale are proportional to concentration (µg/m^3). Color scale is logarithmic. Line from the marker points upwind in the direction of the source. Wind speeds averaged 0.9 m/s. Arcs show the bin distances for the analysis.

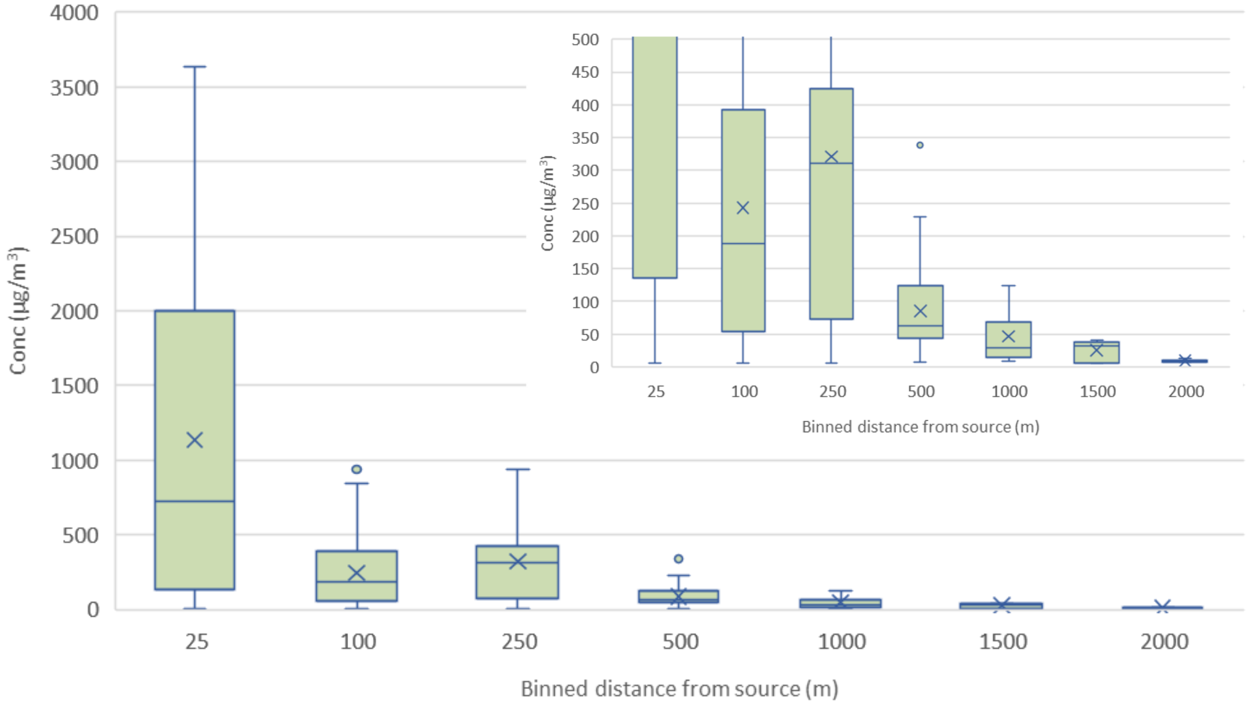

Figure 56 Alkane concentration as a function of distance from a point (presumed source location) in Arvin, October 2021 . All evening measurements binned by distance from source with bin minimum distance given. Inset: same data with concentration scale from 0 – 500 µg/m^3. Box plots show interquartile range (shaded), median (line), mean (X), and outliers as point markers. Data are filtered out below the detection limit (5 µg/m^3).

3.5.1.4 Central Bakersfield – Unidentified source

An example of plume tracing to identify the source of the emissions is shown in Figure 57. This source in central Bakersfield near Highway 58 was observed during routine measurements and during transport between measurement areas. On one occasion the plume was first observed from a distance of several kilometers downwind and was subsequently followed to an approximate source area, driving from north to south in Figure 57. Winds very light at that time (average wind speed 1.3 m/s). Figure 58 shows concentrations with distance from the presumed source with a half-distance of about 1000 m. Note that no observations were made with a distance between 1000 – 1500 m or 3000 – 3500 m.

This source was outside the scope of the project, so no emissions measurements were made for it specifically. Occasionally an unidentified source of emissions in this vicinity was measured but wind directions were uncertain at that time.

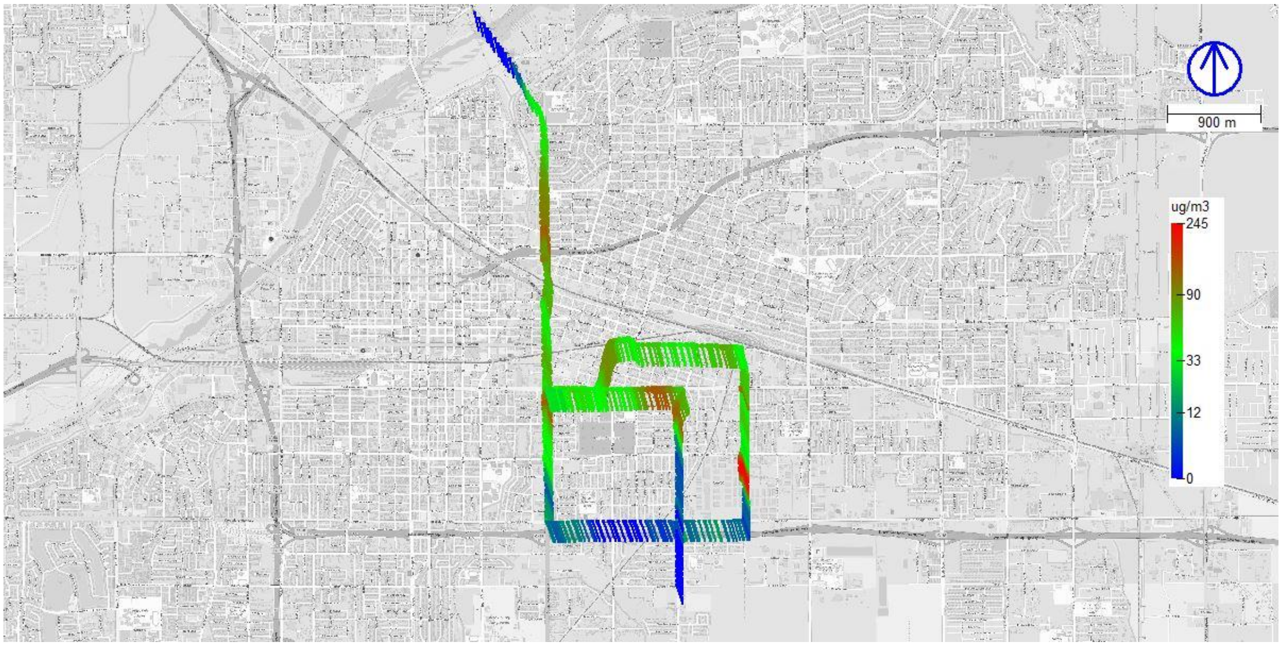

Figure 57 Alkane plume from source in central Bakersfield, 12 October 2021 , 22:47 – 23:16. Marker size and color scale are proportional to concentration (µg/m^3). Color scale is logarithmic. Line from the marker points upwind in the direction of the source. Wind speed average 1.3 m/s.

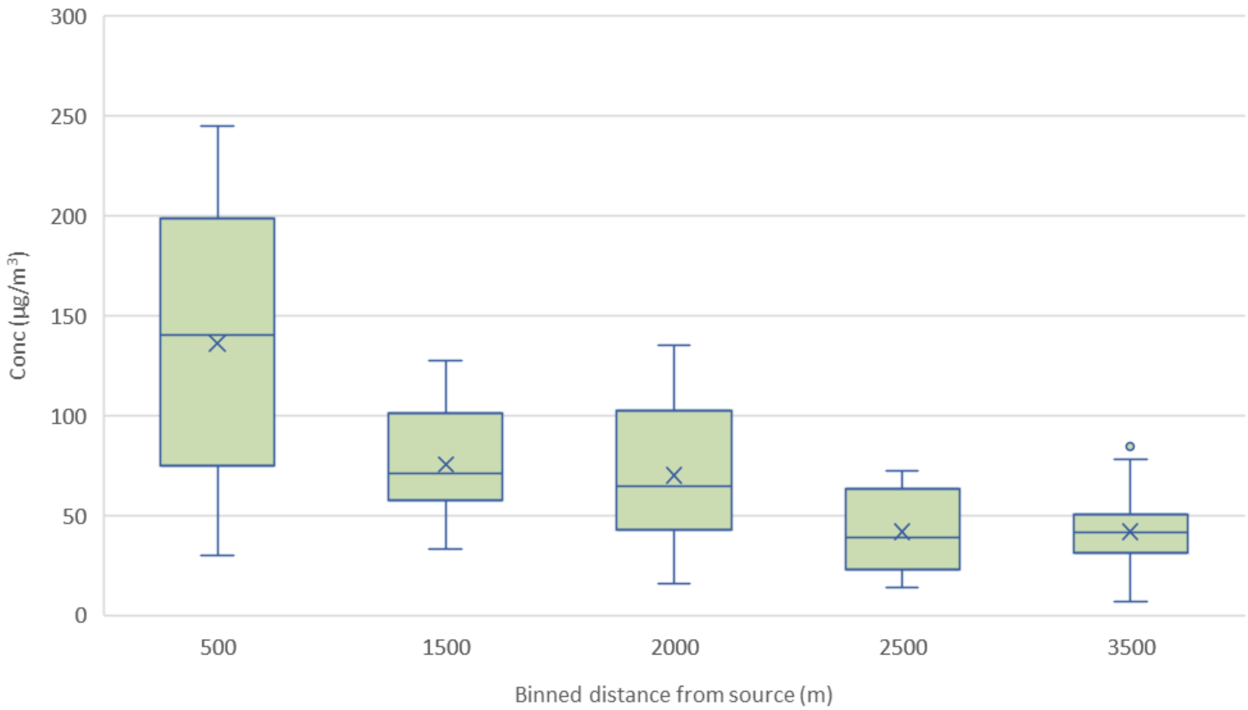

Figure 58 Alkane concentration as a function of distance from a point source in central Bakersfield, 12 October 2021 . Note that no observations were made with a distance between 1000 – 1500 m or 3000 – 3500 m.

3.5.2 South Coast Air Basin

Emissions from the Jefferson Boulevard site were measured on several days and was revisited on one evening for concentration mapping for plume dispersion. Figure 59 shows two measurements of plume dispersion beginning closest the source, which is a well and Processing Site within the Las Cienegas field. There are additional sources slightly further afield which interfered with plume transects beyond this extent. Compared to the plumes studied in SJV, the Jefferson plume had more lateral dispersion, even at a short distance. Figure 60 shows the concentration as a factor of distance from the source with a half-distance of 100 m. It is likely that the dense built environment here enhanced both mechanical mixing as well delaying the stable boundary layer as compared to some of the SJV plume tracing episodes.

Figure 59 Alkane plumes from Jefferson, 7 July 2021 , 20:49 – 21:11 (top) and 21:31 – 22:09 (bottom). Marker size and color scale are proportional to concentration (µg/m^3). Color scale is logarithmic. Line from the marker points upwind in the direction of the source. Wind speed was 1 - 1.5 m/s during the measurements.

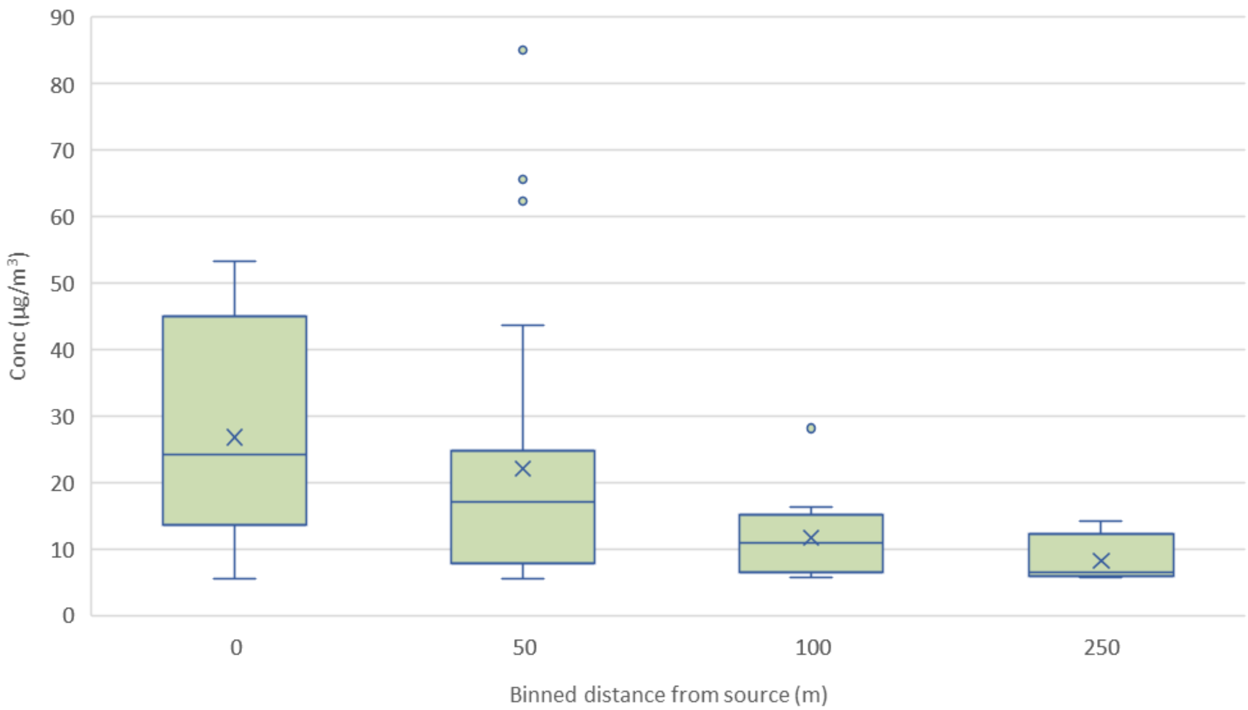

Figure 60 Alkane concentration as a function of distance from Jefferson, 7 July 2021 . Wind speed was 1 - 1.5 m/s during the measurements.

3.6 Concentration monitoring in potential SNAPS and CAPP communities

In the 2021 surveys, concentration measurements of aromatic and other VOCs were made concurrently with emissions measurements and more targeted measurements during the evening and other periods when emission measurements were not possible. In the 2019 survey, concentrations of aromatic species were more limited during times of daytime emissions measurements because of DOAS spectrometer time sharing between the SkyDOAS (SO_2, NO_2, H_2CO) and the MWDOAS BTEX measurements. All results are in enhancement (concentration above background) and are presented by geographic location, and for the western SJV sites also separated by year of measurement.

Daytime conditions in general show stronger vertical mixing and stronger dispersion and thus lower concentrations at ground level than at nighttime. Evening, early morning and night are the times most favorable for encountering higher concentrations with lower wind speeds and less vertical mixing. In this project, concentration measurements were done in parallel to emission measurements during daytime, typically near the fenceline of sites and facilities, and in dedicated concentration screening efforts in communities during evening, nighttime and early morning.

3.6.1 San Joaquin Valley

Concentration monitoring in communities was performed at least one day each in Lost Hills, in and around McKittrick, Derby Acres and Taft (Table 115) during both SJV surveys in October 2019 and September-October 2021, respectively. Concentration mapping in Bakersfield, primarily around Oildale and Kern River and in the communities to the southeast of Bakersfield was conducted in October 2021 (Table 116).

Table 115. Days with targeted concentration mapping in support of Community Monitoring (CM) around Kern County oil fields west of Bakersfield.

Area	Date 2019	Date 2021
Lost Hills	7-Oct (evening), 9-Oct (early morning), 15-Oct (evening)	05-Oct (day & evening), 17-Oct (day & evening), 21-Oct (evening)
McKittrick	13-Oct (evening), 17-Oct (evening)	Multiple days, evenings on Hwy 33, 21-Oct (day)
Derby Acres	13-Oct (evening), 17-Oct (evening)	28-Sep (evening), 21-Oct (day)
Taft	18-Oct (afternoon)	

Table 116. Days with targeted concentration monitoring in support of CM around Kern County oil fields near Bakersfield.

Area	Date 2021
Oildale and Kern River area	05-Oct (day & evening), 17-Oct (day & evening), 21-Oct (evening)
Arvin	Multiple days, evenings on Hwy 33, 21-Oct (day)
Edison and Mountain View Fields	28-Sep (evening), 21-Oct (day)

3.6.1.1 Lost Hills

Lost Hills town is situated just at the eastern edge of the Lost Hills field, essentially between the Lost Hills - North (the northern portion of Lost Hills field, also called Lost Hills 1) and Lost Hills - South (the southern portion of Lost Hills field, 2) fields that are separated by Highway 46 going east-west. Westerly winds should bring oil field plumes (if present) in over the community. A larger oil and gas processing plant is located to the southwest of Lost Hills town approximately 1 km from the edge of the residential area.

In 2019 measurements were made on two evenings with westerly winds and one morning with north-westerly winds such that emissions should have been coming from the direction of the oil fields. On 7 October one residential source of BTEX was observed as well as some VOC enhancement at the southern end of the community (Figure 61) likely originating from oil field sources including Processing 1. On 15 October 2019, a residential BTEX plume was observed in the northern residential park and a VOC plume was noted originating from a small garden fire as shown in the upper graph of Figure 62.

Community concentration mapping was also conducted in Lost Hills on 5, 17 and 21 October 2021, with generally W-SW wind conditions. Figure 63 shows an aggregate plot of concentrations observed, where multiple concentrations within a grid cell of 50x50 m have been averaged. The symbols in the inset indicate number of observations within a grid cell whereas the color show the average concentration (range) observed.

An average alkane enhancement of up to 400 µg/m^3 was seen in the east part of the community and along Lost Hills Rd south of the town, Figure 63. This is directly downwind of the Lost Hills Oil Field with no intervening upwind sources. The corresponding average BTEX enhancement was 1-7.5 ppb (Figure 64). In both the alkane and BTEX maps, other sources such as the fueling stations at the junction of I5 and Highway 46 can also be seen to have an impact. Along 46 and at the intersection of Lost Hills Rd (a 4-way stop) may also impact that particular stretch of road. Benzene concentrations was generally not detectable above 1 ppb as seen in Figure 65. See section 3.5.1 and 3.7.2 for plume tracing and dispersion modeling of specific sources in this region.

Figure 66 shows stationary concentration measurements made over twenty minutes in October 2019 close to the Lost Hills SNAPS measurement location. On this occasion winds were blowing from west, along the highway separating the north and south section of the Lost Hill field. Alkane and BTEX measurements show more short time variation, possibly some traffic related, than methane. Ethane shows both time scale variations. Benzene was below detection level.

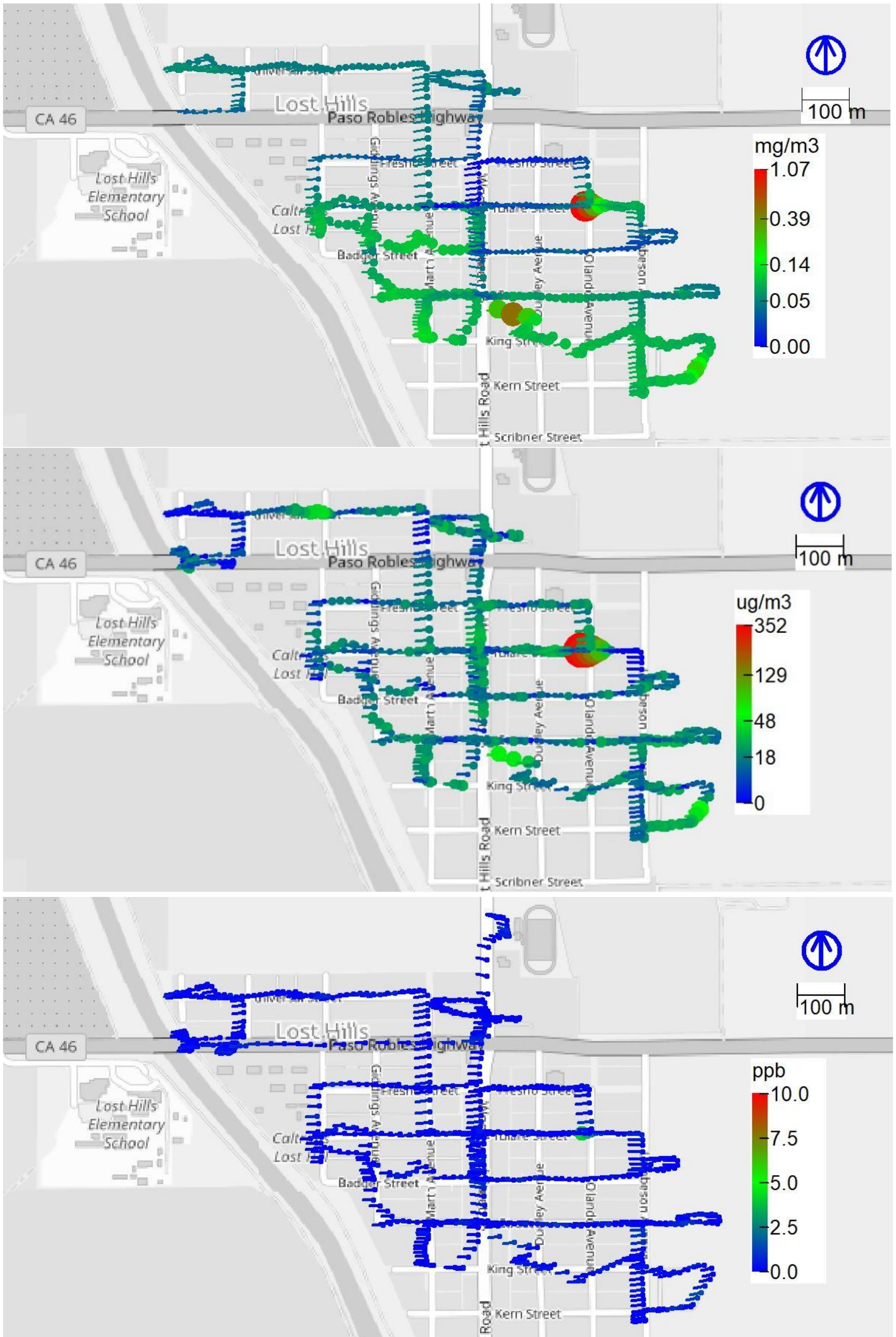

Figure 61. Mobile concentration measurements for community monitoring in Lost Hills 7 October 2019 , 20:33 – 21:39. Color scale and point size show alkane concentrations (mg/m^3, upper), BTEX concentrations (μg/m^3, middle) and benzene concentrations (ppb, lower). The lines point up in wind (e.g. westerly wind here). Note: **Alkanes** and **BTEX** are plotted with logarithmic color scale.

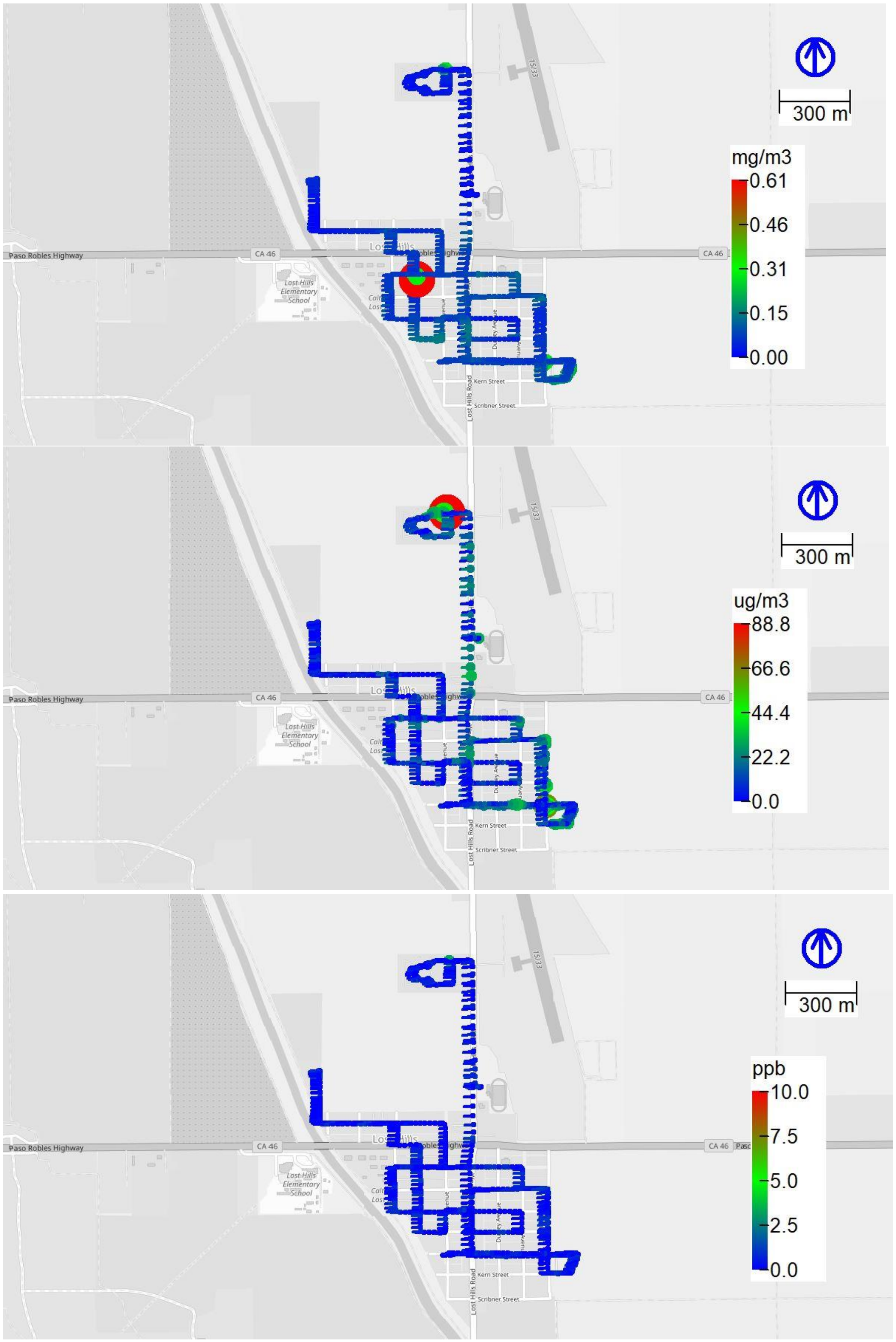

Figure 62. Mobile concentration measurements for community monitoring in Lost Hills 15 October 2019 , 19:30 – 20:35. Color scale and point size show alkane concentrations (mg/m^3, upper), BTEX concentrations (μg/m^3, middle) and benzene concentrations (ppb, lower). The lines point up in wind (e.g. westerly wind here). The middle plot highlights a residential source of BTEX.

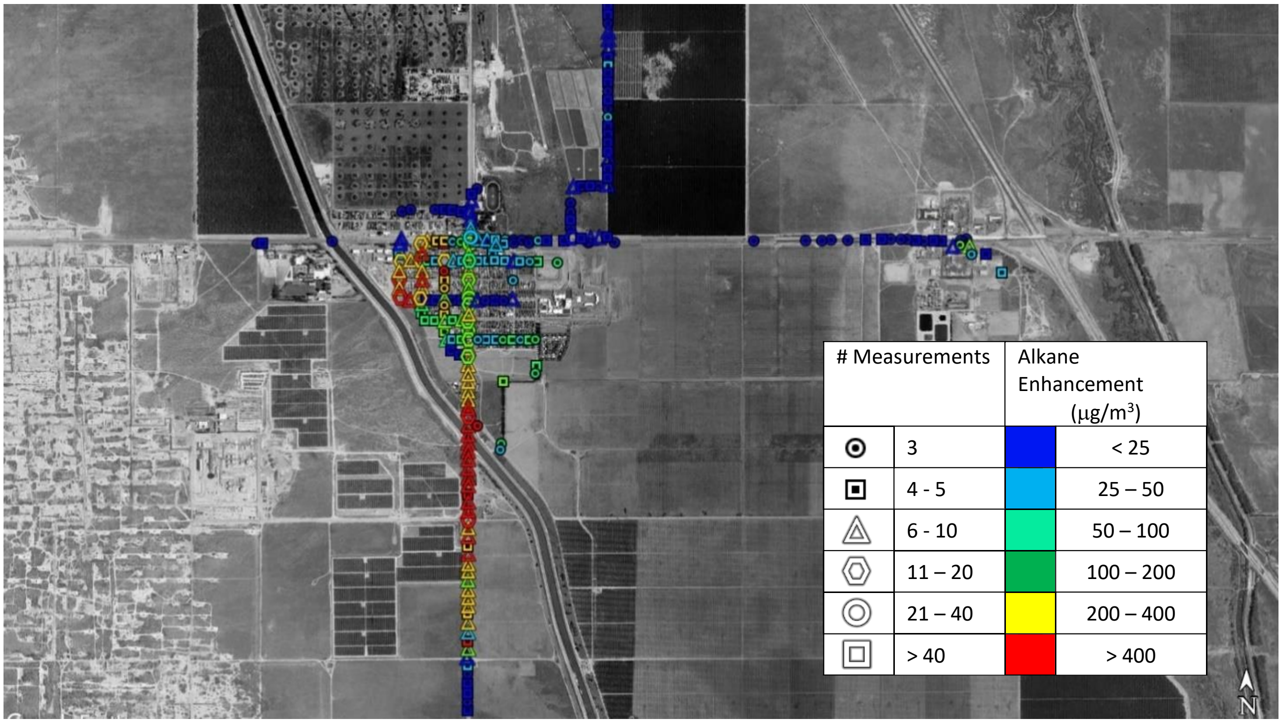

Figure 63. Concentration map of **alkanes** in the Lost Hills area based on several days, October 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

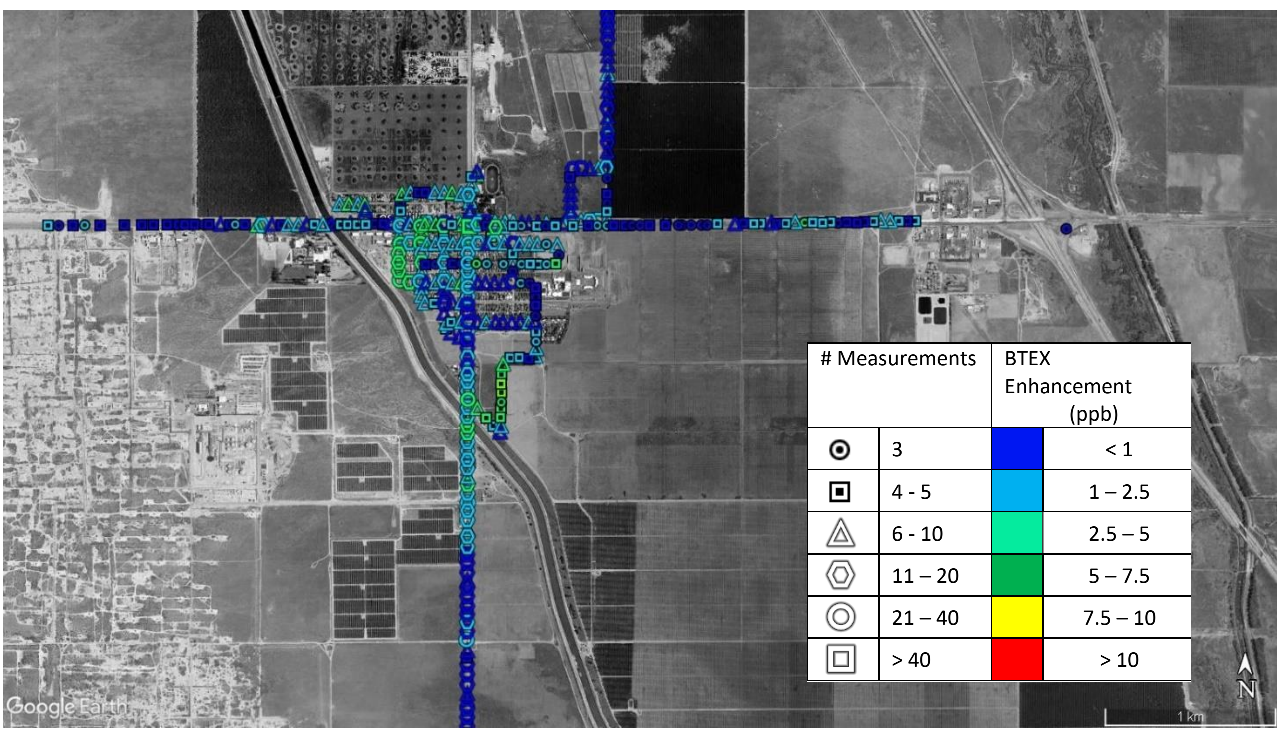

Figure 64. Concentration map of **BTEX** in the Lost Hills area, October 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

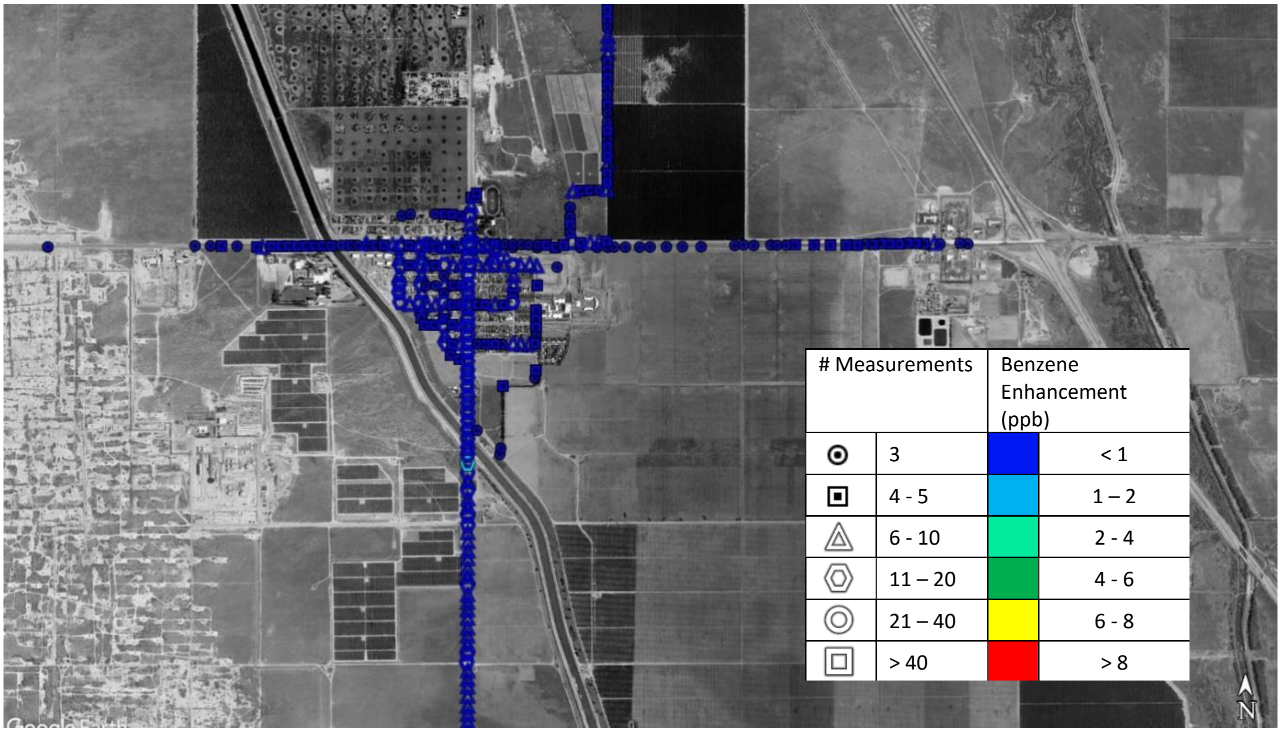

Figure 65. Concentration map of **benzene** in the Lost Hills area, October 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

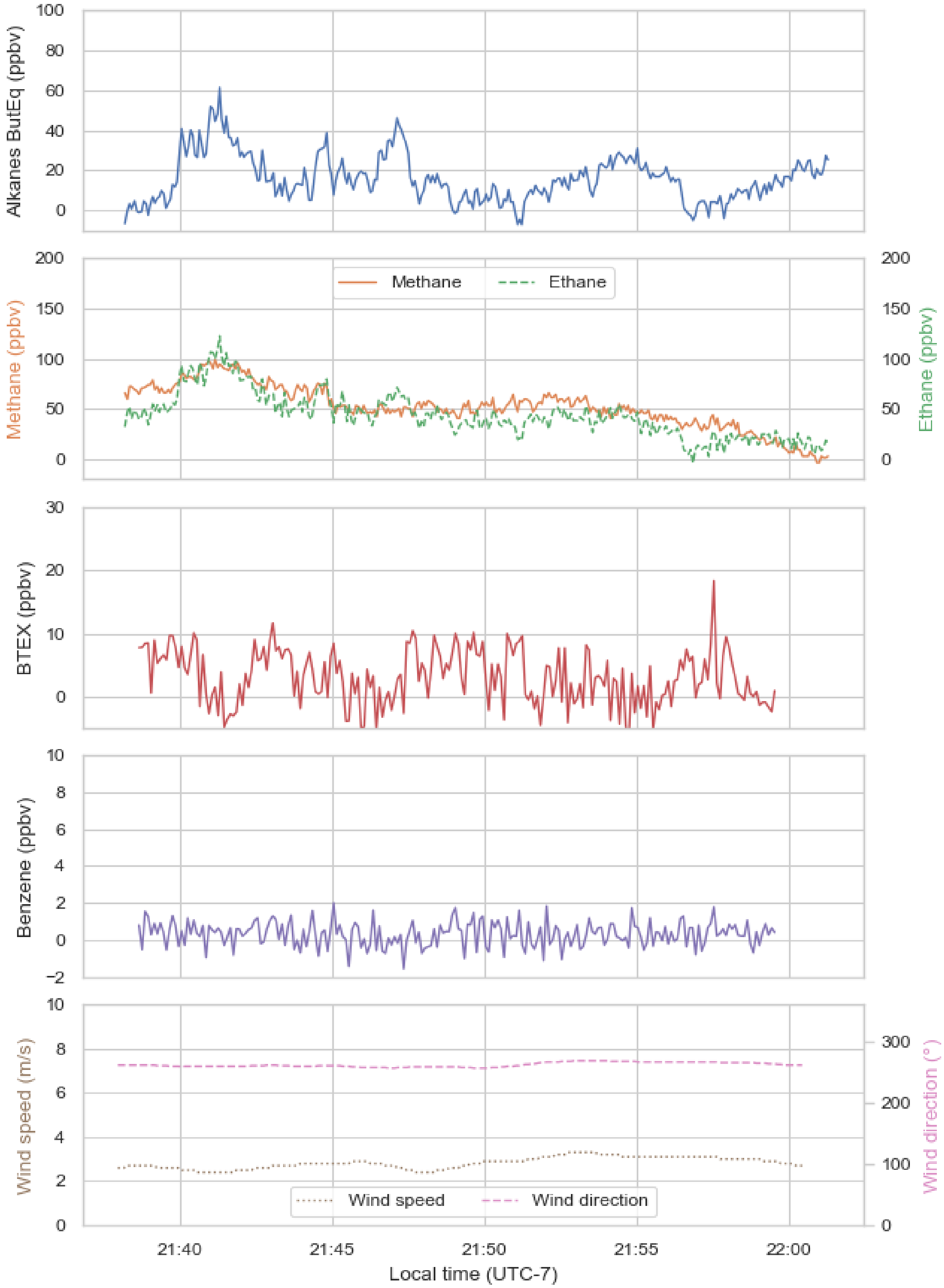

Figure 66. Stationary (enhancement) concentration measurements just outside the Lost Hills Water Resources on 7 Oct 2021 . Winds were along Highway 46.

3.6.1.2 McKittrick

With most of the focus of the survey in Lost Hills during the October 2019 survey, only one evening was dedicated for measurements further afield including the communities of McKittrick. No notable BTEX plumes from the surrounding oil fields or facilities were observed in McKittrick (Figure 67, lower plot) during this evening and only a general minor enhancement of alkanes in the oil field region west of the community (Figure 67, upper plot).

Figure 67. Mobile concentration measurements of **alkanes** (mg/m^3, above) and **benzene** (ppb, below) in and around the McKittrick 13 Oct 2019 . Color scale and point size show concentration and the lines point up in wind.

The few roads within the small McKittrick center were only driven once during the 2021 survey so aggregate plots cover mostly the major roads bisecting McKittrick, Highway 33 and Reward/Reserve Road. Figure 68 and Figure 69 show average BTEX and benzene enhancement where at least 3 measurements within a 50 m grid were made. Alkane and methane enhancements are dominated by in field plumes on Reward Road.

A BTEX enhancement (2-5 ppb) was concentrated along Reward Rd where high alkane concentrations were also often encountered (Figure 68). No consistent benzene plumes were seen in these measurements in the vicinity of McKittrick (Figure 69).

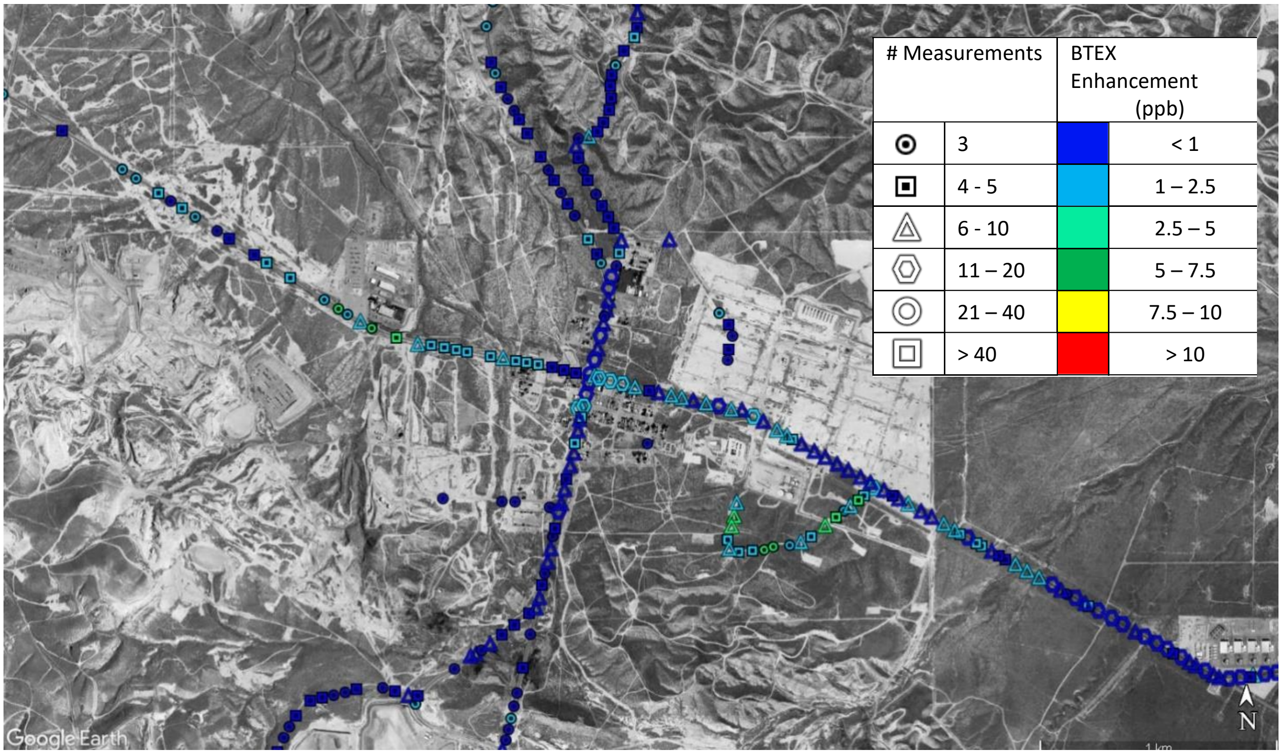

Figure 68. Concentration map of BTEX in the McKittrick area, October 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

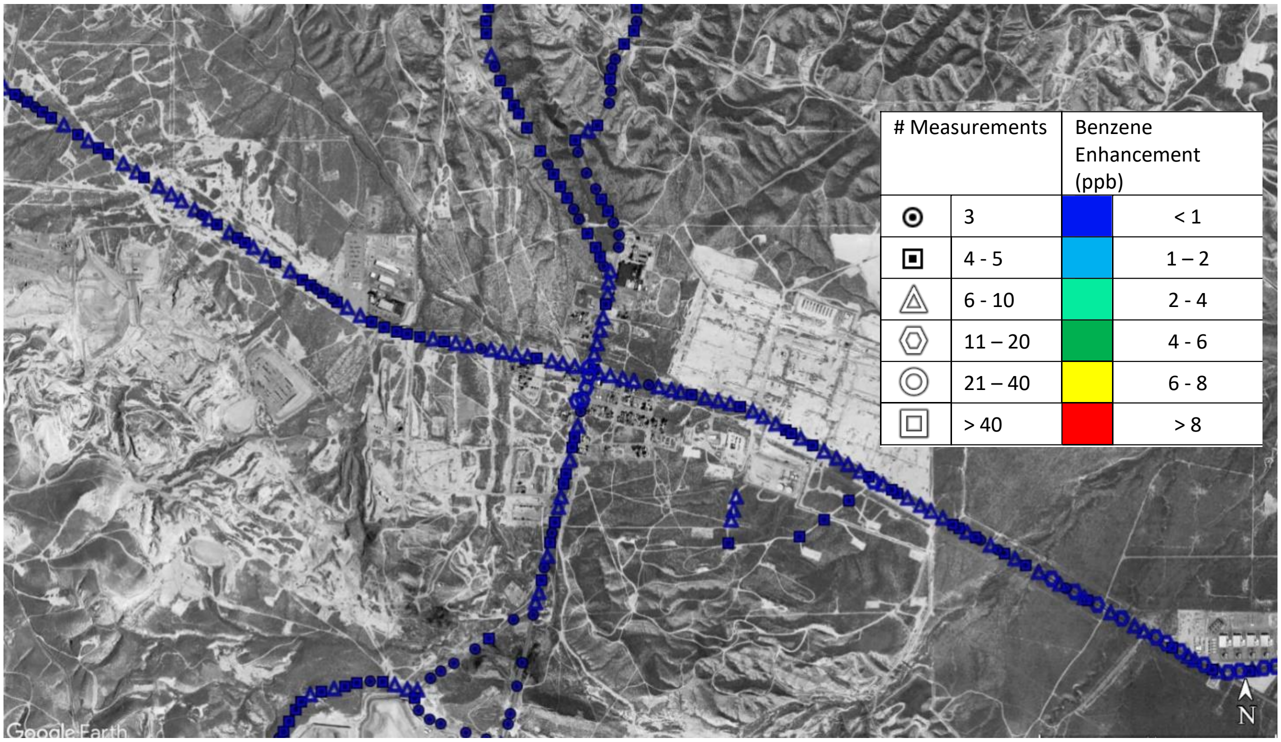

Figure 69. Concentration map of **benzene** in the McKittrick area, October 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

3.6.1.3 Derby Acres

Community concentration mapping was conducted in Derby Acres on the 13 October 2019. The wind was weak and northwesterly during the measurements. No enhancement of alkanes, BTEX or benzene (Figure 70, lower) were detected inside the community but a sharp and consistent methane plume east of Hwy 33 was found (see Figure 70, upper). This was likely related to a presumed residential/domestic gas leak (could not be confirmed) at the Hwy 33 and Derby Ave intersection and not to any source in the surrounding oil and gas field.

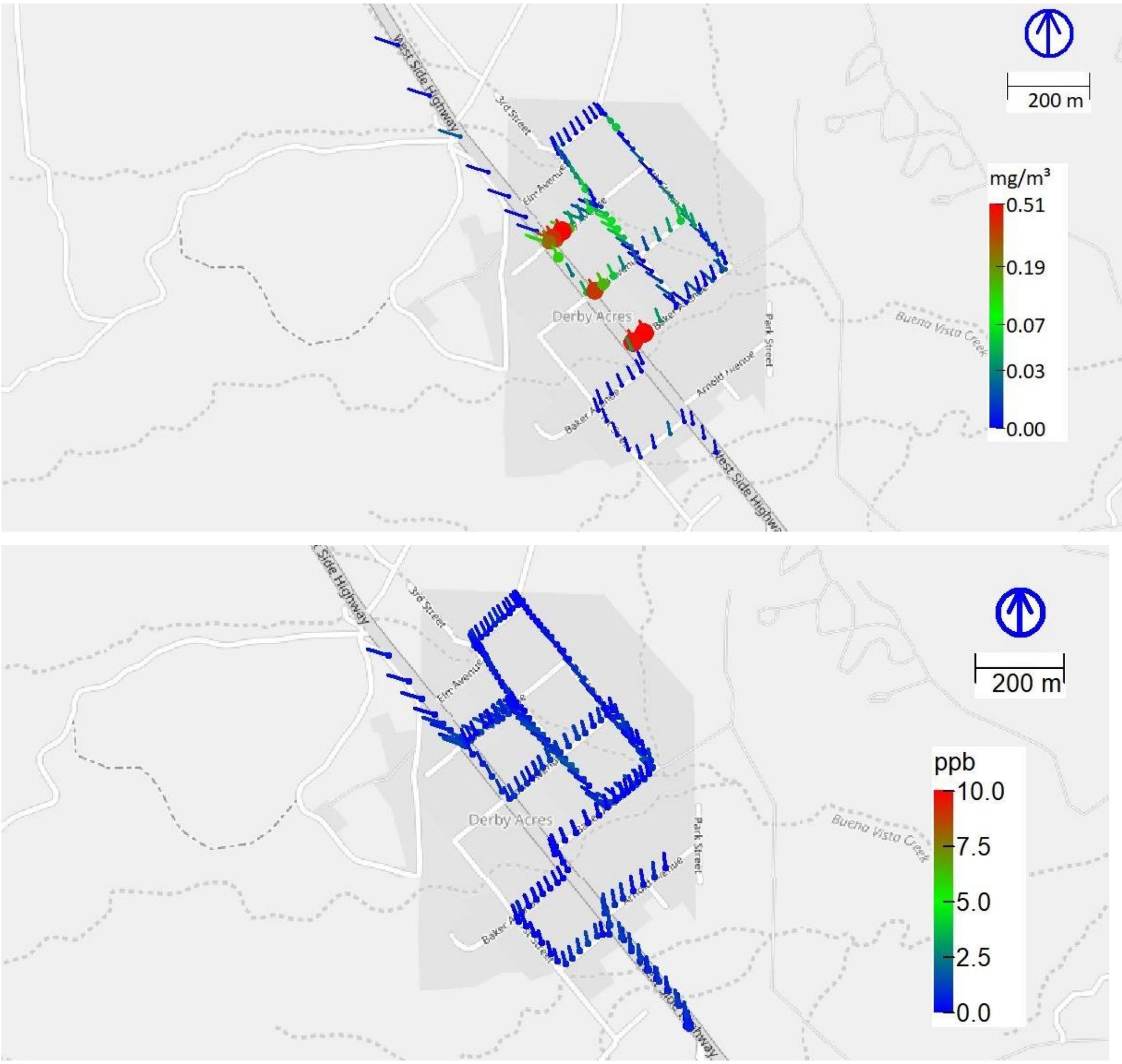

Figure 70. Mobile concentration measurements of **methane** (upper) and **benzene** (lower) in and around the Derby Acres, 13 Oct 2019 . Color scale and point size show benzene (ppb) and the lines point in the instantaneous wind direction.

The community was revisited 28 September 2021, 6 October and 21 October 2021. Winds were westerly on the 28th and easterly the other occasions. Figure 71 to Figure 73 show aggregate results of measured alkanes, BTEX and benzene concentrations respectively. A general alkane enhancement of 100 μg/m^3 within the community was seen (Figure 71) with no corresponding BTEX or benzene enhancement (Figure 72 and Figure 73).

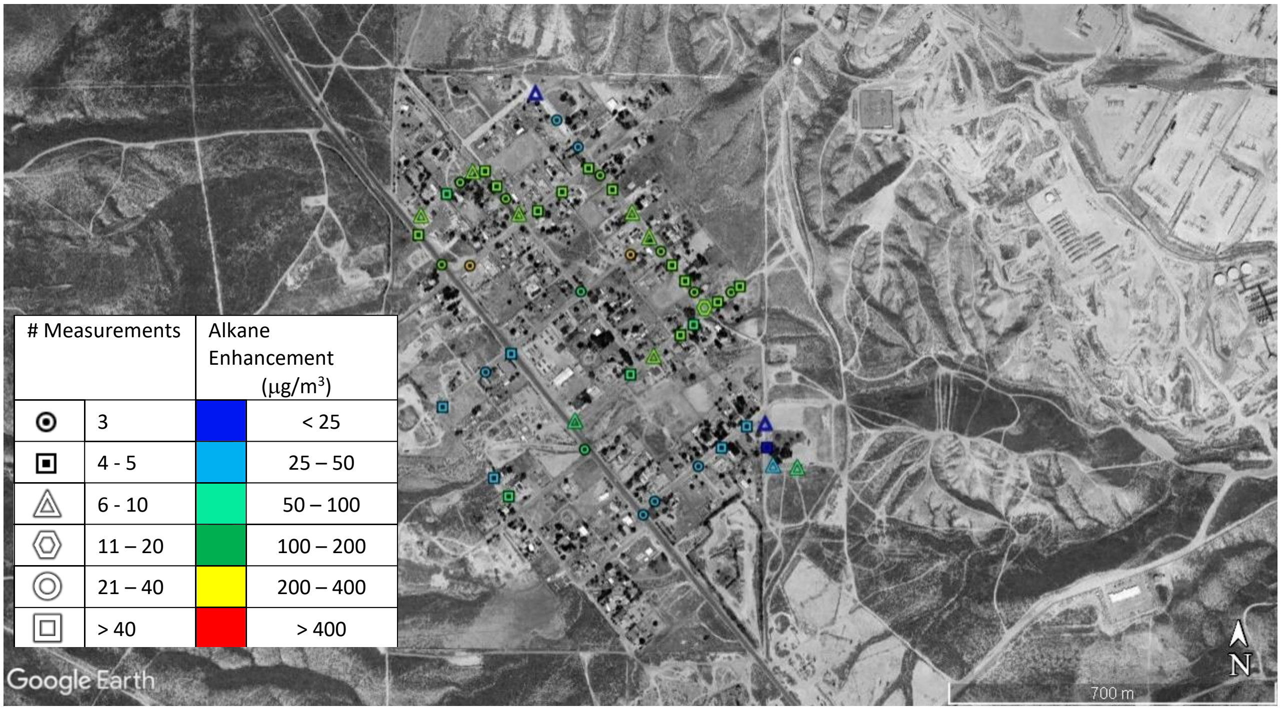

Figure 71. Concentration map of **alkanes** in the Derby Acres area, September - October 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

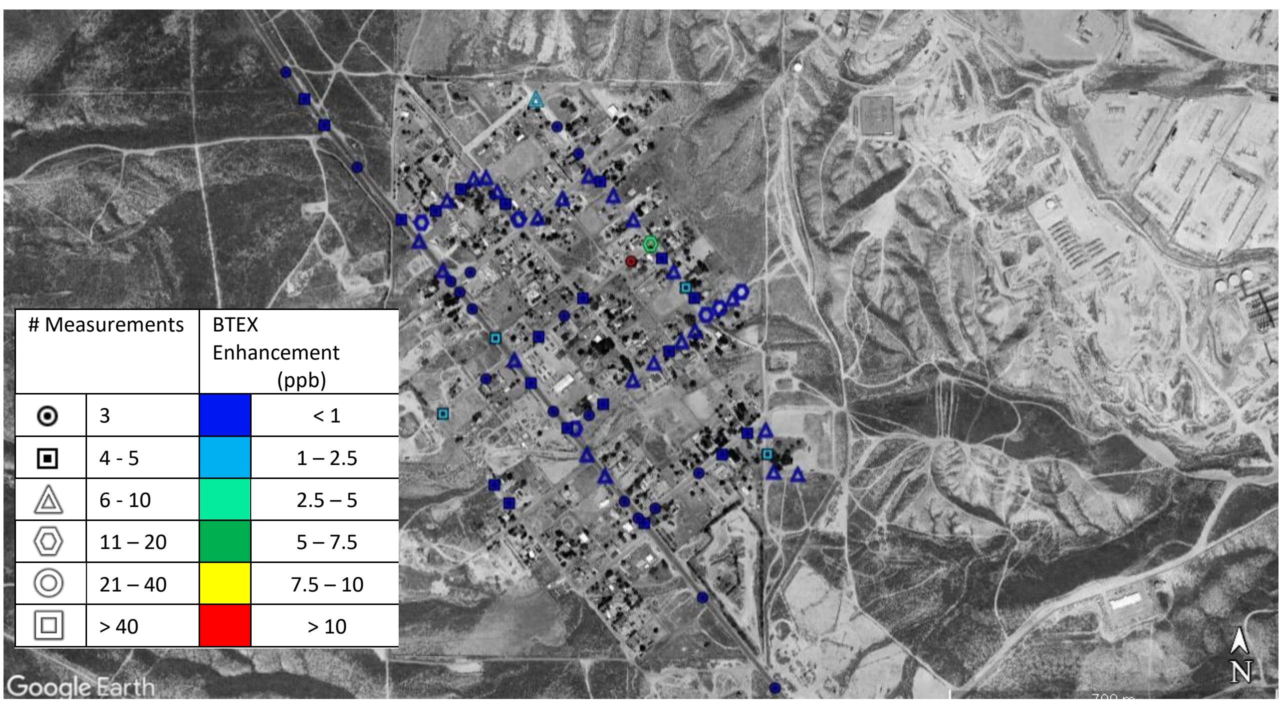

Figure 72. Concentration map of **BTEX** in the Derby Acres area, September - October 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). The few measurements in the middle of Derby Acres with higher BTEX concentrations are most likely from temporary domestic or motor vehicle sources and are not related to the oil & gas sector. Map from Google Earth™, 2021.

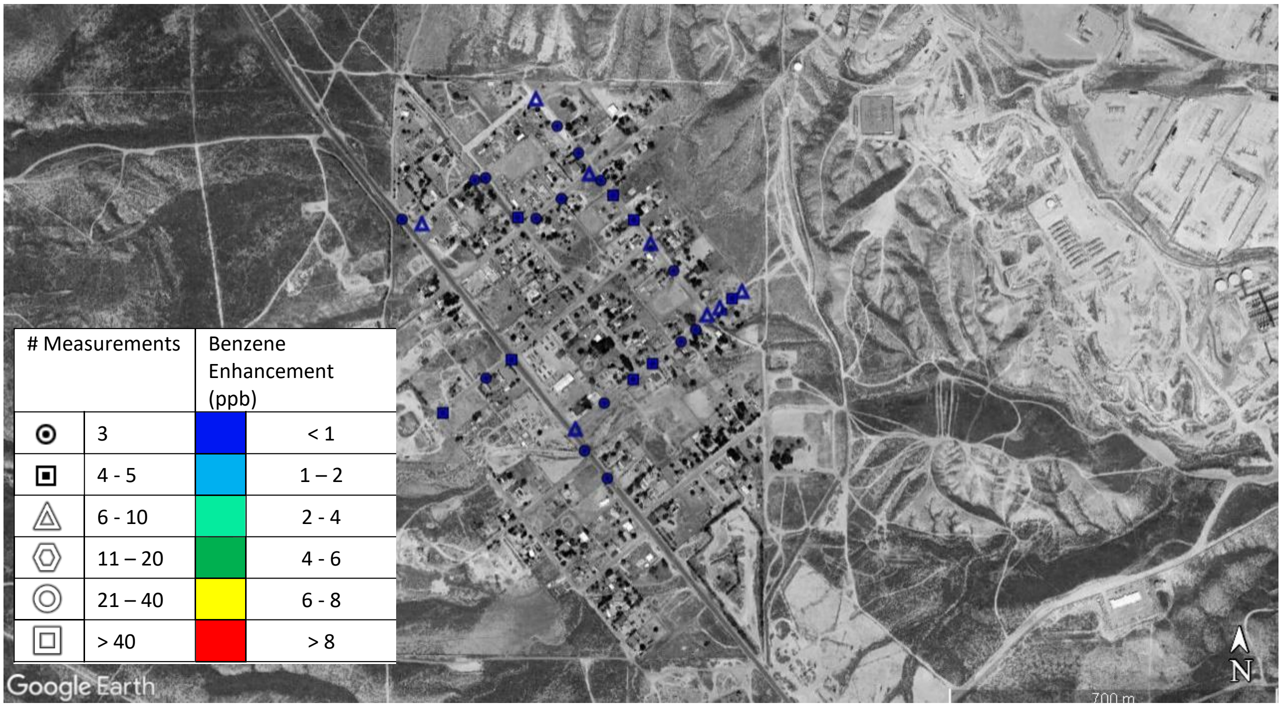

Figure 73. Concentration map of **benzene** in the Derby Acres area, September - October 2021. Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

3.6.1.4 Taft

Concentration measurements were done in the northeastern part of Taft on 18 October 2019, focused around the pond area. The measurement was done during daytime (afternoon) and the wind was weak from east to northeast. An alkane enhancement of 300 µg/m^3 was seen along Taft Hwy (119) south of Ash St, see Figure 74 (upper). This likely emanates from the oil field east of Taft Hwy and/or proximate sources to the area around Cedar St, Taft Hwy and Cedar St. No detectable concentrations of benzene were found in this plume, see Figure 74 (lower).

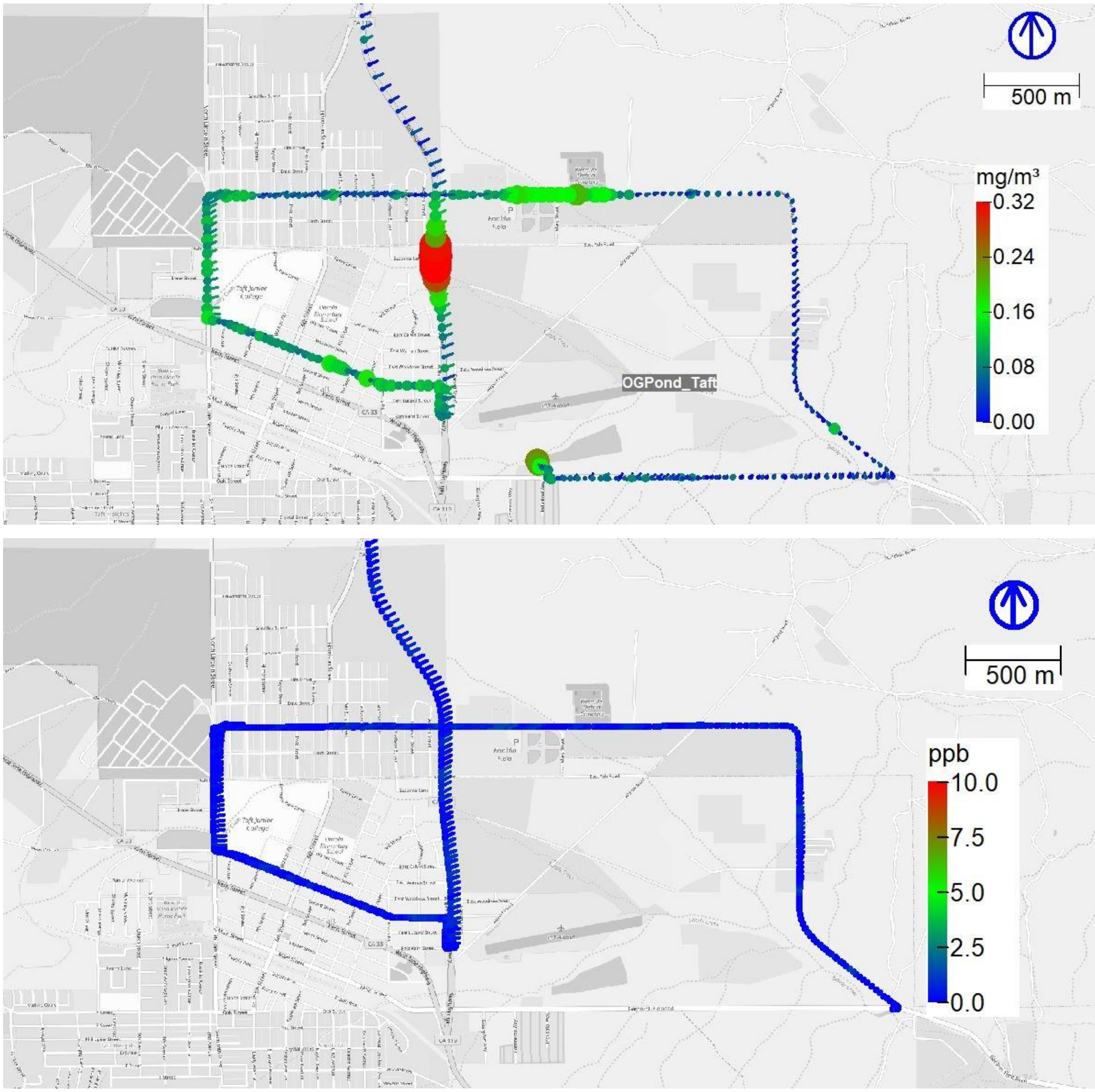

Figure 74. Mobile concentration measurements of **alkanes** (upper) and **benzene** (lower) in and around the Taft, 16 Oct 2019 . Color scale and point size show mg/m^3 for alkanes and ppb for benzene and the lines point up in wind.

3.6.1.5 Oildale & Kern River

The Oildale community is situated adjacent to both Kern River and Kern Front oil fields and was monitored during 5, 17 and 21 Oct 2021. Figure 75 to Figure 77 show aggregate results of measured alkanes, BTEX and benzene concentrations respectively. Winds were light and were from the northeast to southeast during all measurements.

Average enhancements of alkanes (of around 100-200 μg/m^3) were seen along Manor St west of Standard Park and along China Grade Loop crossing the Kern River oil field, see Figure 75. BTEX enhancement of more than 10 ppb were seen in communities at around the intersection Manor St and China Grade Loop and along N Chester Avenue, 750 m further west of

Manor St, BTEX enhancement of 5-7.5 ppb was seen (Figure 76). Benzene was mainly below 1 ppb except for a few occasions/locations reaching a couple of ppb, coincident with the highest BTEX enhancements (Figure 77). Alkane enhancements are likely emanating from a combination of general oil & gas field emissions and specific facilities within or adjacent the field. Fueling stations, traffic and domestic sources may contribute to the BTEX enhancement. See section 3.5.1 for plume tracing of some of these sources in this region.

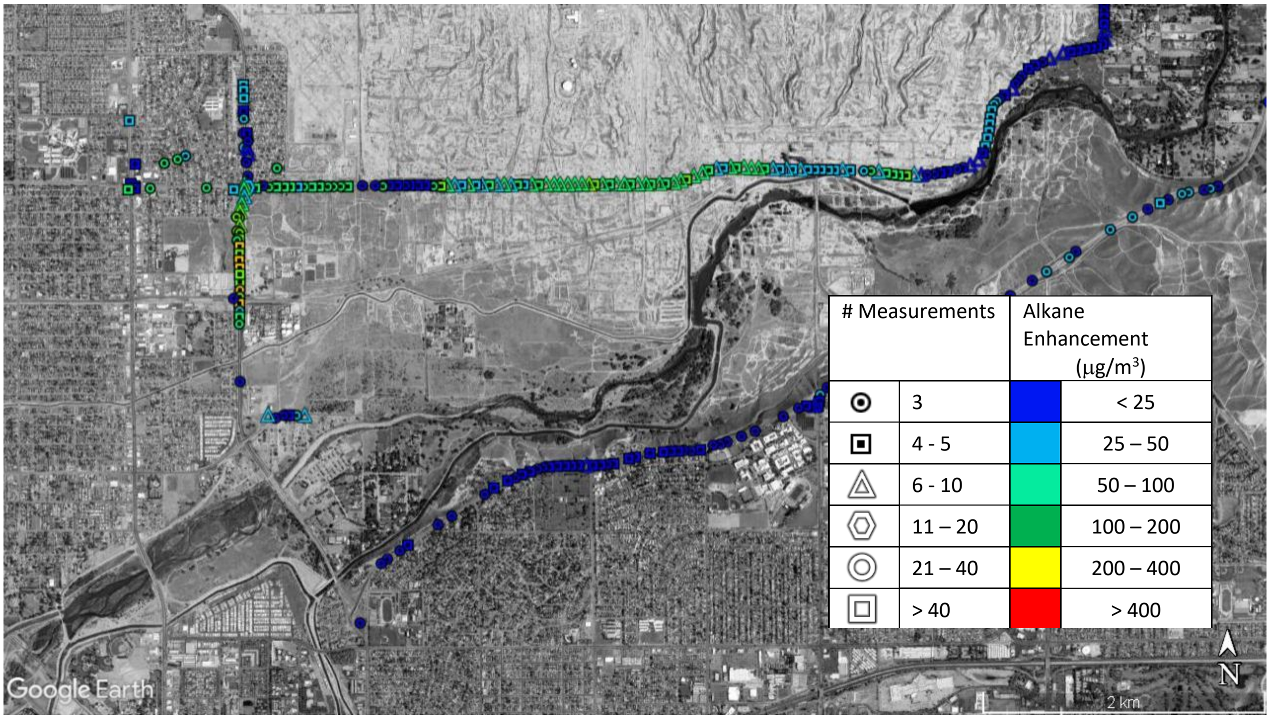

Figure 75. Concentration map of **alkane**s in the Oildale-Kern River area, October 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

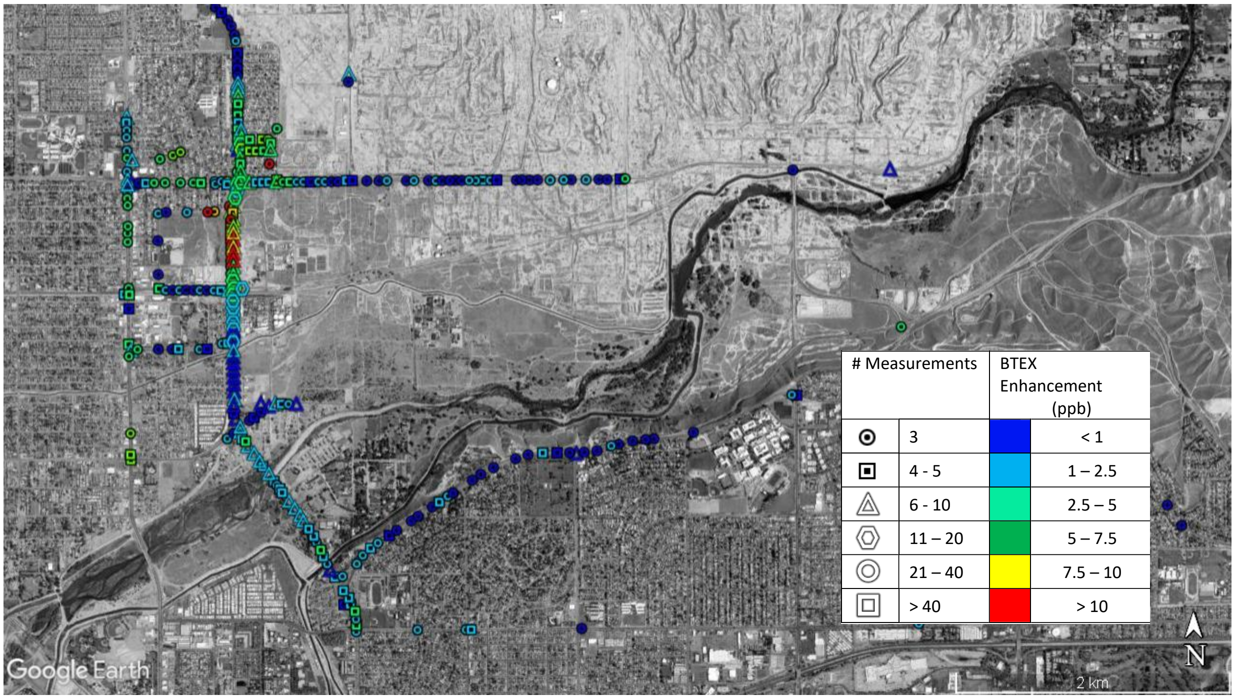

Figure 76. Concentration map of **BTEX** in the Oildale-Kern River area, October 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

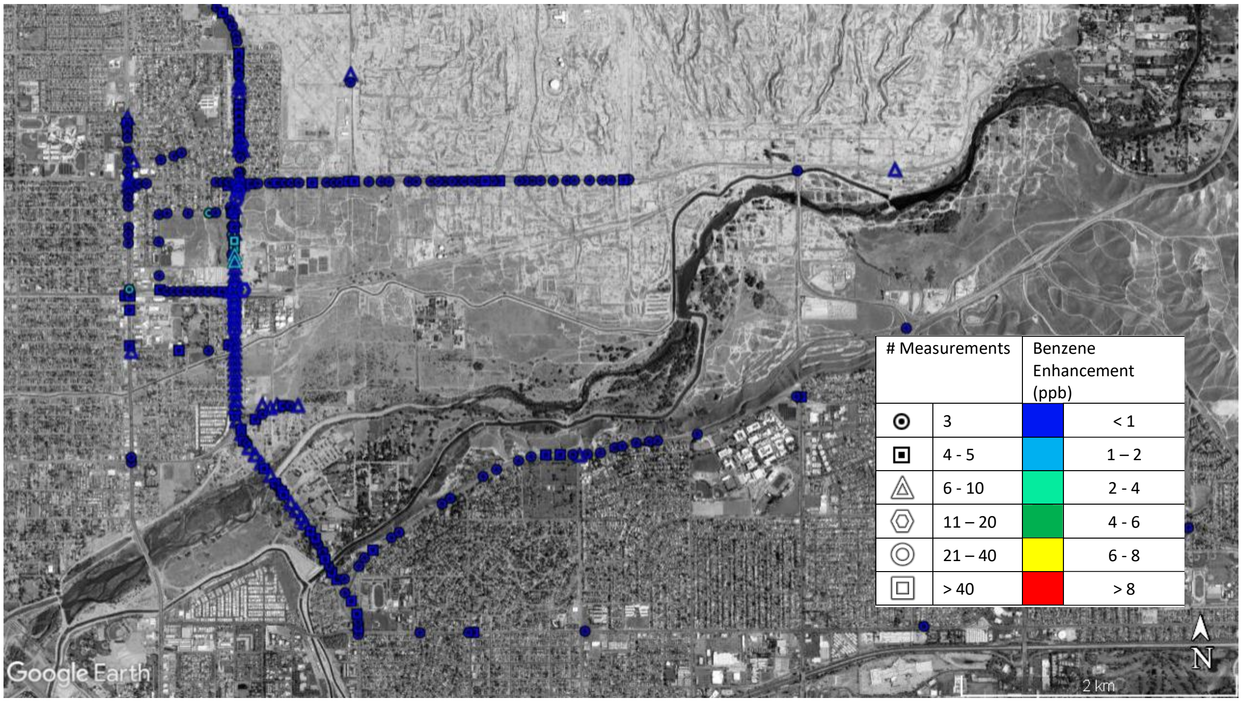

Figure 77. Concentration map of **benzene** in the Oildale-Kern River area, October 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

3.6.1.6 Arvin

Concentration mapping of alkanes, BTEX and benzene in the Arvin community were performed during multiple days in October 2021. Figure 78 and Figure 79 shows an aggregate plot of measured concentrations observed, where multiple concentrations within a grid cell of 50 m have been averaged, of alkanes and BTEX, respectively.

A source area of both alkanes and BTEX was observed near Shane Ct, southeast of the crossing of Bear Mountain Blvd and S Comanche Dr. (Arvin – Well Site A). Based on more than 20 measurements per grid cell, average alkane concentrations of 50-100 $\mu g/m^3$ were observed. For BTEX corresponding enhancements of above 10 ppb were observed close to the anticipated well source, based on 10-20 observations (Figure 79). Further away, out on S Comanche Dr, BTEX concentrations in the range 2.5-10 ppb were seen. According to the DOC CalGEM database there's an active oil and gas well site here.

VOC enhancement was also encountered near the crossing of Malaga Rd and Sunset Blvd northwest of Arvin. Grid cell averages of alkanes in the range 25-50 to above 400 $\mu g/m^3$ were observed here, while BTEX was below 2.5 ppb. At this location there is an active oil lease on both sides of Malaga Rd (according DOC CalGEM). Benzene (not shown) was in the below 1 ppb range for grid cell averages. In single measurements concentration of benzene was above detection near Well Site A.

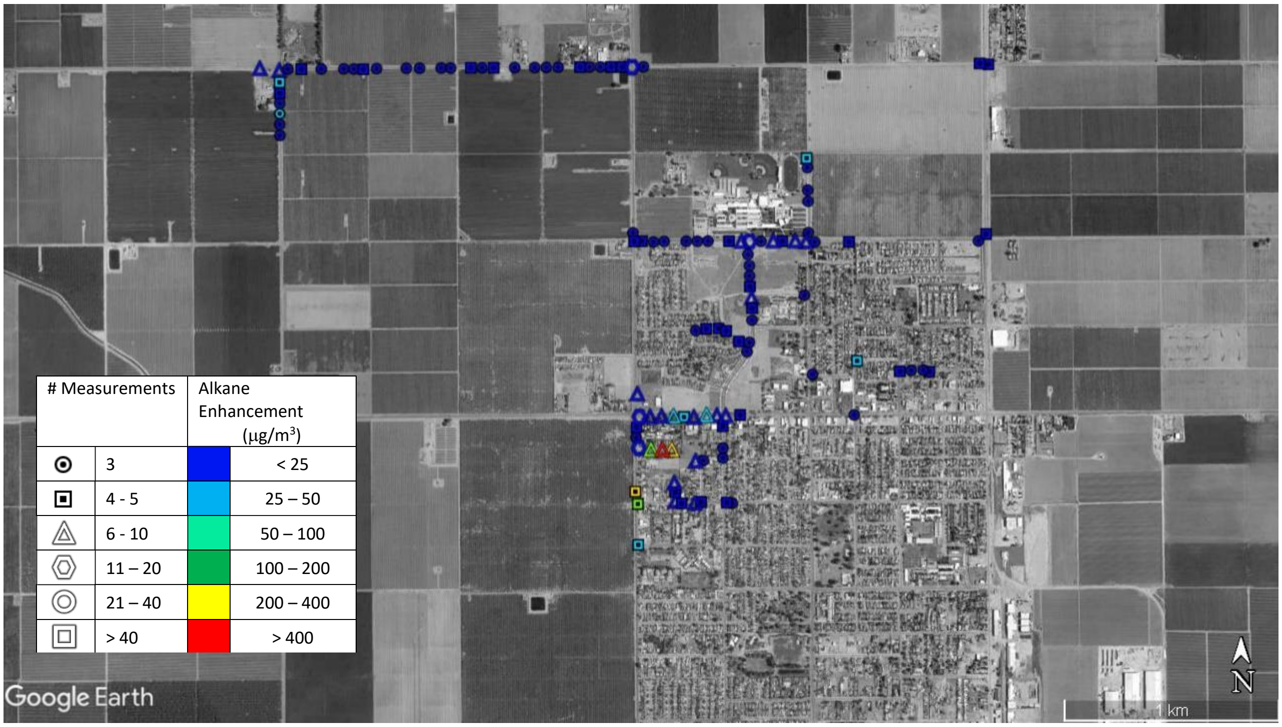

Figure 78. Concentration map of **alkane**s in the Arvin area from several days, October 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

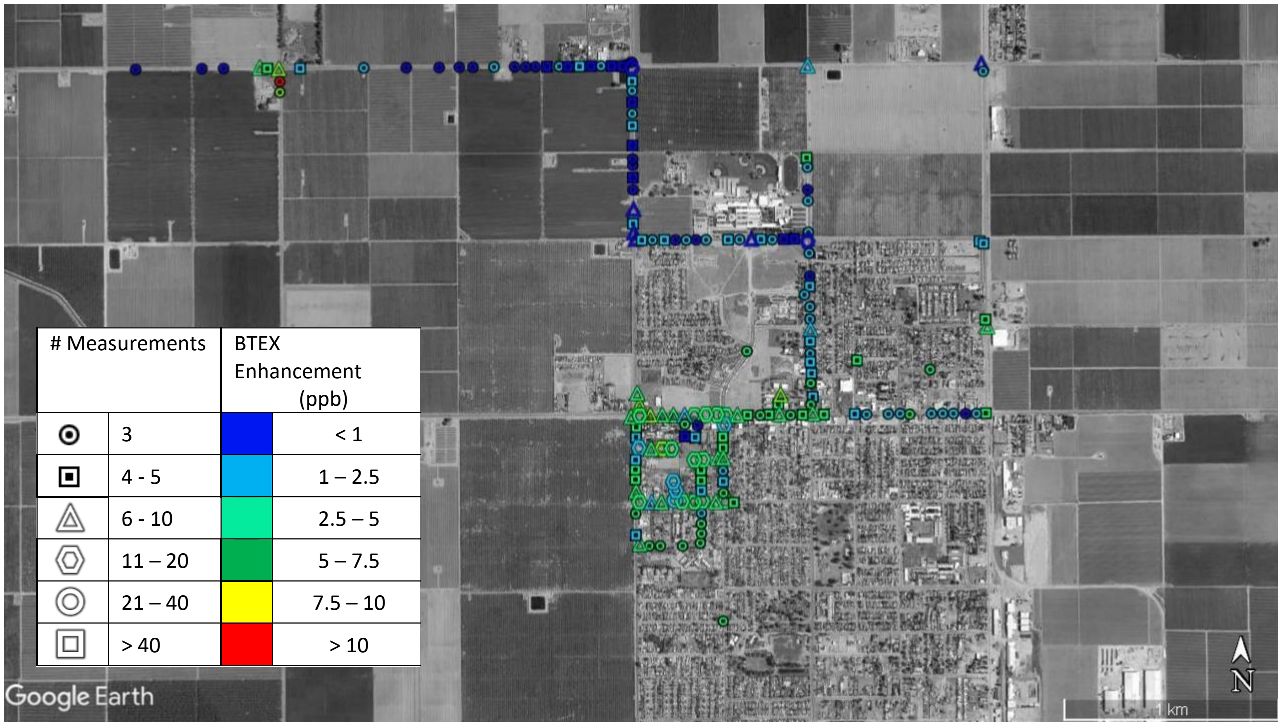

Figure 79. Concentration map of BTEX in the Arvin area, October 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

3.6.2 South Coast Air Basin

Concentration mapping in communities close to active oil fields and Processing Sites was performed with simultaneous alkane, methane and aromatic VOC (BTX) concentration measurements during the 2021-LA survey, see Table 117. The measurements were done in conjunction with the emission measurements as presented in section 3.1 and 3.2. Focus was on Inglewood and Las Cienegas oil fields. Evening or early morning are the times when it's more likely to encounter higher concentrations with lower wind speeds and less vertical mixing. Winds were weak and southwesterly during the entire survey. Ethylbenzene was below the detection limit and was removed from the BTEX total in the data retrievals to reduce the overall noise level in BTX (sum of benzene, toluene, m- and p-xylene).

Table 117. Days with concentration mapping in support of CM around the Inglewood and Las Cienegas oil and gas fields.

Area	Survey dates, June-July 2021
Inglewood	19 June (day), 23 June (day), 26 June (day), 28 June (morning), 29 June (day), 30 June (day), 1 July (day), 5 July (day/evening/night), 7 July (day)
Las Cienegas	23 June (day), 24 June (day), 25 June (day), 2 July (day), 7 July (evening/night)

3.6.2.1 Las Cienegas

Concentration mapping of methane, alkanes, BTX and benzene in Las Cienegas and surrounding communities were performed during five days/nights in June and July 2021. Wind direction was from southwest during all measurements and the wind speed in the range 1 to 5 m/s. Only two of the four sites, Jefferson and Murphy, are currently active.

Consistent enhancements of methane were seen downwind the Jefferson and Murhpy sites, see Figure 80. Other small enhancements were also seen, probably related to domestic sources. Alkane enhancements in the 10-50 $\mu g/m^3$ range were measured near the Murphy and Jefferson sites (Figure 81). Enhanced alkane concentrations were also seen along busy roads/intersections, related to traffic (mobile sources). BTX (Figure 82) and benzene (Figure 83) concentrations were generally below or close to the detection limits but some enhancements were seen related to traffic and/or domestic sources.

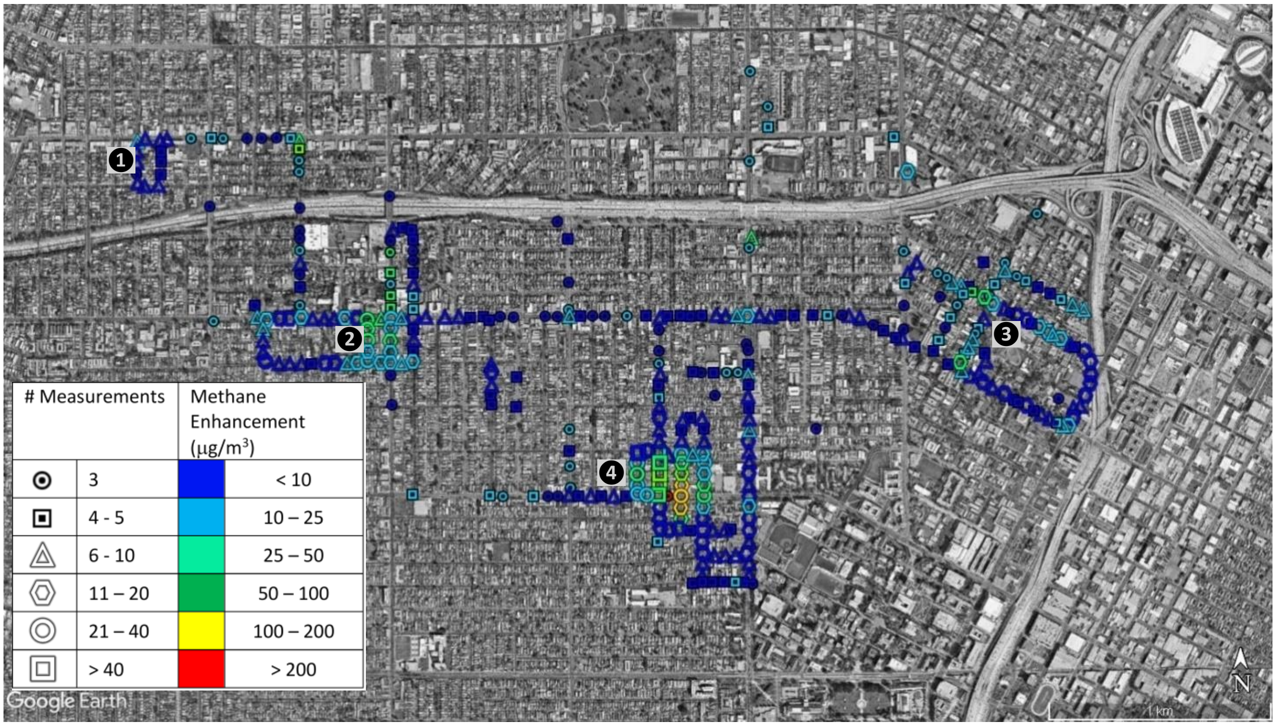

Figure 80. Concentration map of methane in the Las Cienegas area, June-July 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021. Sites: 1) Fourth Avenue, 2) Murphy, 3) St. James Lease, 4) Jefferson.

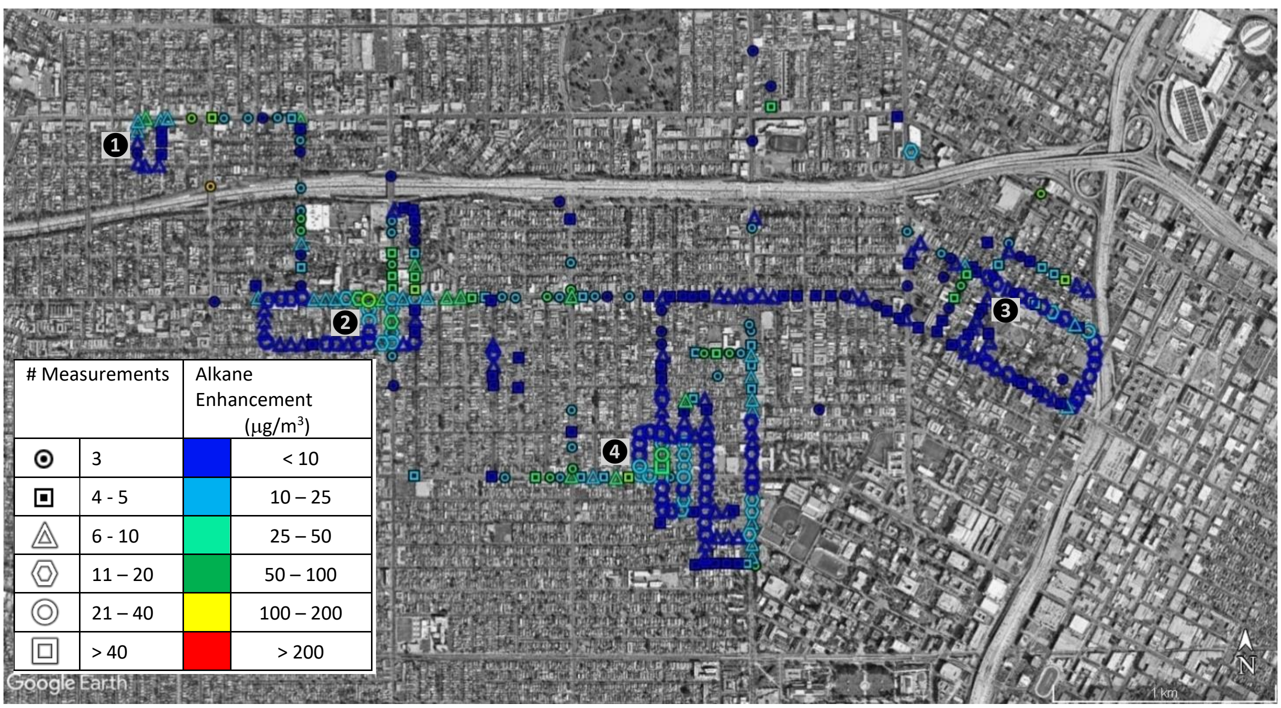

Figure 81. Concentration map of alkane in the Las Cienegas area, June-July 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021. Sites: 1) Fourth Avenue, 2) Murphy, 3) St. James Lease, 4) Jefferson.

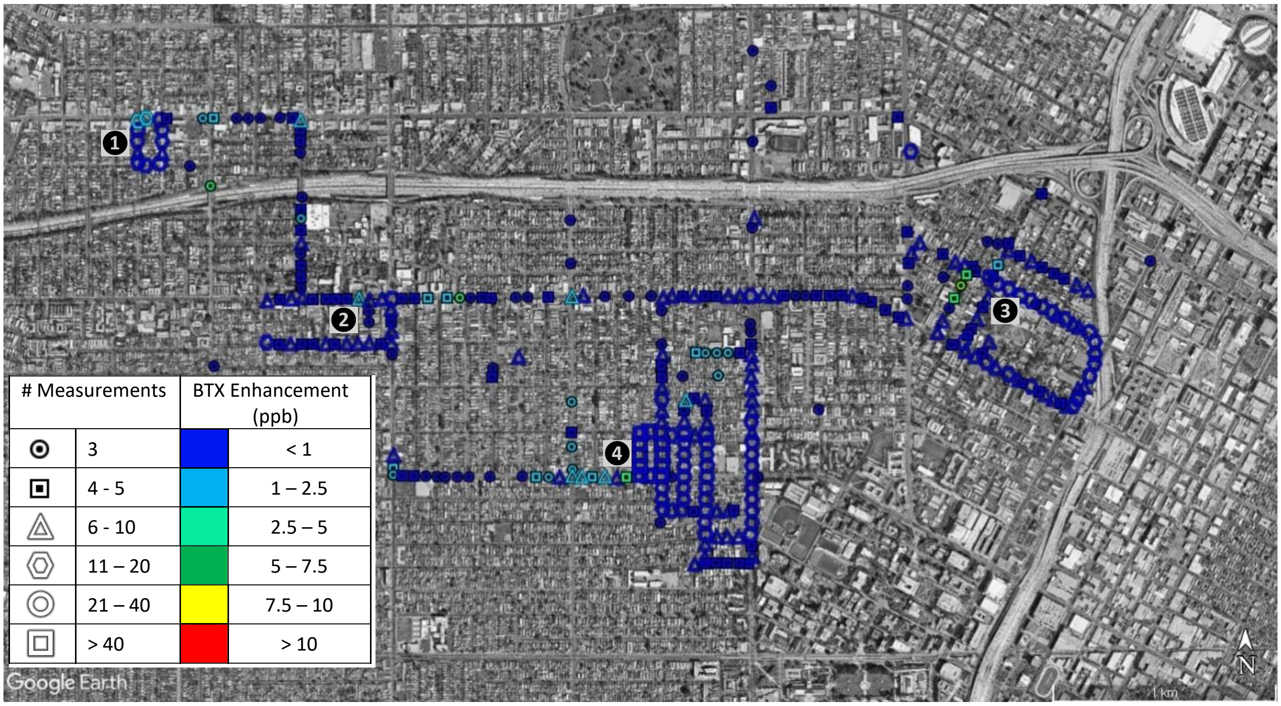

Figure 82. Concentration map of BTX in the Las Cienegas area, June-July 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021. Sites: 1) Fourth Avenue, 2) Murphy, 3) St. James Lease, 4) Jefferson.

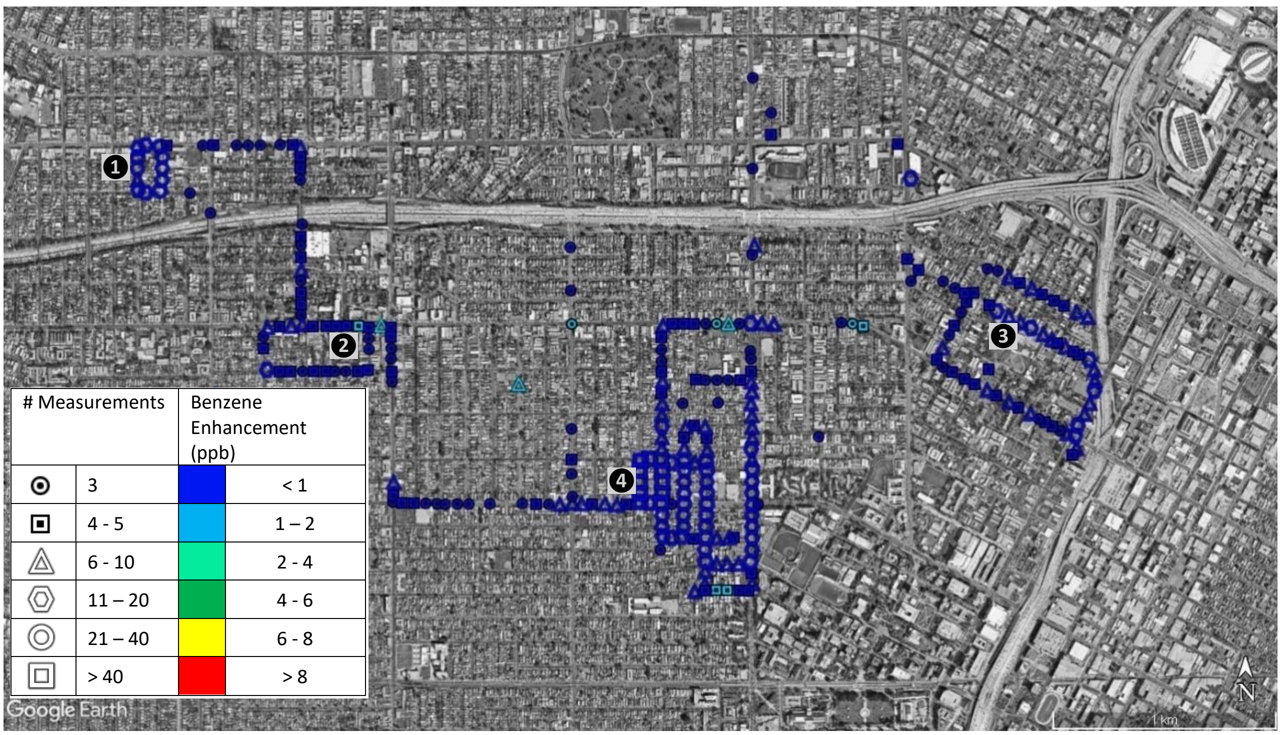

Figure 83. Concentration map of benzene in the Las Cienegas area, June-July 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021. Sites: 1) Fourth Avenue, 2) Murphy, 3) St. James Lease, 4) Jefferson.

3.6.2.2 Inglewood

Concentration mapping of methane, alkanes, BTX and benzene near the Inglewood oil field and surrounding communities were performed during nine days/nights in June and July 2021. The wind direction was from southwest during all measurements and the wind speed in the range 1 to 5 m/s.

Largest enhancements of methane (Figure 84 and Figure 85) were seen in the center of the oil field (along La Cienega Blvd) with 100-200 $\mu g/m^3$, close to the to Kenneth Hahn State Recreation Area (SRA) (25-200 $\mu g/m^3$) and northwest of the oil field along Jefferson Blvd likely related to a sewer or natural gas facility (>200 $\mu g/m^3$).

Alkane enhancements (Figure 85) in the 10-25 $\mu g/m^3$ range were (as for methane) seen in the center of the oil field, in the Kenneth Hahn SRA location and on the downwind side of the south part of the field, but generally alkane enhancements were seen along busy roads/intersections from traffic-related (mobile) sources.

Oil and gas related BTX and benzene concentrations were observed in the Kenneth Hahn SRA location, showing on average 1-2.5 ppb BTX (Figure 86) and 1-2 ppb benzene (Figure 87) enhancement. As for alkanes, BTX and benzene enhancements were seen along busy roads/intersections from traffic-related (mobile) sources.

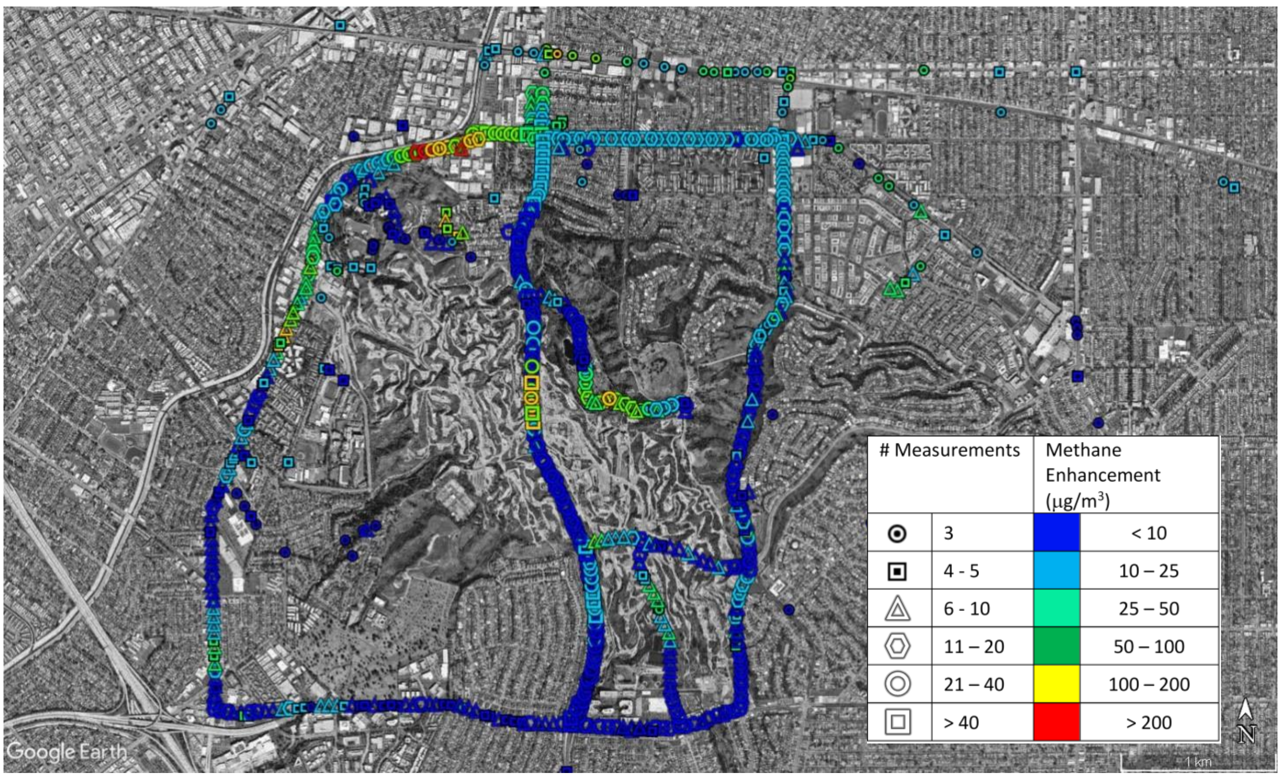

Figure 84. Concentration map of **methane** in Inglewood Oil field area, June-July 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

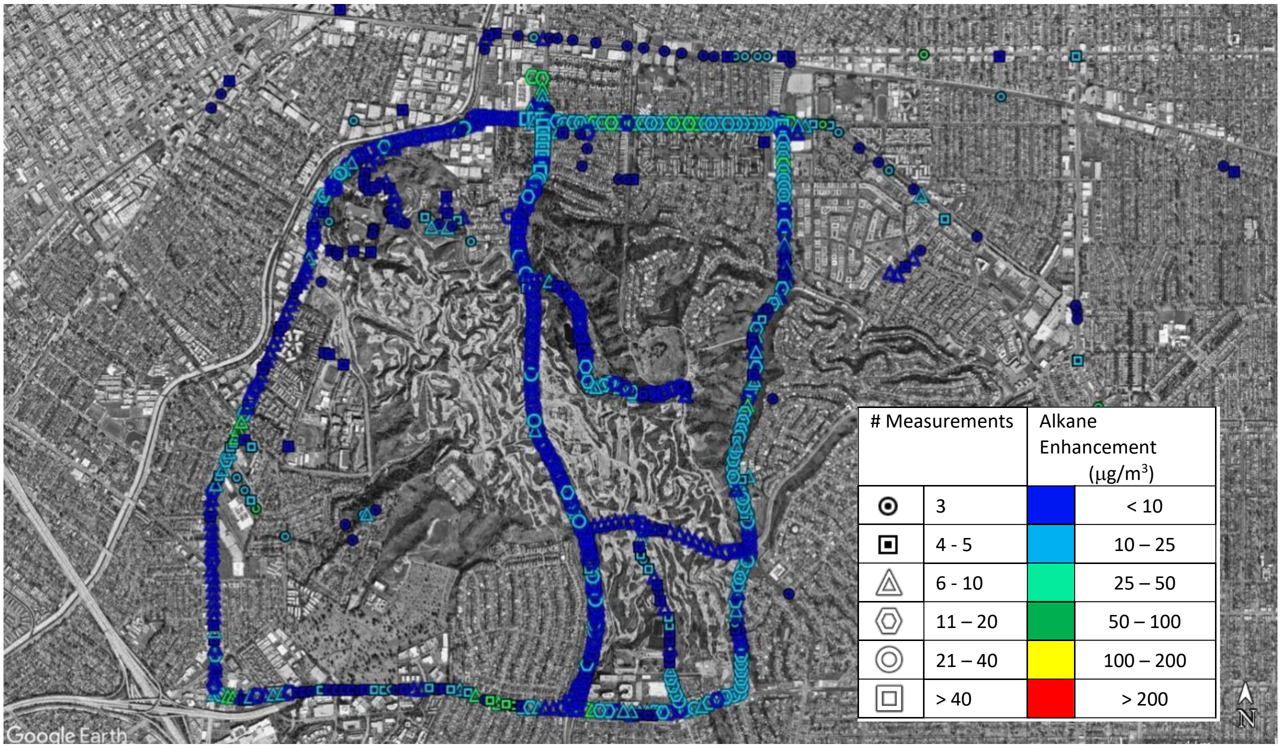

Figure 85. Concentration map of **alkanes** in Inglewood Oil field area, June-July 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

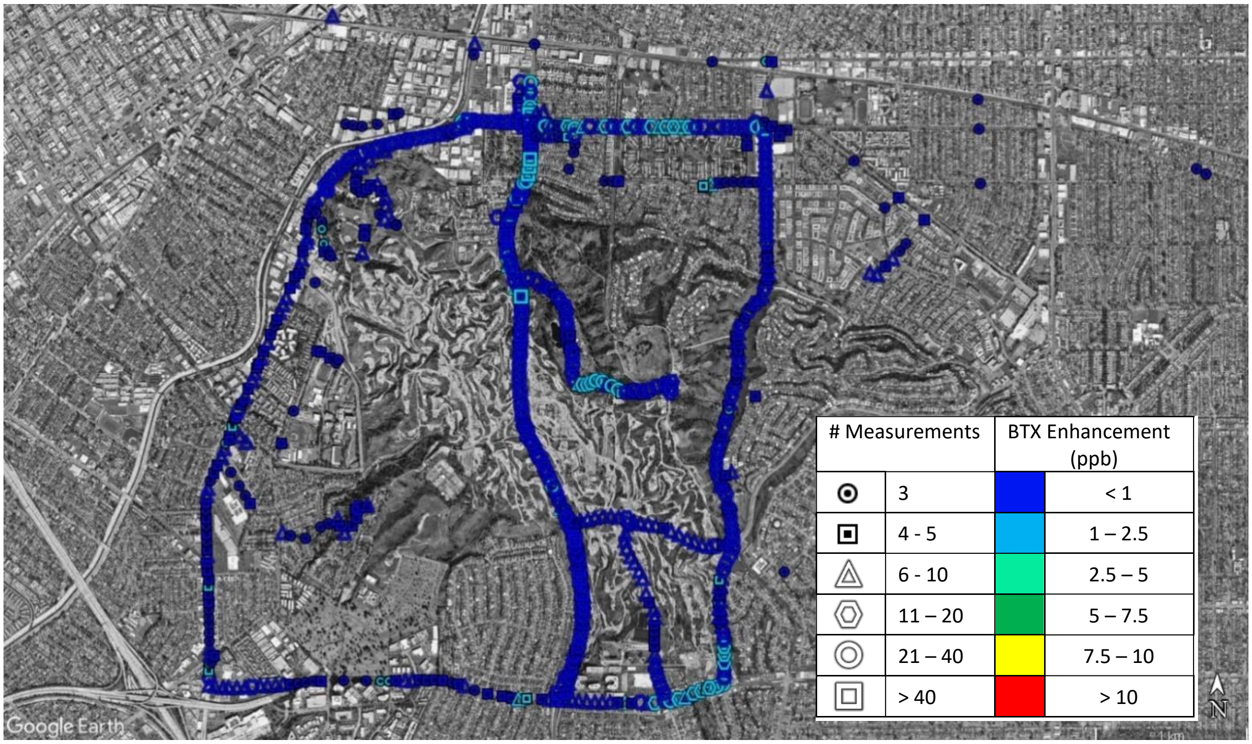

Figure 86. Concentration map of **BTX** in Inglewood Oil field area, June-July 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021.

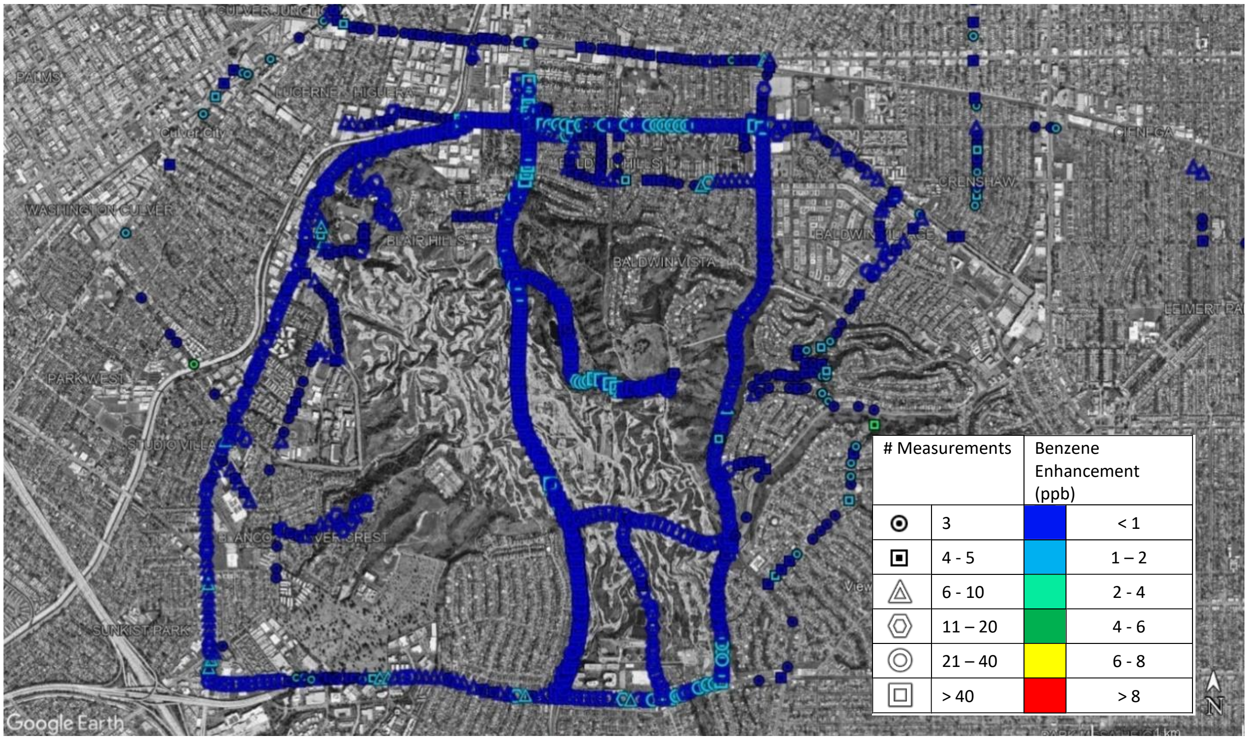

Figure 87. Concentration map of **benzene** in the Inglewood Oil field area, June-July 2021 . Number of measurements (min. 3) within an approximately 50 x 50 m grid cell (by symbol) and mean enhancement within the cell (by color). Map from Google Earth™, 2021

3.6.2.3 Inglewood- Stationary Measurements

In addition to the mobile concentration mapping in and around the Inglewood oil field (see previous section), stationary measurements at specific locations close to SNAPS communities, were also made during the survey. Four locations were monitored during 30 to 90 minutes each; Hillcrest Drive, Marycrest Manor, Sentinel Peak Resources site #1 and Sentinel Peak Resources site #2, see Figure 11. Winds were weak and southwesterly during all the measurement occasions.

The concentration time-series from Hillcrest Drive 26 June 2021 showed a sharp alkane and BTX enhancement (about 20 ppb butane equivalents (ButEq) and 2 ppb BTX) at 15:55 and 16:22 from an upwind local source, and a broader alkane/methane baseline increase over time probably from regional (multi-source) oil field emissions, see Figure 81. Measurements at the Marycrest Manor site on 26 June 2021 showed no significant enhancements above the detection levels, see Figure 89. Sentinel Peak Resources site #1 measurements series from 26th and 28th of June showed several episodes of correlating alkane/methane and BTX enhancements from upwind oil and gas wells and a single (non-correlated) alkane peak at 10:20 on the 28th, possible from the treatment facility, see Figure 90 and Figure 91. Measurements from Sentinel Peak Resources site #2 from 26 June 2021 showed no enhancements above the detection levels, see Figure 92.

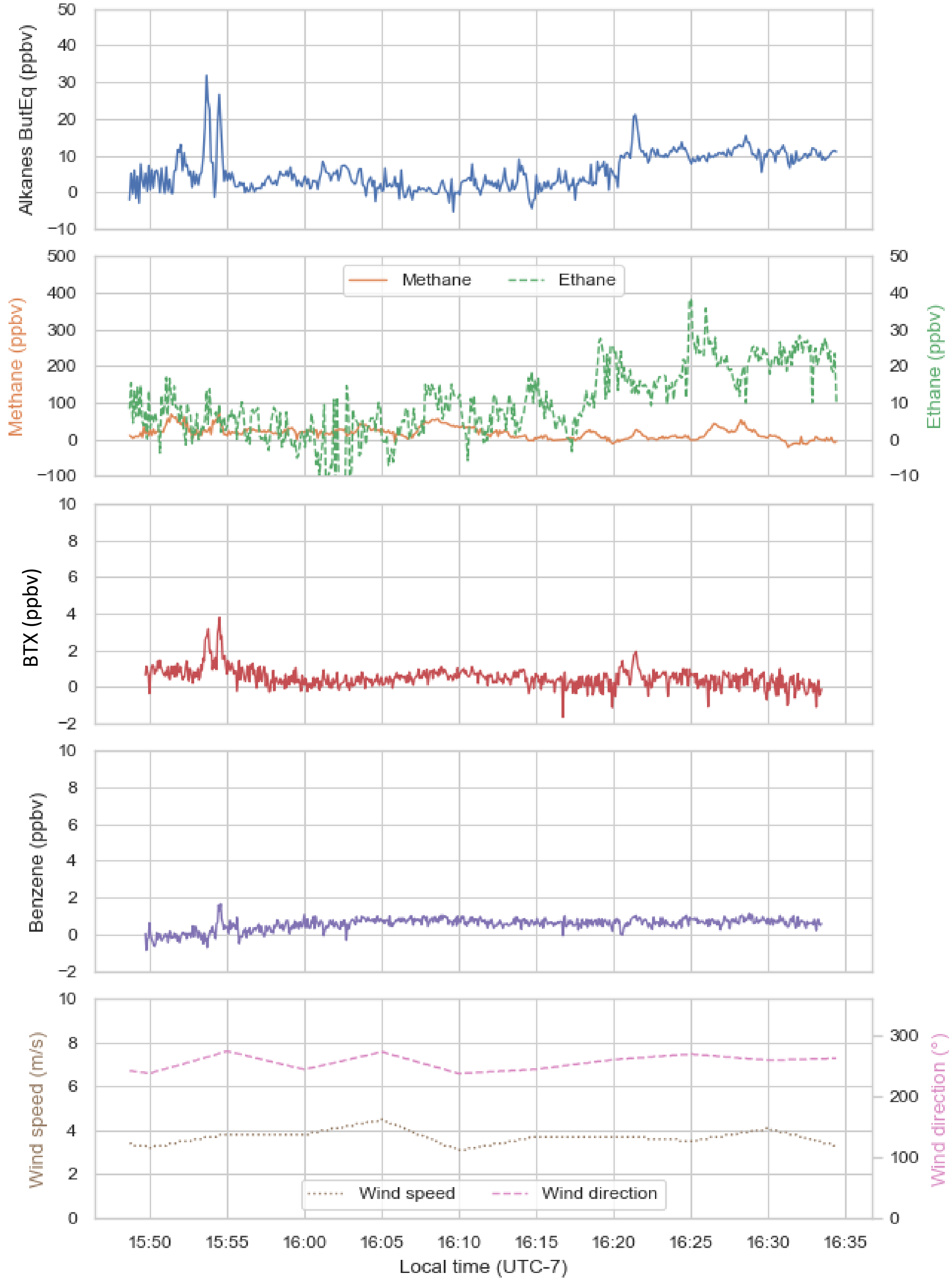

Figure 88. Stationary (enhancement) concentration measurements at the Hillcrest Drive location on 26 June 2021.

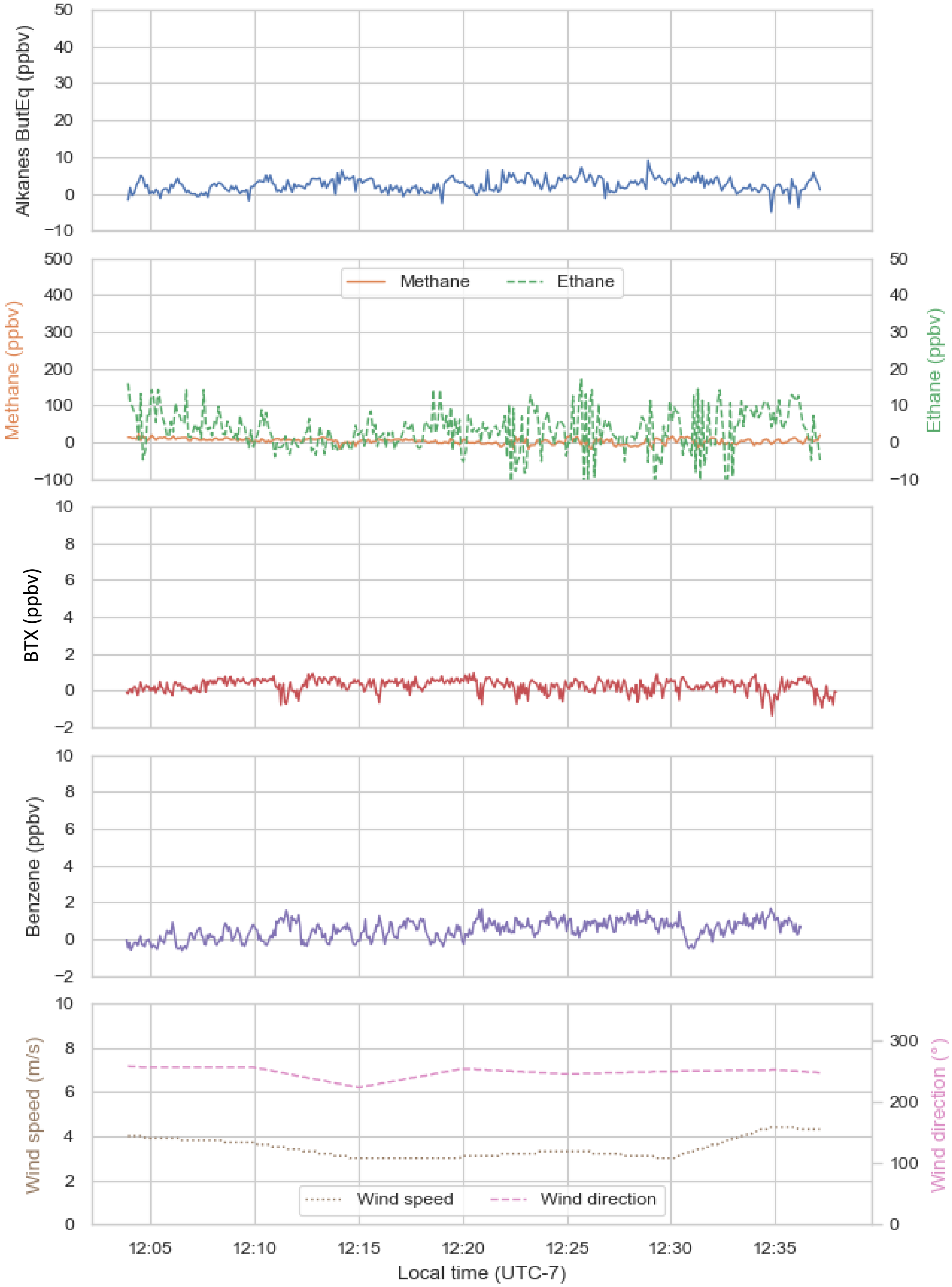

Figure 89. Stationary (enhancement) concentration measurements at the Marycrest Manor location on 26 June 2021.

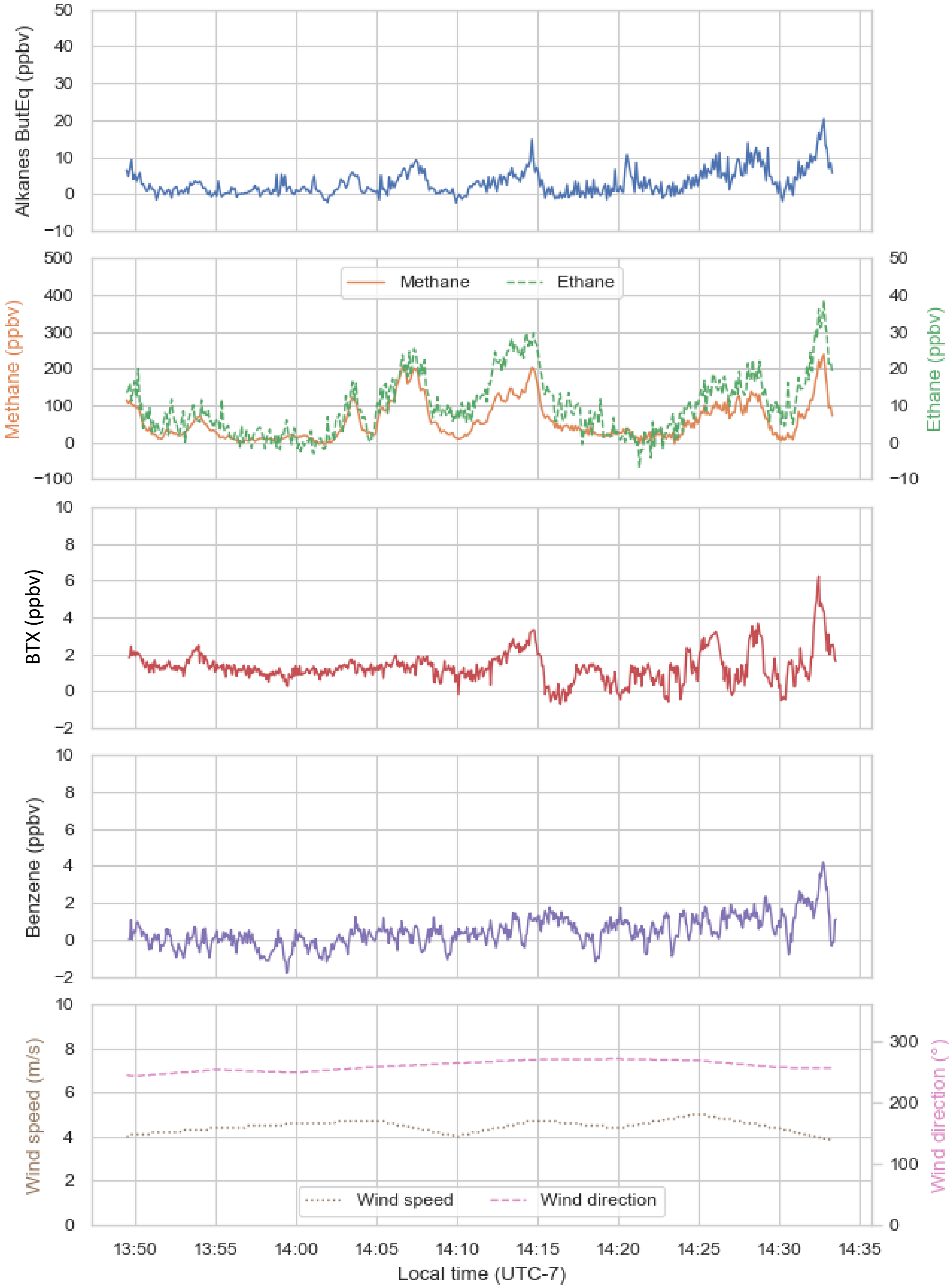

Figure 90. Stationary (enhancement) concentration measurements at the Sentinel Peak Resources site 1 location on 26 June 2021.

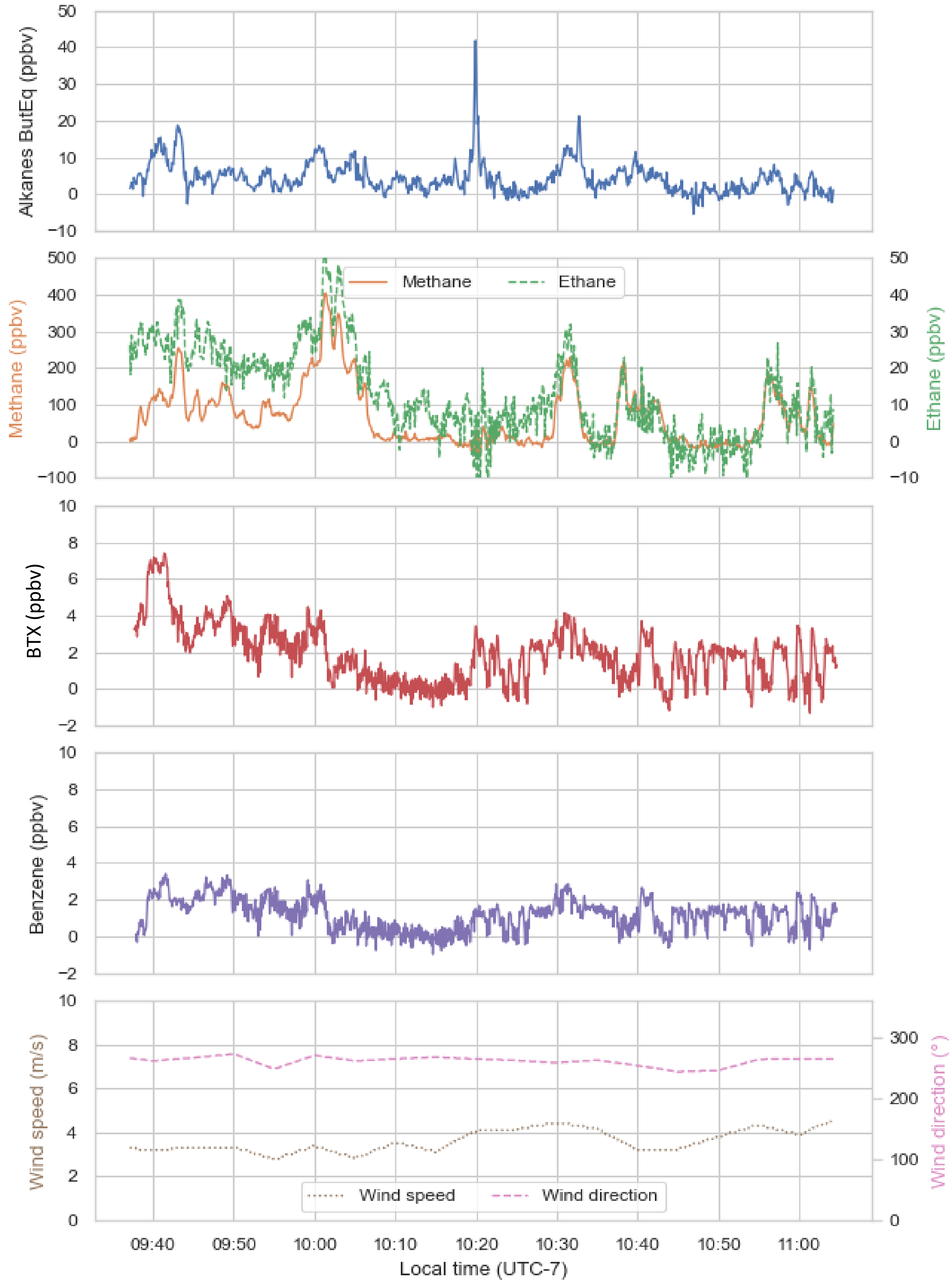

Figure 91. Stationary (enhancement) concentration measurements at the Sentinel Peak Resources site #1 location on 28 June 2021.

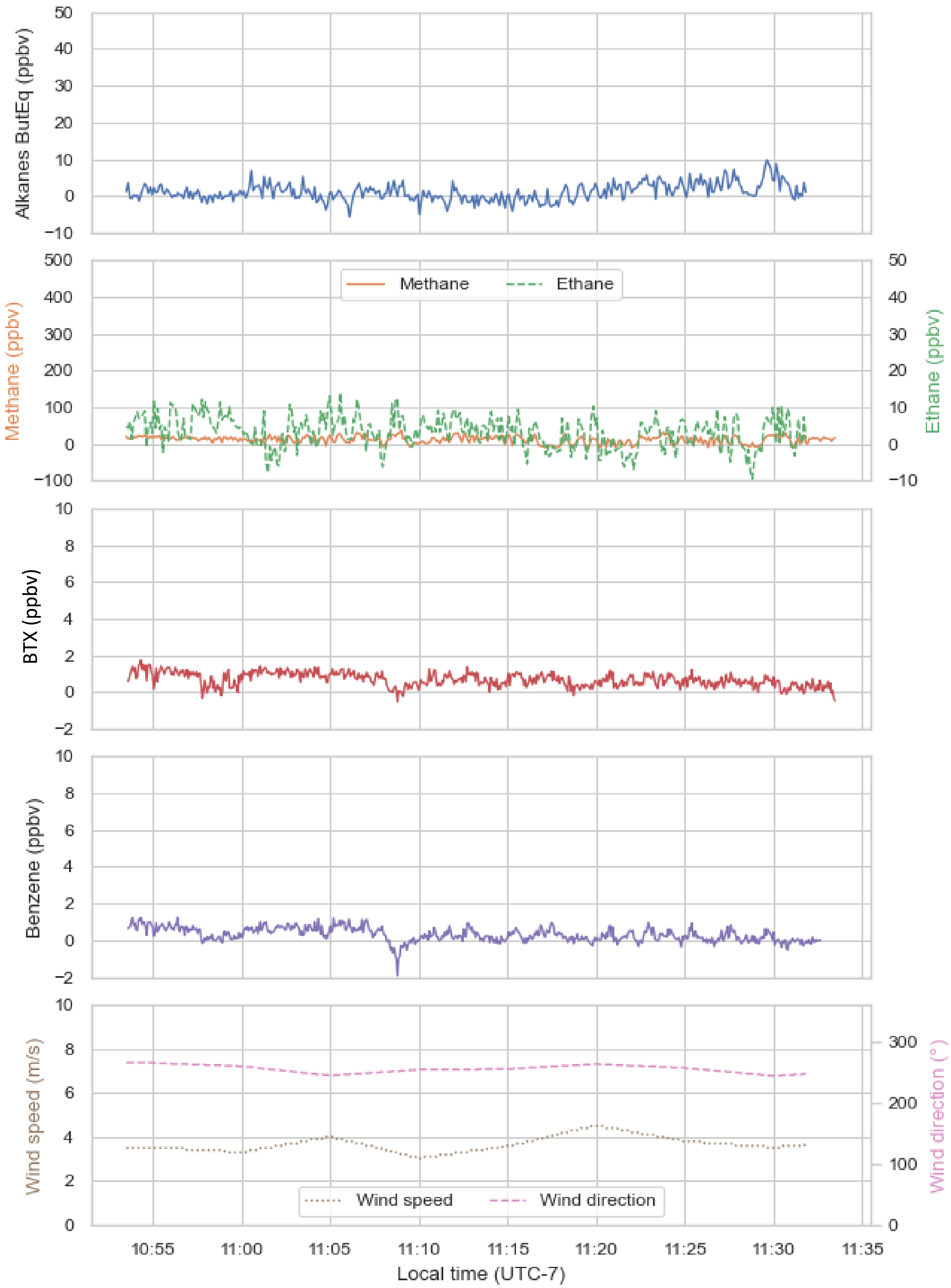

Figure 92. Stationary (enhancement) concentration measurements at the Sentinel Peak Resources site 2 location on 26 June 2021.

3.7 Site-specific dispersion modeling

The plume dispersion model described in the methods section was applied to two different setups, one to model the emissions from 3 sources at or around the Kern Oil refinery, and one for 4 sources in Lost Hills South. For the Kern Oil Refinery site whether these sources are operated by the refinery is unknown and not relevant to the modeling effort. What is key is that alkanes emissions from each of these sources have been measured repeatedly with SOF. The emission rates used for the simulations were all based on average emission rates measured with SOF. Since modeled emissions are held constant, any variability in source emissions e.g. diurnal, activity related (tanker loading), upset emissions, are not examined here.

3.7.1 Kern Oil refinery

The extent of the innermost domain used for the Kern Oil refinery simulations is shown in Figure 93 together with the locations of the 3 emission sources. Source 2 is the main refinery site with the process and tank storage, source 1 is the train loading facility, and source 3 is a truck loading facility and some more tank storage. The alkane emission rates used in the simulations were 18.6, 39.7, and 16.5 kg/h for source 1, 2, and 3 respectively. Simulations were run for two different time periods, October 10-12, 2021, and October 19-21, 2021. These periods were chosen to overlap with SOF measurements at the sites to allow for relevant comparisons. Meteorological conditions for the first period were clear and cool for the season with very high winds on 11 October, and for the second period, were light winds, clear nights with some daytime cloudiness. The modeling results are most affected by the clear nighttime conditions.

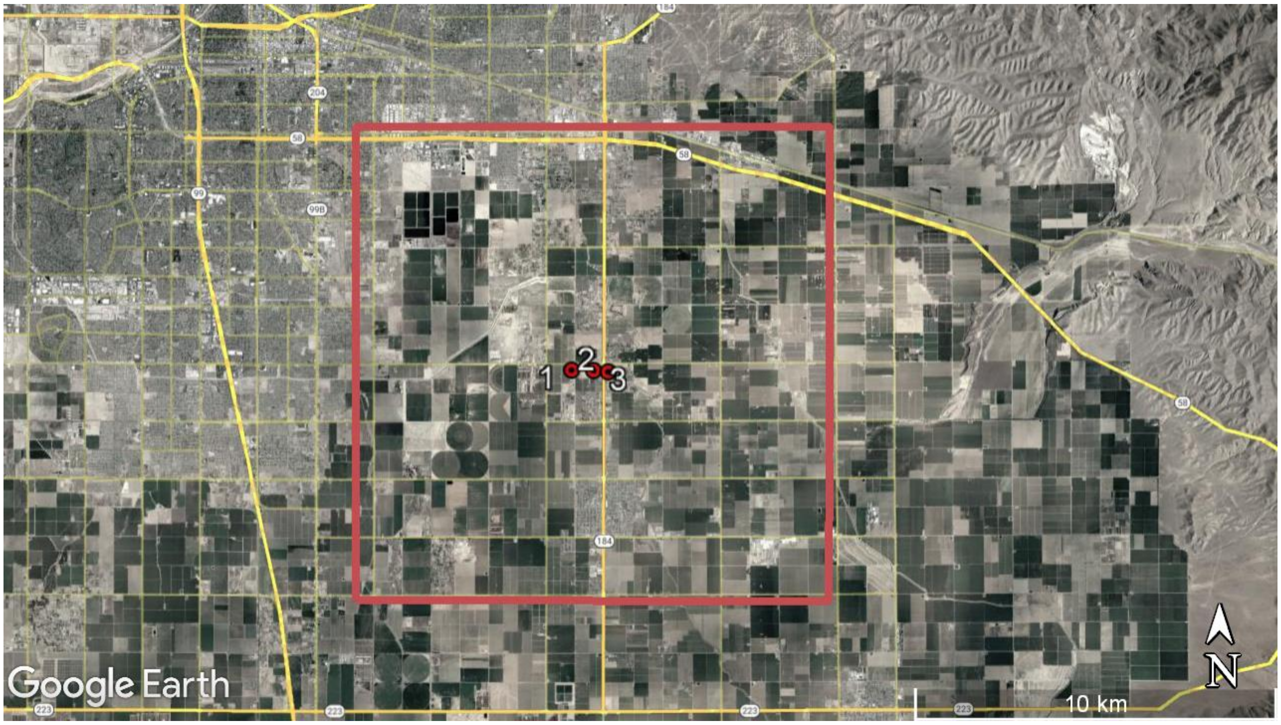

Figure 93 Overview map showing the extent of the innermost domain (Domain 4, 12x12 km) and location of the 3 sources included in the simulations for the Kern Oil refinery site . Map from Google Earth™, 2021.

As a validation check on the model, the wind LIDAR 10 m data was compared to the corresponding data from the simulations (at the location of the wind LIDAR at the same time) for each day. The comparison for two days, October 12 and October 19, are shown in Figure 94. These illustrate that wind speeds and wind directions were realistic within the model, although there could also be deviations probably due to slight mismatches in timing between the input model data and winds on this side of the valley. This is a reasonable level of agreement at this spatial scale.

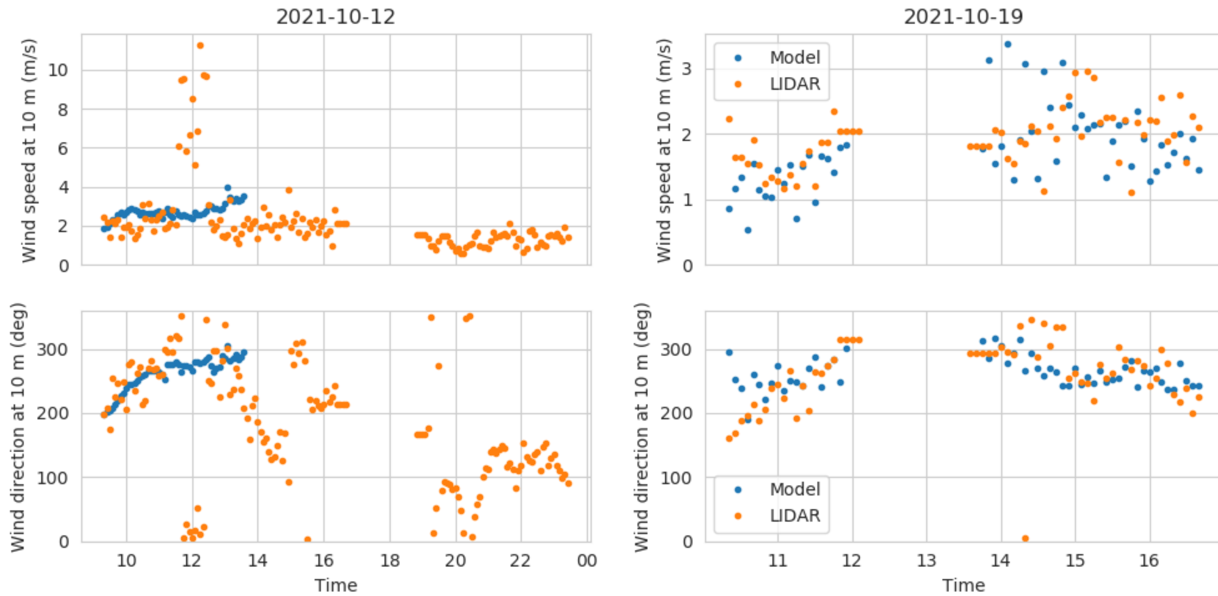

Figure 94 Comparisons of 10 m wind data as measured by wind LIDAR and as resulting from the WRF simulations for the Kern Oil refinery (at the location of the LIDAR). Data for October 12 is shown on the left and data for October 19 is shown on the right. The wind LIDAR was being moved (out of the model domain) around 12 o'clock on October 12, which explains the large deviations around that time.

Another type of validation of the simulation results was accomplished by comparing the vertical alkanes columns measured in SOF transects downwind of the sources to the corresponding columns as predicted by the simulation for the same times and locations. Examples of such comparisons for the Kern Oil refinery sources are shown in Figure 95 to Figure 100. These figures show a heat map of the simulated columns with measured columns on top, as well as a plot of both measured and simulated columns as functions of distance along the measurement transect. There are a few notable differences between the model and measurements that lead to dissimilarities for nearby measurements. The modeled sources (constant emissions, >100 m area sources uniformly distributed vertically) are both larger in extent (less concentrated) and less variable (0%) than true emissions. For measurements that were made within a few grid cells of the sources, reproducing the SOF plume exactly should not be the criteria for model validation. That being said, the results could be remarkably similar, enhancing confidence in the model. Times where the model differed substantially from the measurements could be attributed to varying emissions (instantaneously high emissions) or timing of the meteorology (shift in wind direction, temporary lull or gust).

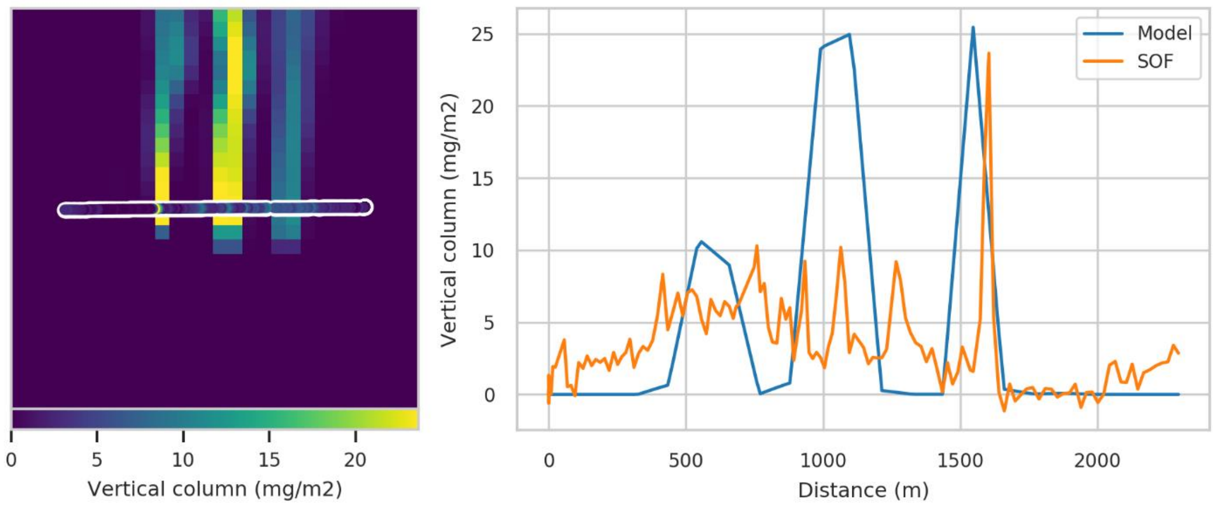

Figure 95 Comparison between vertical alkanes columns measured with SOF and the corresponding columns in the WRF model simulations for a measurement transect at the Kern Oil refinery site around 09:35 on October 12, 2021 . A portion of the innermost domain for the simulation (111 m x 111 m grid cells) is shown on left with the model vertical columns (integrated concentrations) shown as a heatmap on the grid. The SOF transect with SOF column values are overlayed on the grid and marked with a white border. The plot on the right shows both model and SOF column values as a function of driving distance.

Figure 95 shows an example of a SOF measurement very close to the sources in a southerly wind. While the model is not expected to perfectly replicate the spatial distribution of the plume on this scale, the approximate location, and total area under the curve agree. Figure 96 shows an example along the same road in south-westerly wind, where most of the plume shows very good agreement between model and measurements, except for a narrow peak at the edge of the plume. In some cases, the wind direction in the model was a little bit different from what the measurements indicated, as seen in Figure 97, but approximate size and location of the plume was still quite good.

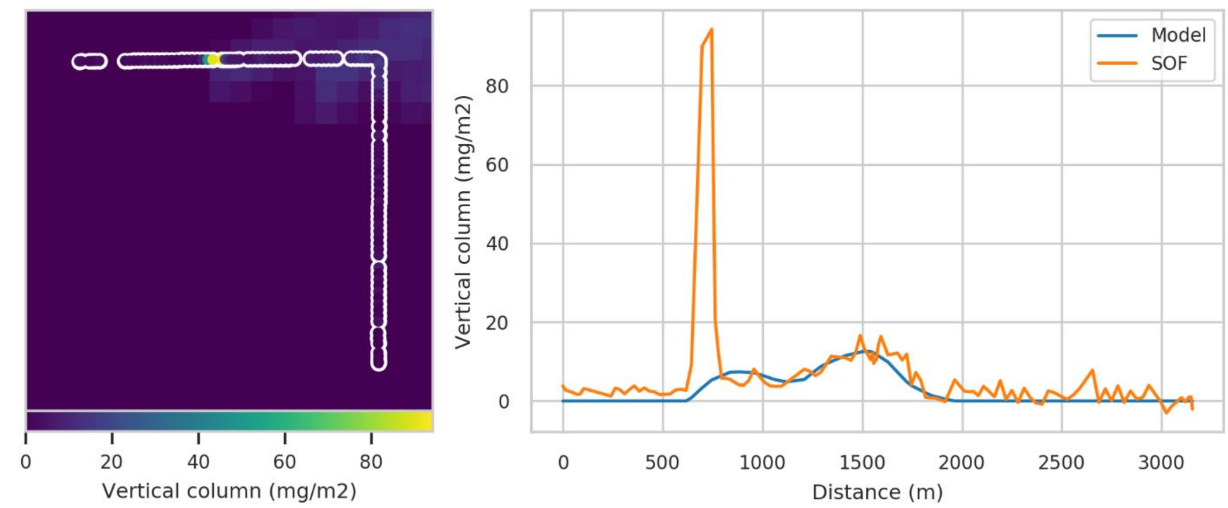

Figure 96 Comparison between vertical alkanes columns measured with SOF and the corresponding columns in the WRF model simulations for a measurement transect at the Kern Oil refinery site around 10:49 on October 12, 2021 . A portion of the innermost domain for the simulation (111 m x 111 m grid cells) is shown on left with the model vertical columns (integrated concentrations) shown as a heatmap on the grid. The SOF transect with SOF column values are overlayed on the grid and marked with a white border. The plot on the right shows both model and SOF column values as a function of driving distance.

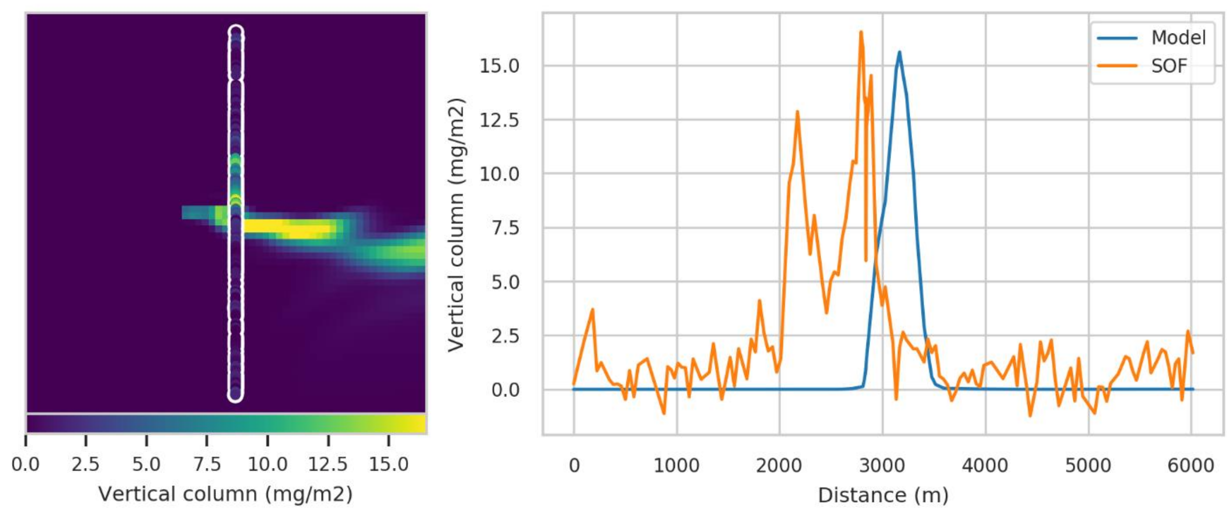

Figure 97 Comparison between vertical alkanes columns measured with SOF and the corresponding columns in the WRF model simulations for a measurement transect at the Kern Oil refinery site around 14:16 on October 12, 2021 . A portion of the innermost domain for the simulation (111 m x 111 m grid cells) is shown on left with the model vertical columns (integrated concentrations) shown as a heatmap on the grid. The SOF transect with SOF column values are overlayed on the grid and marked with a white border. The plot on the right shows both model and SOF column values as a function of driving distance.

In several cases, such as shown in Figure 98 and Figure 99, the model predicted plume location, width, and magnitude very well. Overall, these examples indicate that the model seems to get the general patterns of the plume dispersion right, although it cannot probably not be trusted to get it right at every particular point in time. Finally, Figure 100 shows an example where the model seems to correctly predict the point of interception with a SOF measurement transect on Highway 58, more than 6 km downwind of the Kern Oil refinery. Arguably, the SOF measurements are a bit noisy due to driving fast on a highway, and there are likely other sources influencing this transect, but it does seem that the model can, at least sometimes, predict relatively long-range transport quite accurately.

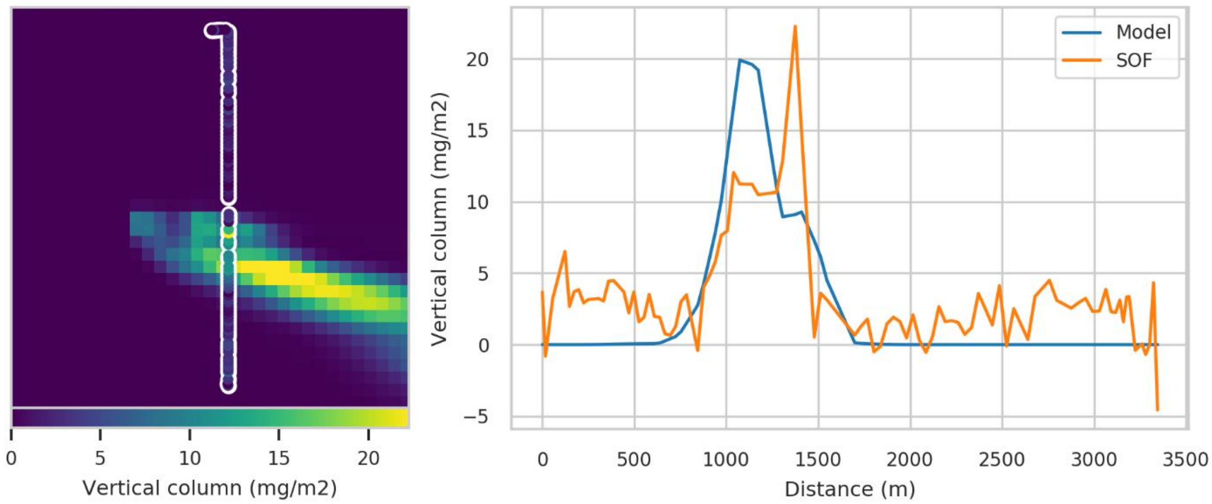

Figure 98 Comparison between vertical alkanes columns measured with SOF and the corresponding columns in the WRF model simulations for a measurement transect at the Kern Oil refinery site around 14:01 on October 13, 2021 . A portion of the innermost domain for the simulation (111 m x 111 m grid cells) is shown on left with the model vertical columns (integrated concentrations) shown as a heatmap on the grid. The SOF transect with SOF column values are overlayed on the grid and marked with a white border. The plot on the right shows both model and SOF column values as a function of driving distance.

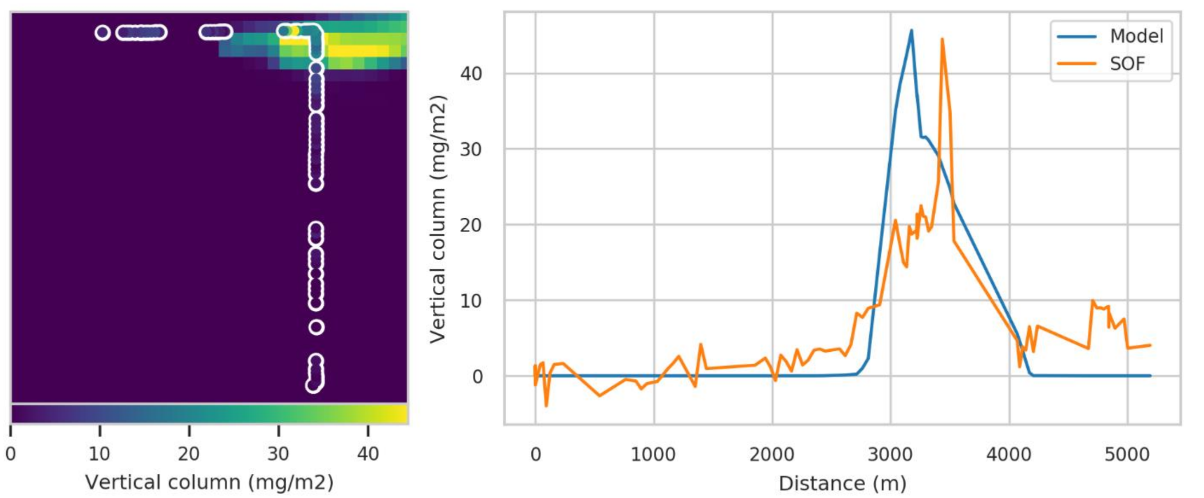

Figure 99 Comparison between vertical alkanes columns measured with SOF and the corresponding columns in the WRF model simulations for a measurement transect at the Kern Oil refinery site around 11:55 on October 19, 2021 . A portion of the innermost domain for the simulation (111 m x 111 m grid cells) is shown on left with the model vertical columns (integrated concentrations) shown as a heatmap on the grid. The SOF transect with SOF column values are overlayed on the grid and marked with a white border. The plot on the right shows both model and SOF column values as a function of driving distance.

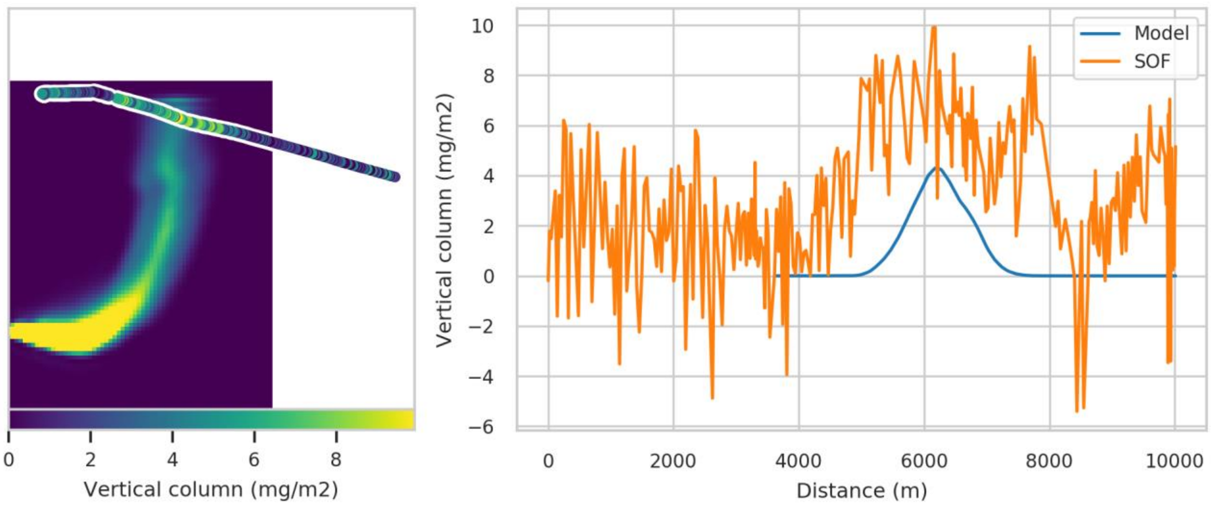

Figure 100 Comparison between vertical alkanes columns measured with SOF and the corresponding columns in the WRF model simulations for a measurement transect at the Kern Oil refinery site around 12:06 on October 20, 2021 . A portion of the innermost domain for the simulation (111 m x 111 m grid cells) is shown on left with the model vertical columns (integrated concentrations) shown as a heatmap on the grid. The SOF transect with SOF column values are overlayed on the grid and marked with a white border. The plot on the right shows both model and SOF column values as a function of driving distance.

After model validation, the simulation results have been used to estimate local concentrations due to the emissions modelled. Figure 101 shows two heat maps of the maximum alkanes ground concentrations (in butane equivalent parts per billion) for each cell in the domain during daytime and nighttime respectively. Daytime has been narrowly defined as the period 10:00-17:00 each day, since this was the period during which the model typically displayed strong vertical plume mixing, and the rest of the time was defined as nighttime. The daytime maximum concentration heat map is clearly dominated by one or two episodes of stagnant wind and/or low vertical mixing, while the nighttime simulation results seem to exhibit more frequent episodes with very high concentrations several kilometers from emission sources.

Perhaps more relevant are the mean concentrations, as presented in Figure 102. During the daytime, southwesterly winds seem to dominate, resulting in mean alkanes concentrations of 5 ppb (butane equivalent) or more up to 3 km away from the sources. During nighttime, the wind direction seems to be more variable, but with a preference for easterly winds. Mean exposure levels of 10 ppb or more during nighttime are attained as far away as 6 km from the sources and levels of 20 ppb or more are attained up to 3 km from the sources.

Most cells in the modeling domain are not downwind of the sources for most of the simulation time, so mean exposure values in Figure 102 are dragged down by including a lot of zero values. Therefore, the mean concentration does not give an accurate view of typical concentrations for downwind exposure. One way to get a better idea of this is to examine the 90th percentile of ground concentrations instead, as shown in Figure 103. This shows more clearly the stark difference between day- and nighttime exposure levels, with apparently 50 ppb or more 10% of the time up to 3 km from the sources during nighttime.

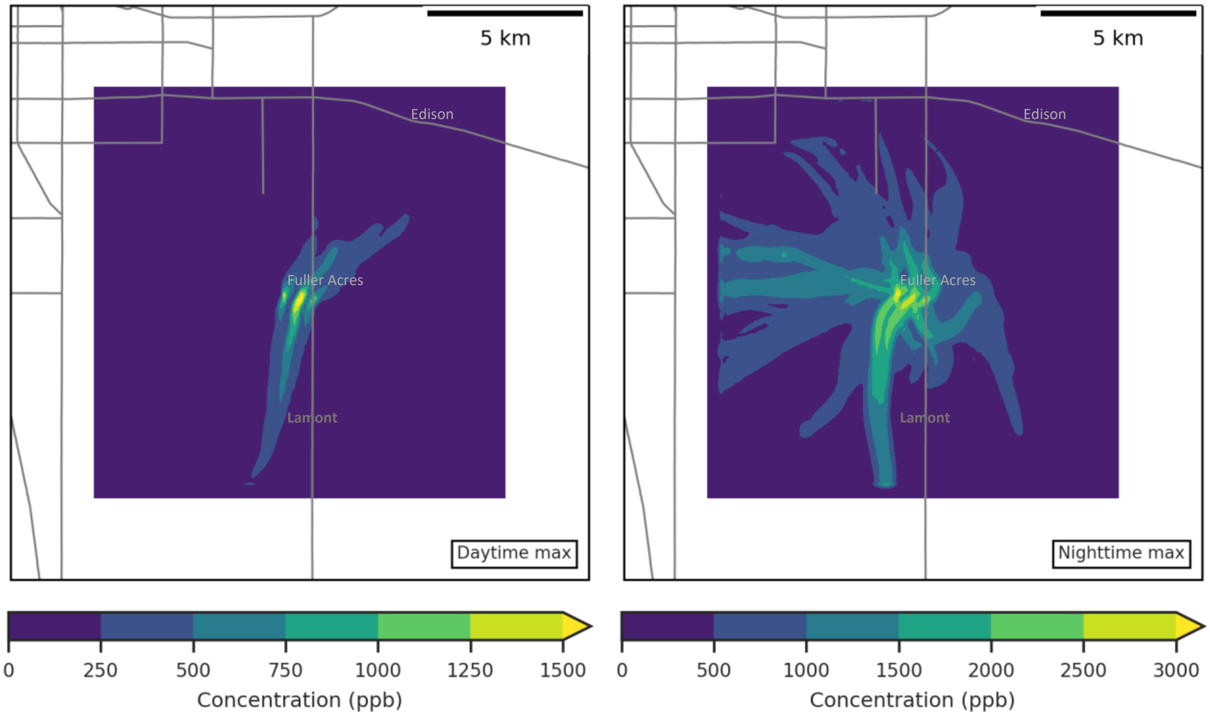

Figure 101 Maximum daytime (left panel) and nighttime (right panel) concentrations in the plume dispersion simulations for Kern Oil refinery during the periods October 12-14 and October 19-21.

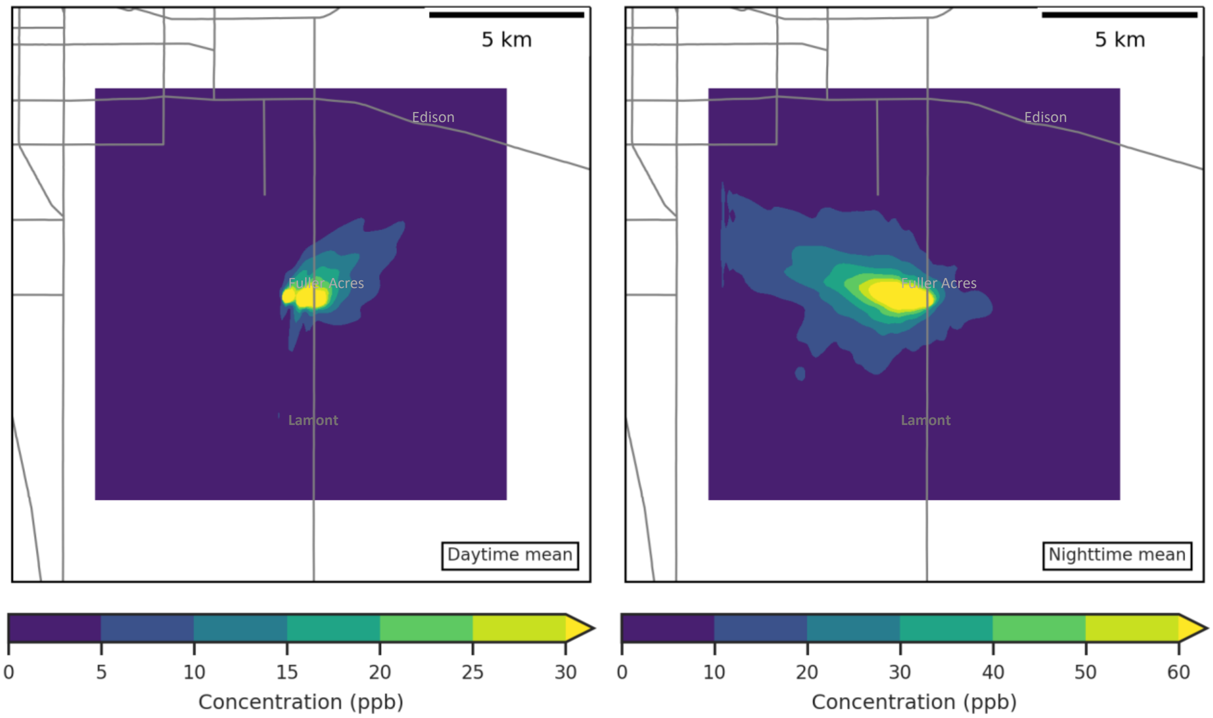

Figure 102 Mean daytime (left panel) and nighttime (right panel) concentrations in the plume dispersion simulations for Kern Oil refinery during the periods October 12-14 and October 19-21.

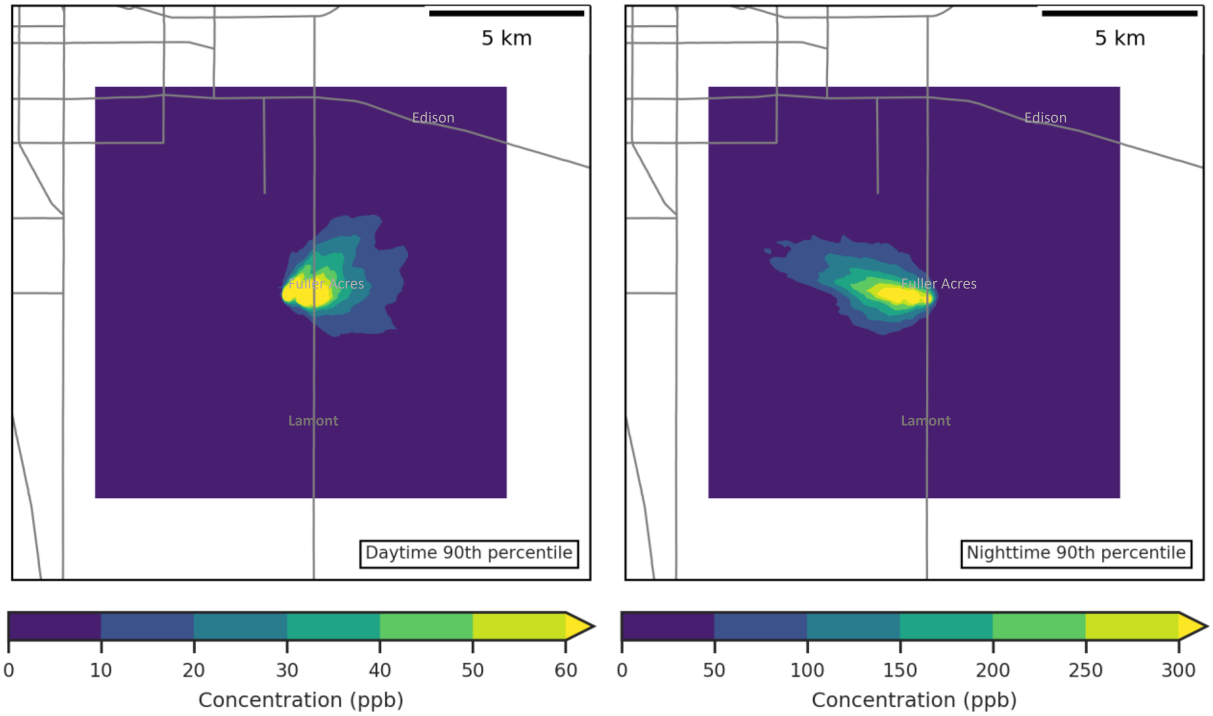

Figure 103 90th percentile of daytime (left panel) and nighttime (right panel) concentrations in the plume dispersion simulations for Kern Oil refinery during the periods October 12-14 and October 19-21.

A more sophisticated method to investigate typical in-plume concentrations requires some way of keeping track of where the plume is during the simulation. Our approach assumes the maximum concentration at each distance is within the plume and is representative of total plume dispersion at that distance. Grid cells were first grouped into distance intervals and then the maximum concentration for each group was calculated for each time step. This maximum represents the "in-plume" concentration for that distance interval at that time step. Figure 104 shows the results as distributions of in-plume concentrations over the distance intervals for daytime and nighttime in a boxplot. The daytime plot shows that the median concentrations at a distance 0-100 m was approximately 150 ppb, with a quite rapid drop-off rate down to around 10 ppb at 3.5-5 km distance. The nighttime plot shows approximately 2 times higher concentrations at the closest distance and a very slow drop-off rate in comparison to the daytime. This is most likely mainly due to the lack of vertical mixing during nighttime.

A difference between daytime and nighttime such as that shown in Figure 104, with much more rapid mixing, is what would be expected due to boundary layer convection, but the drop in concentrations with distance during nighttime is perhaps a bit slower than could be expected. It might be that the dispersion model used does not accurately account for the type of vertical mixing that occurs during nighttime. This could be an interesting aspect to investigate further in future studies.

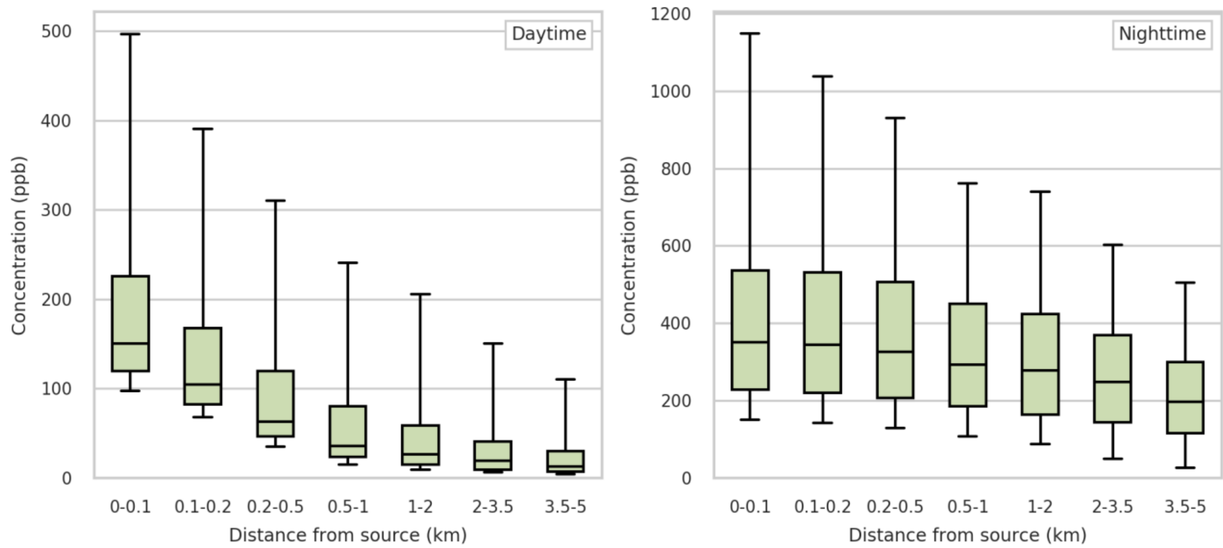

Figure 104 Box plots illustrating the distributions of plume max concentrations for different distance intervals from the source in the simulations for the Kern Oil refinery . The boxes indicate lower quartiles, medians, and upper quartiles, while the whiskers indicate 5th and 95th percentiles. The left panel shows daytime distributions, while the right panel shows night-time distributions.

3.7.2 Lost Hills Processing 1

Figure 105 Overview map showing the extent of the innermost domain (Domain 4, 12x12 km) and location of the 4 sources included in the simulations for Lost Hills Chevron Processing 1 . Map from Google Earth™, 2021.

Lost Hills was chosen as a second site for plume dispersion modeling with Processing 1 as the primary emissions source. A similar domain configuration to the Kern Oil refinery simulation was used, but with the domains centered on location of Lost Hills Processing 1 instead. Figure 105 shows the extent of the innermost domain and the 4 emission sources. Source 3 is the main Treatment Facility and source 4 is the wastewater Processing Site. Sources 1 and 2 are two smaller treatment plants to the northwest and west of the main site. The alkanes emission rates used in the simulation were 3, 5, 27, and 32 kg/h for source 1, 2, 3, and 4 respectively. The simulation for this domain was run for the period 17-22 October, 2021, which was chosen due to its overlap with MeFTIR measurements in the area.

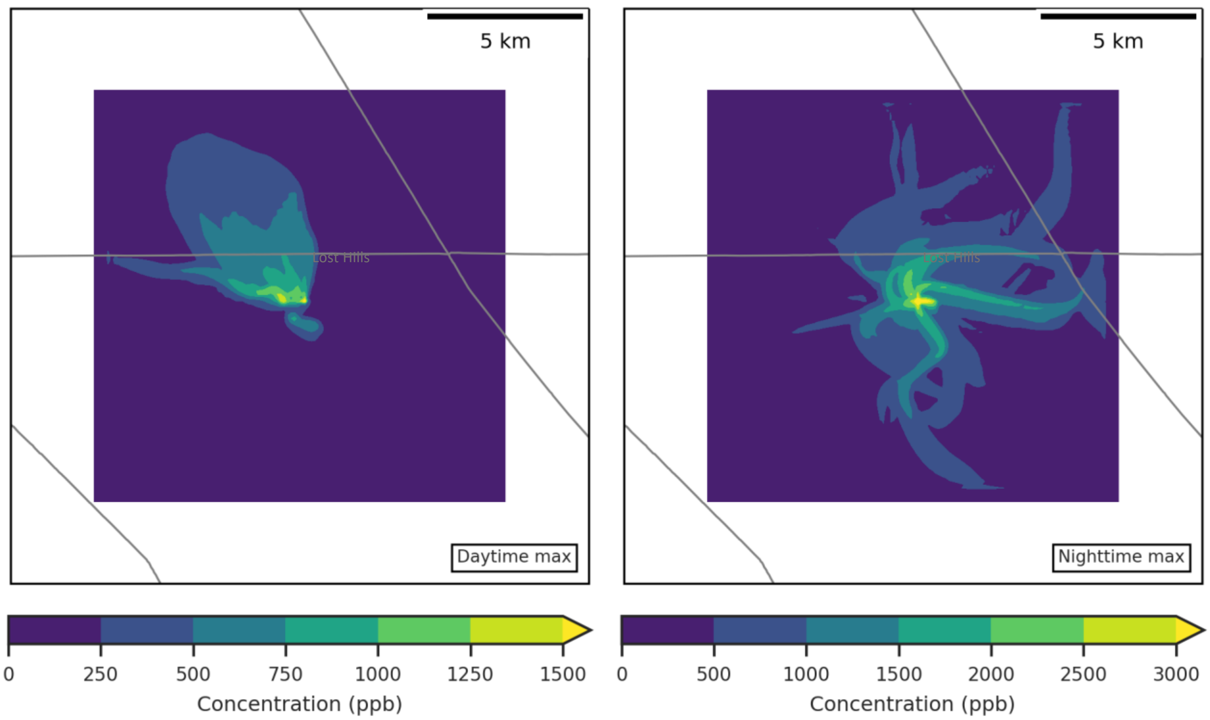

Figure 106 Maximum daytime (left panel) and nighttime (right panel) concentrations in the plume dispersion simulations for Lost Hills Processing 1 during the period 17-22 October 2021.

Figure 106 shows the maximum ground concentrations reached in the WRF simulations for the Lost Hills area. This shows that the highest daytime max concentrations seem to be caused by a single episode with weak southeasterly winds, while very high nighttime concentrations seem to occur at many times in different wind directions. This is quite similar to the results from the Kern Oil simulations. The mean concentrations presented in Figure 107 show that westerly and southerly winds seemed to dominate during the nighttime, resulting in higher exposure east and north of the sources toward the Lost Hills community, while easterly winds dominated during daytime, resulting in more exposure west of the sources. The 90th percentile plots shown in Figure 108 highlights the prevailing winds during day and night even more, especially for daytime, where concentrations of 10 ppb and more were seen 10 % of the time as far away as 5 km from the sources.

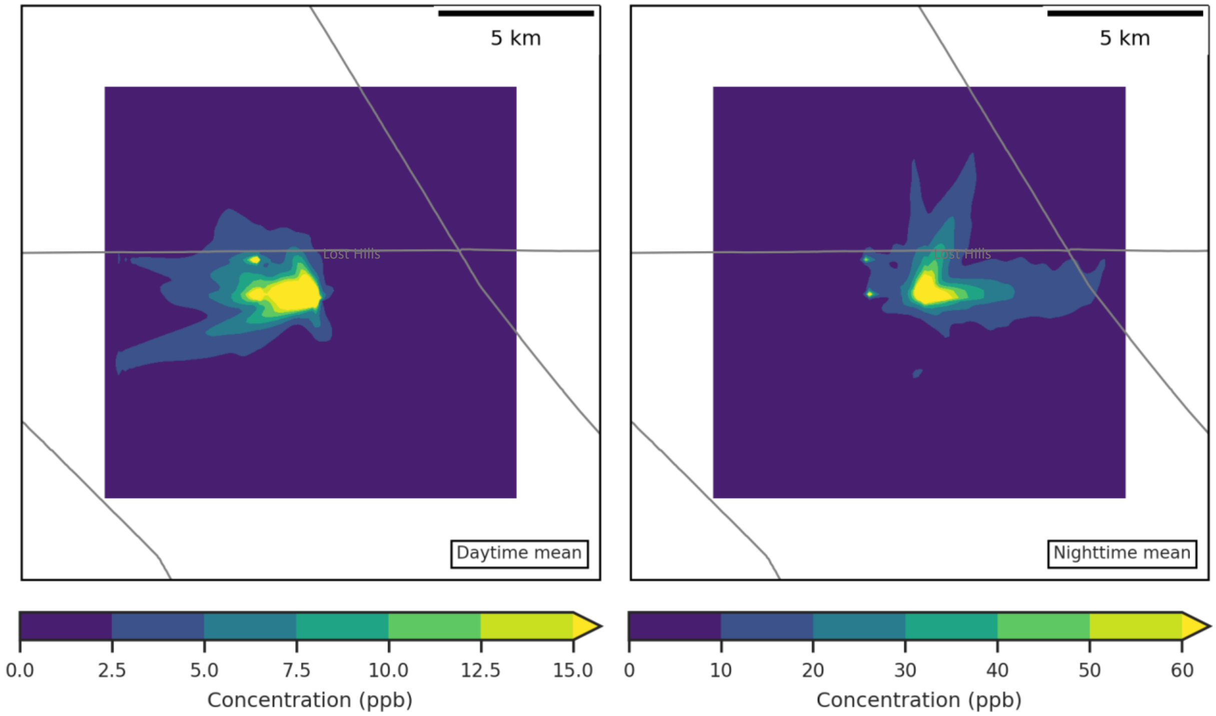

Figure 107 Mean daytime (left panel) and nighttime (right panel) concentrations in the plume dispersion simulations for Lost Hills Processing 1 during the period 17-22 October 2021.

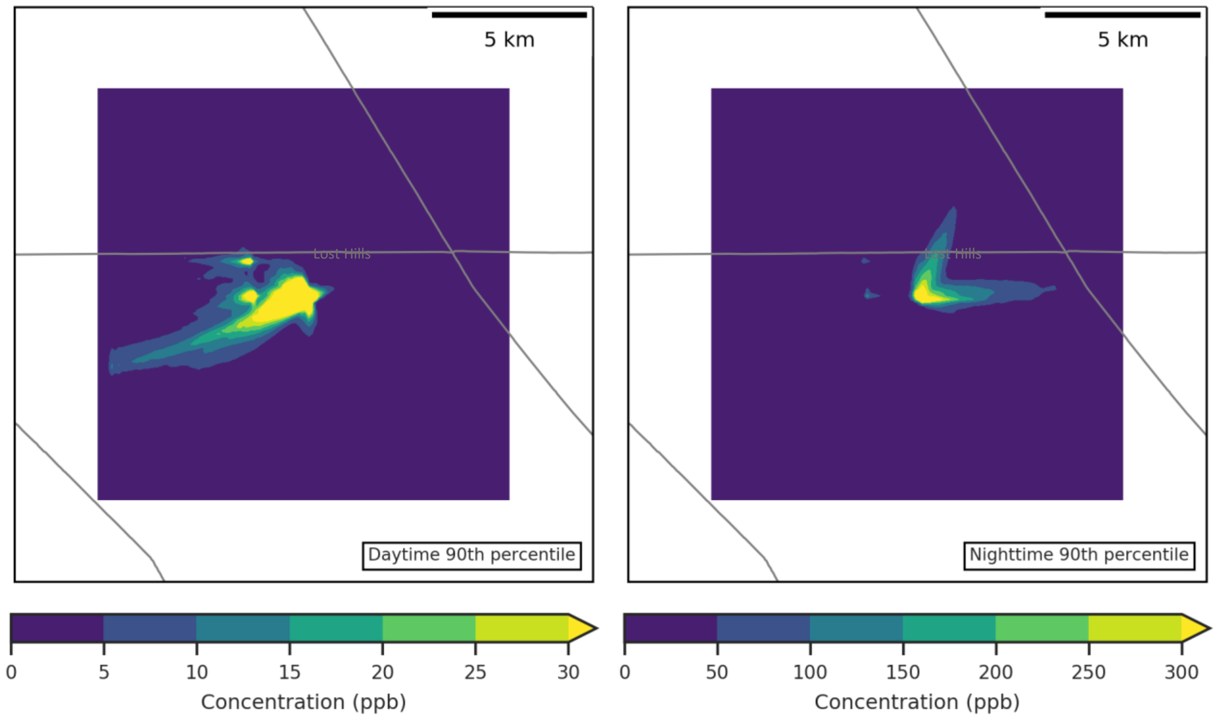

Figure 108 90th percentile of daytime (left panel) and nighttime (right panel) concentrations in the plume dispersion simulations for Lost Hills Processing 1 during the period 17-22 October 2021.

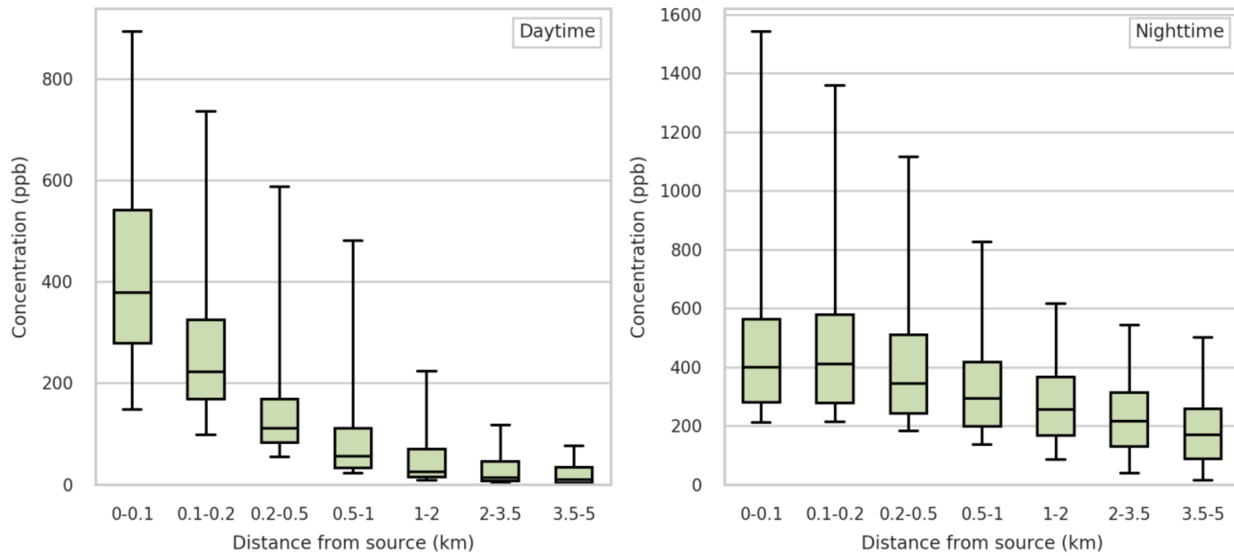

Figure 109 Box plots illustrating the distributions of plume max concentrations for different distance intervals from the source in the simulations for Lost Hills Processing 1. The boxes indicate lower quartiles, medians, and upper quartiles, while the whiskers indicate 5th and 95th percentiles. The left panel shows daytime distributions, while the right panel shows night-time distributions.

The distributions of in-plume max concentrations for different distance intervals from the sources were analyzed in the same way as for the Kern Oil refinery simulations and the results are presented in Figure 109. In these simulations, the stark difference between daytime and nighttime was still apparent, but the concentrations dropped-off more rapidly than for the Kern Oil refinery simulations. During daytime median concentrations dropped from about 380 ppb at 0 to 100 m to about 50 ppb at 500 to 1000 m, and during nighttime, median concentrations dropped from about 400 ppb at 0 to 200 m to about 200 ppb at 3.5 to 5 km.

4 DISCUSSION

OIL AND GAS EMISSIONS

The area surveyed in this project represents a significant portion (60 – 70%, Mellqvist et al., 2021) of the oil and gas production in California. To give an indication of size, the sum of emissions for the fields in Kern County in San Joaquin Valley, wholly or partially measured, amount to 6100 kg/h of alkanes and 10300 kg/h methane. This includes the Elk Hills, Asphalto, North and South Belridge, Coles Levee North, Cymric, McKittrick, Kern Front, Kern River, Edison, Mountain View and Lost Hills fields and is based on measurements from at least one survey in 2019 or 2021. Midway-Sunset was an important emissions source, however, due to a lack of repeats and complete measurements it could not be included in the statistics.

As a comparison, emission measurements in another CARB project (Mellqvist et al, 2021) in October 2018 and May 2019, showed aggregate alkane emissions of about 7600 kg/h from the Elk Hills, Asphalto, Belridge, Coles Levee North, Cymric, McKittrick, Lost Hills, Kern Front and Poso Creek fields. The corresponding emissions for methane were 8000 kg/h.

Production has most likely decreased across all the measured fields since the first survey in October 2019. Figure 110 shows the production data reported for Kern County for the month of October for 2019, 2020 and 2021. Oil production decreased by approximately 17% and similarly, gas production by 17% according to these figures. Whether this is reflected in the emissions measured for October 2019 compared to October 2021 cannot be answered with statistical certainty, but observations do not contradict it at least. Production in May 2019 was in level with October 2019 rates, for reference to the previous study.

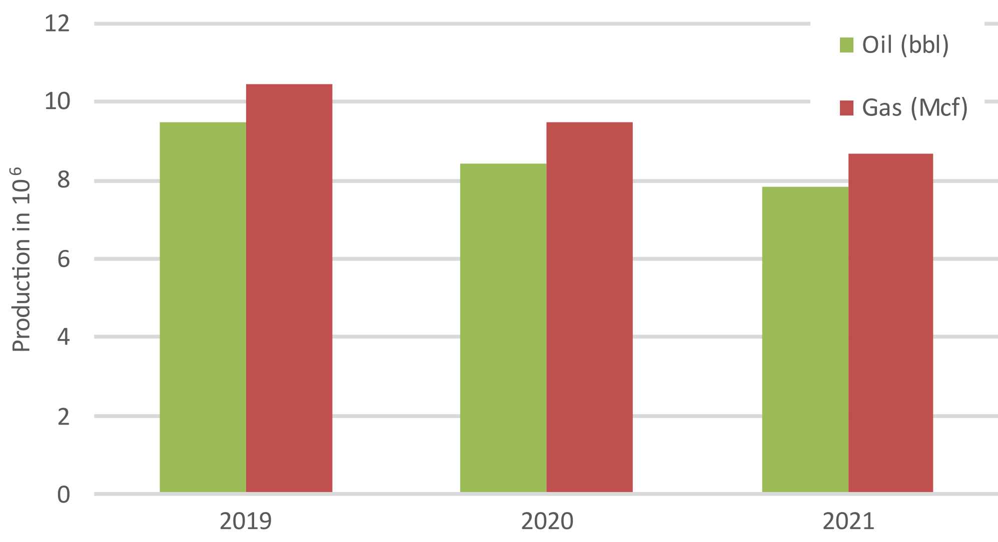

Figure 110 Kern County Oil and Gas Production for October for three years (2019, 2020, 2021). Data source: https://app.powerbigov.us/view?r=eyJrIjoiNGQzZWU1N2QtNjNmYy00ODQyLWJlNDUtODBiYjg2MjYyYzIzIiwidCI6IjRjNTk4OGFlLTVhMDAtNDBlOC1iMDY1LWEwMTdmOWM5OTQ5NCJ9&pageName=ReportSectionf17b88a6302e7136a0b1, 17 Feb 2022.

Table 118 presents alkane emissions and methane emissions (October 2021 survey results) in relation to active wells and reported oil and gas production (November 2020 through October 2021, CalGEM online database 22 December 2021).

Table 118. Oil Field Emission factors by wellhead and oil production. *Field not isolated in measurementss. [a] Also includes contributions from McKittrick wells/areas east of Hwy 33, Asphalto, the Midway Sunset area north of Hwy 33 and the Buena Vista areas north of Midway Rd and Hwy 119. [b] includes contributions from McKittrick wells/areas north of Reward Rd. [c] Excludes McKittrick areas east of Hwy 33 and north of Reward Rd. [d] Emissions from 2019, determination not measured separately. The number of active oil, gas and multipurpose wells by field, from CalGEM online database as of 22 December 2021. The production of oil and gas for selected Kern and Los Angeles County Oil and Gas Fields is based on the period Nov 2020 – October 2021 (CalGEM, 2021).

Field	**Number of active oil and gas wells**	**Oil production [kg/h]**	**Gas production [m³/h]**	**Alkane emissions, October 2021 survey [kg/h]**	**Specific well head alkane emission [kg/h/well head]**	**Alkane emission factor [kg/h emitted / kg/h oil produced]**
Asphalto	101	2895	9680	*	*	*
Belridge	6057	292169	26608	1591[d]	0.26	0.54%
Buena Vista	356	12880	33667	*	*	*
Coles Levee N	39	1346	217	226	5.79	16.79%
Cymric	985	183720	6340	841 [b]	0.85	0.46%
Edison & Mountain View	781	8354	340	112	0.14	1.34%
Elk Hills	2883	96147	182339	2246 [a]	0.78	2.34%
Inglewood	415	24832	2509	101	0.24	0.41%
Kern Front	1016	37546	174	143	0.14	0.38%
Kern River	1176	235240	2312	243	0.21	0.10%
Lost Hills	2397	126278	13880	452	0.19	0.36%
McKittrick	357	58899	2161	242 [c]	0.68	0.41%
Total:	**16563**	**1080305**	**280228**	**6197**	**0.37**	**0.57%**

For the production year running November 2020 through October 2021, the average total production rate for the fields that were part of the alkane emissions monitoring in October 2021 was 1,080,310 kg/h of oil and correspondingly 280,230 m^3/h for gas.

The aggregate alkane emissions measured in October 2021 were 6197 kg/h for the 13 oil and gas fields in Table 118 and the corresponding values for methane were 10300 kg/h, as already mentioned in the beginning of this section. The alkane and methane emissions have been normalized to the number of active wells, yielding the *specific well head emission* kg/h/well head). This approach places all field emissions to occur from the well heads. However, emissions from other production/processing facilities in the fields contribute to the overall alkane emissions, and the normalization should be seen as a field-to-field comparison tool. In addition, idle, new or plugged wells might contribute although not included in the normalization well head number. The average specific well head emission of alkanes is 0.37 kg/h/well head (Table 118). The corresponding value for methane is 0.62 kg/h/well head.

The sites Cymric, McKittrick and Elk Hills (also including Asphalto and part of the Belridge and McKittrick fields) show relatively high specific well head emissions. The Coles Levee North field stands out with 5.79 [kg/h/well head] that can be explained by a low number of active wells (39) and emissions apparently originating from a larger facility within field area, as indicated by fenceline measurements.

Alkane and methane emissions have also been normalized against the production-based numbers of oil and gas production, see above, yielding production-based emissions (kg/kg_{prod}). It is assumed that the majority of the alkane emissions occur from the production of oil rather than gas and vice versa for methane. The specific production-based emissions of alkanes range between 0.1 % to 17 % with an average of 0.57 %, as can be seen in Table 118. Again, the Coles Levee N stands out with the highest emission factor. For methane, assuming a 91% methane content by volume of the gross gas for all measured fields, the average value for is 5.6 % (not shown in table).

The October 2019 survey focused on the Lost Hills area and involved in-field measurements at two different operators by the Lost Hills oil and gas field. Quantitative SOF measurements as well as concentration mapping were conducted for a large number of facilities, individual wells and sub-sections of the Lost Hills field. The measurements identified significant emission contributors, attributed to different sectors of the field, showing alkane and methane emissions in particular, but also some instances of BTEX. Most of the larger sources were traced to activities such as workover and other rigs, and vacuum trucks besides production or treatment facilities.

No large well head leaks were encountered in the survey. In a dedicated well head emission effort, alkane emissions were quantified from two different sub-sections with 196 and 113 active wells, respectively. Averaging the obtained sector emissions of 12 kg/h and 39 kg/h resulted in well head specific emissions of 0.06 kg/h and 0.35 kg/h. It should be noted that the latter sector with the higher rate included more production/processing facilities than the first, likely biasing the well head estimate higher. In another approach, 54 SOF measurements on 21 individual well units showed an average well head emission rate of 0.66 kg/h, however the individual measurements were generally below the quantification limit for SOF in most instances and these measurements were subject to selection bias. Tracer gas derived emission quantification with MeFTIR on four well units showed average alkane emissions in the range 0.02-0.1 kg/h/well. Altogether, the in-field wellhead emission estimates are quite comparable to the overall field wellhead emission approach discussed prior to here, with 0.19 kg/h/wellhead for Lost Hills in particular, and the range 0.14-0.85 kg/h/wellhead in general for the studied oil fields. This rate would include emissions from both well heads and other production facilities associated to the field, normalized to total number of active wells.

The oil and gas fields and sites in this report covers most of the sources in the SJV but only a fraction of the existing oil and gas sites in SCAB. The Las Cienegas Production Sites were targeted because of their proximity to SNAPS and CAPP communities, not because they are suspected to be strong VOC emitters. Previous studies of oil and gas sources in the SCAB reveal a dominant contribution from small sources (processing sites and storage) where some individual sites were in parity with refinery emissions, i.e. 100-300 kg/h of alkanes (Mellqvist et al, 2015a, 2015b). The Signal Hill area stood out as regional hot spot for VOC emissions in the 2015 studies.

PLUME TRACING AND DISPERSION MODELING

Plume tracing (successive plume traversal at increasing distance downwind) and atmospheric dispersion modeling were used in the study to investigate how ground concentrations of VOCs vary with downwind distance from the emissions sources and how they may potentially impact nearby communities. In both modeling and measurements, a clear diurnal pattern emerged. In the model simulations, daytime concentrations typically dropped by an order of magnitude within the first 500-1000 m downwind, while nighttime concentrations had generally not dropped by more than a factor of 2 at a distance of 2-5 km downwind. Likewise in measurements, daytime plumes could only be seen adjacent the site, or before the growth of the daytime boundary layer. Nighttime measurements showed possibly more initial dispersion, then a similar gradual decline in concentration with distance. The most obvious and trivial explanation for this is the rapid convection-driven vertical mixing during daytime opposed to the shallow stable nocturnal boundary layer.

Qualitatively, the plume tracing measurements confirm the results of the model simulation, particularly in the daytime. On sunny days convection and dispersion are strong enough that it is difficult or impossible to make plume tracing measurements. While this is due to a combination of factors (limited roads, emissions measurements are prioritized) the main factor is that ground concentrations of the emitted VOCs rapidly fall below detection limits moving away from the source. Despite this qualitative agreement between simulation results and measurements, there seems to be some disagreement about the rate at which concentrations decay with distance during nighttime. Since overall community exposure is most likely dominated by the high ground concentrations seen during nighttime, it is critical to get the nighttime concentrations correct in order to assess the impact of the VOC emissions.

There are several possible explanations or factors for this seeming discrepancy between model simulation and measurements. First, we consider where the simulation may be deficient. One possibility is that the simulation does not account for nighttime vertical mixing accurately. Daytime vertical mixing is driven by strong convection due to solar heating of the ground, and it seems that the simulation is able to account for this reasonably well, but during the nighttime clear sky cases during this simulation, the convection dies off and vertical mixing may be dominated by other processes, such as mechanical turbulence, which the simulation does not reproduce accurately at this scale. Most of the plume tracing measurements were made relatively early in the evening, when there may be some residual, stored heat still causing some convection. While not fully analyzed at this time, surface temperatures may cool too rapidly to support early evening convection which supports this conjecture.

Another possibility is that the model actually agrees better with the measurements in the early evening, but that this agreement is lost when looking at the nighttime results as a whole. In addition to potential insufficient vertical mixing, there are indications that the simulation does not produce sufficient horizontal crosswind dispersion. The observed evening plumes are more in agreement with limited lateral dispersion than the more laminar meandering flow seen in the simulations. This could indicate a lack of turbulence in the simulation compared to actual conditions, but one that could be corrected by adjusting the surface layer scheme in the model.

Another factor can be the limited spatial resolution of the dispersion model, which may be a limiting factor when comparing to the measurements close to the source. The grid cells in the dispersion model are 111 m wide and the lowest layer has a height of approximately 25 m and the full source strength is distributed uniformly throughout the cell. For the closest measurements it is likely that the true emissions plume has a smaller extent than the simulated plume. This naturally results in lower concentrations for the simulation near the source than the true source plume has. Being already distributed uniformly vertically in a shallow stable boundary layer the simulated plume would show less effect from vertical dispersion.

A final factor also relates to the source modeling, that the source has vertical velocity or temperature difference, either from stack emissions or heated surface which can lead to initial plume rise and enhance vertical dispersion. The land-surface model in the simulation does not capture the process heat generated by the facilities which would generate convection above the facility.

The limitations of plume tracing also need to be considered, in general and in relation to the simulation. In comparison to the simulation the measurements are few, limited to roads and by detection limits while the model is more limited by the spatial resolution of the sources and the representation of turbulence. Plume tracing can be difficult, especially at longer distance from the source. The plume may meander as the measurements progress, particularly with weak winds, and there is no way to know for sure whether the full plume was intercepted at each distance. As the distance from the source grows larger, the distance needed to be driven to ensure full plume coverage grows and the measurements are often limited by the availability and accessibility of suitable roads. The further afield the plume, the greater likelihood for interfering sources which add uncertainty to the measurements.

Finally, it should be noted that these comparisons were made for relatively small datasets, both for the measurements and the modeling. The model was run for 6 days each for the Kern Oil Refinery and the Lost Hills site. It is quite possible that atypical meteorological conditions during some of these days could bias the results. To investigate plume dispersions further it would be interesting to look more deeply into how both vertical and horizontal mixing are parametrized in the WRF model and to run more extensive simulations to get results representative of longer time periods.

CONCENTRATION MONITORING IN COMMUNITIES

The primary concern of community concentration monitoring is typically air toxics (BTEX in this project), and secondarily NMVOC concentrations. Several residential neighborhoods and communities close to oil and gas sources showed enhanced BTEX concentrations in 2021. The cases in point were in Lost Hills and Oildale where winds transported plumes from oil and gas sources in over the communities. Specific treatment and processing facilities were seen to have impacts on concentrations in proximate communities.

The main results of community monitoring are maps where measured concentrations are visualized. In order to remove the effects of temporary or mobile sources and provide consistent data, measurements should be repeated and data aggregated. With the allotted time for different project objectives, this was only possible in 2021 but even then, the repeated measurements are relatively few. For the data from 2019 only individual measurements maps are presented due to a lack of repeats.

Ground level concentrations are sensitive to many parameters such as source strength, source distance, source elevation, wind speed and atmospheric stability and turbulence. The CM implementation also depends on available/accessible roads. Wind direction is an important parameter for communities adjacent to external sources. In addition, the time-of-day should be considered since evening/nighttime show significantly higher ground-level concentrations than daytime measurements (see discussion on modeling above). This has not been done fully consistently in the surveys due to time limitations and conflicts with other survey objectives or planning issues.

5 SUMMARY AND CONCLUSIONS

OIL AND GAS EMISSIONS

The area surveyed in this report represents a significant portion of the oil and gas production in California. Cumulative emissions for the fields in Kern County in San Joaquin Valley, wholly or partially measured, amount to 6100 kg/h of alkanes and 10300 kg/h methane. This includes the Elk Hills, Asphalto, Belridge, Coles Levee North, Cymric, McKittrick, Kern Front, Kern River, Edison, Mountain View and Lost Hills fields. A partial measurement of Midway-Sunset showed alkane emissions above 1000 kg/h but lacked verification with repeated measurements. VOC emission measurements of 4 Oil & Gas sites (refinery and treatments sites) were also carried out in the SJV.

For the South Coast region, Inglewood was the only oil field included in its entirety, showing an alkane emission of 101 kg/h. Corresponding methane emissions were 121 kg/h. Four well sites, part of the Las Cienegas field in the South Coast region, were measured in June-July 2021 showing alkane emissions of 6 kg/h in total. The Honor Rancho and Playa Del Rey gas storage facilities showed emissions of about 25 kg/h of alkanes all together. Corresponding methane emissions were 6 kg/h from the four La Cienegas well sites and 107 kg/h from the Honor Rancho and Playa Del Rey gas storage sites.

In-field measurements at the Lost Hills oil field in October 2019 screened sub-sections of the field and could identify specific sectors and facilities with enhanced emissions. Sector measurements averaging alkane emissions from 100-200 well heads, pointed to average wellhead emission rates of 0.06-0.35 kg/h with the higher end estimate correlated with a sector including more production/treatment facilities.

A large portion of the emissions from the oil fields in SJV appeared to be diffuse and relatively few hotspots were observed. It was however difficult to obtain a comprehensive overview since the measurements generally were carried out at fenceline or further away, with exception for campaign 1 in Lost Hills that comprised in-field measurements.

DISPERSION MODELING AND PLUME TRACING

The Weather Research and Forecasting (WRF) model 4.3 was used for dispersion modeling, and model simulations were produced for two sites in San Joaquin Valley having repeatedly measured emission sources. Results of the simulations were validated with wind and SOF alkane column measurements showing that the models performed relatively well.

Column measurements showed good reproducibility in terms of shape and integrated concentration. Both modeling and measurements confirmed that under strong daytime convective conditions, concentration dispersion occurred rapidly. Nighttime simulations were dominated by shallow inversion layers and minimal plume dispersion. This allowed modeled plume concentrations to continue several kilometers without decreasing to less than half of initial concentrations. Evening plume tracing observations showed that concentrations dropped off more rapidly near the source facility but also showed on a number of occasions the transport of plumes taking place over long distances (kilometers).

CONCENTRATION MONITORING IN COMMUNITIES

Repeated concentration mapping on multiple days in the Lost Hills town showed that enhanced alkane concentrations in the range from 200 to above 400 $\mu g/m^3$ could readily be seen in evenings when the wind direction brought the emissions from the Lost Hills field in over town. Corresponding BTEX enhancement was in the 2.5-7.5 $\mu g/m^3$ range on average. Concentration mapping around Oildale in Bakersfield showed BTEX concentrations of 5-7.5 ppb about 800 m away from the nearest oil and gas source, and above 10 ppb closer by during evening measurements. Evening concentration mapping in Arvin identified a well site source in the southwest of town. Average alkane concentrations in the immediate vicinity (about 125 m), were above 400 $\mu g/m^3$ and BTEX concentrations in the 2.5 – 5 ppb range. During daytime monitoring for all sites, BTEX and benzene concentrations at ground level were generally close to or below detection limits, except for in proximity to particular facilities.

6 RECOMMENDATIONS

In this study it has been shown that the oil and gas sector exhibits relatively high emissions of VOCs, primarily consisting of methane and alkanes but also BTEX. It appears that the alkane emissions are (strongly) underestimated when using production-based emission factors (Mellqvist et al, 2021). The pollutants from the emission sources spreads in the proximate communities, with some cases showing significant concentration enhancement persisting several kilometers from the sources. The emissions in this study are generally difficult to measure due to the large numbers of sources, their variability and the large distances that need to be covered to complete the measurements. Another difficulty is the impact of topography, making sources difficult to reach and affecting the wind field.

Based on the learnings summarized above, we recommend:

a) *Monitoring and characterization of all oil and gas fields.* The oil and gas sector exhibits large and sometimes variable emissions of VOCs and there are available measurement techniques for monitoring of these, as demonstrated in this project. Measurements should be carried out at least during one occasion (including multiple repeats). If large emissions are found, regular revisits should be done and concentration measurements should be carried out down-wind the sources and, when appropriate, a dispersion model (WRF) should be used to extrapolate the emissions values to annual/seasonal concentration fields. For the largest emitters, an annual monitoring program should be devised with quarterly emission measurements by SOF and stationary concentration measurements to better assess the annual variability and provide input to WRF-modelling.

b) *Performance of complementary measurement close to the sources to identify sources and leakage processes to be able to provide recommendations how to abate the emissions*. The present study was limited by sparse site access to the gas and oil fields (except for Lost Hills). It is also important to compare bottom-up (summing emissions from individually measured areas, activities, facilities, etc) measurements with top-down (fenceline) to make sure that the significant emission sources have been identified. In such a work it would be useful to complement the current mobile optical measurements with drone-based measurements of methane and other VOCs to map concentrations across the entire oil field. It may also be possible to use a small portable SOF instrument that can be carried around or flown on a bigger drone. The WRF-model used in this project could further be used to connect the emissions from the sources with the measured downwind fluxes.

c) *Improved emission measurements by complementary drone studies and modelling*. The largest emitters in this study correspond to large oil and gas production fields, covering vast areas. The emission measurements by the SOF method utilizes both wind speed and direction at multiple heights and assumptions about the vertical gas concentration profile downwind the source as part of the emission calculation. The local and regional topography has large impact on the wind direction and for instance in one of the fields (Elk Hills) there appears to be a distinct shear in the wind direction within the field. The variability in the abovementioned parameters (wind and concentration profile) causes uncertainties in the emission values of 30-40 % and sometimes larger (Mellqvist et al., 2021). In order to minimize the uncertainties, complementary drone measurements should be carried out to investigate concentration- and wind profiles. The WRF modelling in this project is a useful tool for characterizing the wind field and columns downwind the sources. This modeling should be further streamlined into an operational tool for assessing the wind field when carrying out SOF measurements in order to further minimize the measurement uncertainties. Height concentration profile measurements by drones are also recommended to minimize measurement uncertainties for indirect emission measurements of methane and BTEX.

d) *Further WRF modeling efforts with more validation evening/nighttime simulations*. Investigate and improve upon evening/nighttime dispersion in the model, using mobile measurements of concentration at different distance from the source for validation; here Oildale is a specific area of interest with strong sources and many residents.

e) *Running WRF model over longer time frames* and combining with wind field assessment for SOF measurements, see bullet point a, b and c.

f) *Combining mobile community monitoring with stationary 24/7 measurements* to study temporal variability as well as spatial, see bullet point a.

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8 GLOSSARY OF TERMS, ABBREVIATIONS AND SYMBOLS

Abbreviations

AB	Assembly Bill
BPD	Barrels per day
ASOS	Automated Surface Observation System
BTEX	Sum of Benzene, Toluene, Ethylbenzene, p-Xylene, m-xylene
BTX	Sum of Benzene, Toluene, p-Xylene
C_2H_4	Ethylene
C_3H_6	Propylene
C_6H_6	Benzene
CH_4	Methane
CalGEM	California Geologic Energy Management Division
CAPP	Community Air Protection Program
CARB	California Air Resources Board
CEC	California Energy Commission
CI	Confidence interval
CM	Community Monitoring
DOAS	Differential Optical Absorption Spectroscopy
DOGGR	Division of Oil, Gas, and Geothermal Resources
EF	Emission factor
EPA	Environmental Protection Agency
FTIR	Fourier Transform InfraRed
GHG	Greenhouse Gas
GPS	Global Positioning System
H_2CO	Formaldehyde
IME	Indirectly Measured Emission, combining direct emission with concentration ratios
IQR	Inter Quartile Range
JPL	NASA Jet Propulsion Laboratory
KBFL	ASOS wind station Meadows Field
LIDAR	Light Detection and Ranging
MeDOAS	Mobile White cell DOAS
MeFTIR	Mobile extractive FTIR
NA	Not Applicable
ND	Not Detected / No Detection
NM	Not Measured / No Measurements

NMVOC	Non-methane volatile organic compound, used interchangeably for C_3+ alkanes here
NO_2	Nitrogen dioxide
PPB	Parts per billion, used interchangeably for ppbv (ppb by volume) here
QA	Quality Assurance
QC	Quality Control
ROG	Reactive Organic Gases
SB	Senate Bill
SCAB	South Coast Air Basin
SD	Standard deviation
SJV	San Joaquin Valley
SkyDOAS	Scattered Skylight DOAS
SNAPS	Study of Neighborhood Air Near Petroleum Sources
SO_2	Sulphur dioxide
SOF	Solar Occultation Flux
VOC	Volatile organic compound, used interchangeably for non-methane VOC

Units

Air temperature	degrees C
Atmospheric Pressure	mbar
Relative Humidity	%
Wind direction	degrees North
Wind speed	m/s
Column	mg/m^2
Concentration	mg/m^3, µg/m^3, ppmv, ppbv
Flux	kg/h

Unit Conversions

1 lbs = 0.4536 kg

1 kg/h = 52.9 lbs/day

1 bbl = 159 l

1 bbl/day = 5.783 kg/h (crude oil)

1 Mcf = 1000 cf

1 (short) ton = 907.2 kg

1 kton/year = 104 kg/h

1 klbs/year = 0.052 kg/h

1 µg/m^3 Alkane = 0.421 ppb Butane equivalent (1 atm, 25 C)

Terms and Definitions

All concentrations or columns are shown as **enhancement**, i.e. the value relative a reference outside the plume, so as to better visualize the contribution from the nearest sources. For species without significant background concentrations such as benzene, the measured concentration approaches the absolute concentration. For other species such as methane, the background concentrations or columns can vary markedly especially near widespread sources such as in agricultural, wetlands or oil producing areas.

Alkane or **Alkanes** are considered to be all non-methane alkane species larger than ethane, e.g. C_3+.

Processing Facility or **Site** is an unspecified or unknown facility or unit for processing, treatment, temporary storage, etc. of oil and gas.

Tank Park or **Tank Farm** are areas with oil and gas storage consisting of more than one aboveground storage tank

9 APPENDIX

Plume height assessment

The height of the plume influences which wind speed and direction to apply in the flux calculation. In this study for the October 2019 survey we used the average wind speed of the wind LIDAR between ground and 300 m altitude as the main wind speed and direction. This is based on other studies showing a typical vertical mixing speed of 0.5 m/s (Mellqvist, 2009). Given the spatial extent of the oil fields the orthogonal transport distance to the geographic center line generally leads to plume height estimates above 300 m. However, for many of the measurements in this campaign near-field sources may dominate, which leads to lower plume height estimates.

Therefore, appropriate wind profiles were applied individually. For large scale oil field fluxes, 10 – 300m winds were used, and for within field sources with ground level emissions, e.g. pump jacks, gathering lines, and to some extent separators, 10 m winds from the in-field mast were used. For Lost Hills measurements made on GP Road, Holloway Rd and Highway 46, 10 – 100m winds were used. Because the 10-100 m and 10-300m winds are very similar this had little impact on the measured emissions.

An example of applied plume height estimation is shown in Figure 111. In this example plume heights are estimated at least 130 m for the Holloway Road measurement and above 210 m for the Highway 33 measurement. First order plume height estimates based on measurements are given in Table 119. Calculated plume height from rise time is based on average distance from mid-field source and wind speed during measurements and a vertical rise of 0.25 m/s.

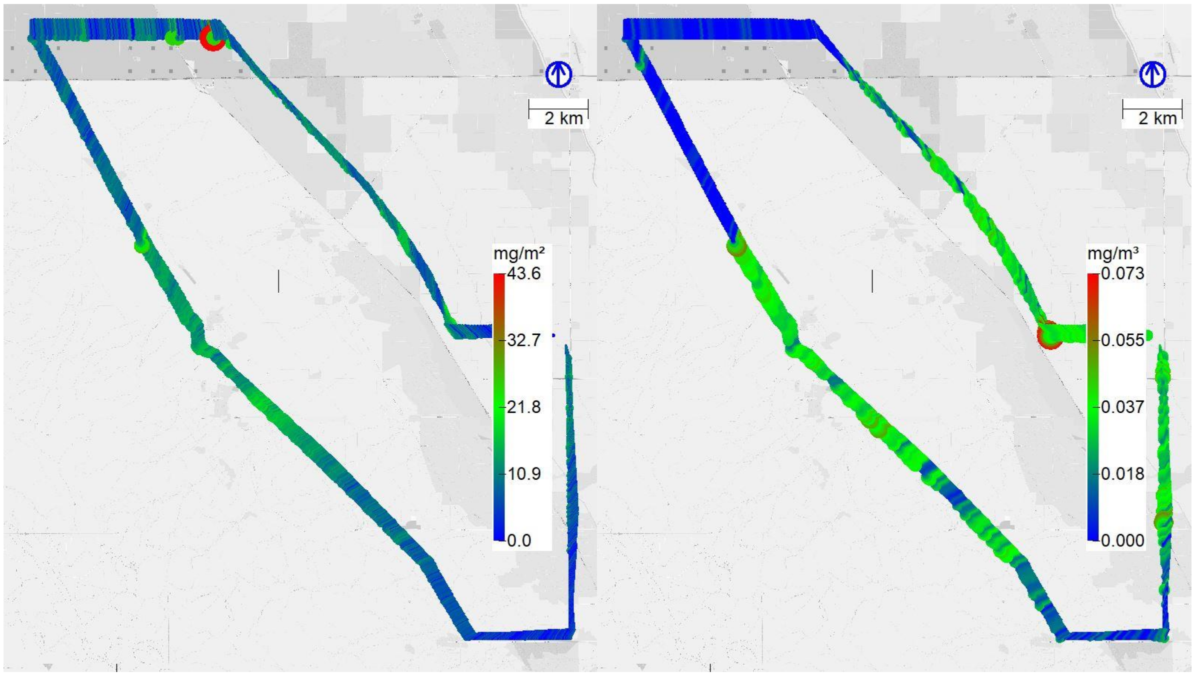

Figure 111. Plume height measurement example showing SOF alkane slant column (left) and MeFTIR alkane concentration (right) around Lost Hills. Two measurements are shown, one in the near field on Holloway and Highway 46 and the other in the far-field along Highway 33. The first order plume height estimates are 130 and 210 m, respectively.

Table 119 First order plume height from rise time (distance, d, divided by wind speed, U) estimation and measurements (SOF column/MEFTIR concentration for alkanes).

Area (fields and associated facilities)	Average Distance, d (m)	Rise Time, d/U (s)	Height, Rise Time (m)	Height, measured (m)
Lost Hills	4725	1970	492	210
Lost Hills N of Hwy 46	1940	747	187	150
Lost Hills S of Hwy 46	3779	1774	444	230
Cymric & McKittrick	3011	1187	297	540
Belridge	5073	2169	542	520