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

VOC Emissions Monitoring in the Lost Hills Vicinity, San Joaquin Valley

2019

Summary REPORT

FluxSense Inc

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Title: VOC Emissions Monitoring in the Lost Hills Vicinity, San Joaquin Valley

Authors: Johan Mellqvist[1,3], Jerker Samuelsson[1], Brian Offerle[2], Tobias Lysvret[2], Samuel Brohede[2] and Marianne Ericsson[1]

[1]FluxSense Inc, 113 W G Street # 757, San Diego, CA 92101
[2]FluxSense AB, Sven Hultins gata 9, SE-41288 Göteborg, Sweden
[3]Chalmers University of Technology, Hörsalsvägen 11, SE-41296, Göteborg, Sweden

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Principal Investigator: Johan Mellqvist,
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DISCLAIMER

Executive summary

Objective

Study carried out by FluxSense Inc on behalf of California Air Resources Board (CARB). The objective is to provide ground-based flux measurements of VOCs, methane and air toxics from oil and gas production in the San Joaquin Valley (SJV). The study also characterizes ground concentrations of the above-mentioned species at community scale to provide insights on concentration levels particularly in disadvantaged communities near emission sources and to identify emissions sources and their contributions to observed concentration levels. This project complements community monitoring efforts by CARB staff who have measured speciated VOCs and other toxics of concern.

Background

This is a report from the first SJV project survey primarily focused on the Lost Hills area. This report also includes investigations of the impact of various sources on the concentration levels in some of the communities near the oil and gas production area.

The emission fluxes (kg/h) of alkanes, ammonia, SO_2, NO_2 and formaldehyde were quantified using Solar Occultation Flux (SOF) and mobile SkyDOAS (Differential Optical Absorption Spectroscopy). MWDOAS (Mobile White Cell DOAS) and MeFTIR (Mobile extractive Fourier Transform Infrared) techniques were used to measure ground level concentrations of alkanes, BTEX and methane, which allowed to indirectly obtain emission fluxes when combined with measured SOF fluxes.

SOF is a proven technique that has been developed at Chalmers University of Technology in Sweden and further developed and applied by FluxSense in over 100 fugitive emission studies around the world. In Europe the SOF technique is considered Best Available Technology (BAT) for measurements of fugitive emissions of VOCs from refineries, and in Sweden it is used in conjunction with tracer correlation and optical gas imaging to annually screen all larger refineries and petrochemical industries. The estimated uncertainty for SOF emission measurements is typically 30 % for total site emissions. The estimated measurement uncertainties have been verified in several (blind and non-blind) controlled gas release studies and in side-by-side measurements with other measurement techniques.

The instrument systems above were operated in the FluxSense mobile laboratory and the measurement were conducted while driving outside the source area fence-lines along public roads. For parts of the study, on site measurements were done on two distinct portions of the Lost Hills oil field. Background columns and concentrations were subtracted by encircling the sites, when possible, or by measuring upwind columns and concentrations, so that only emissions from within the facilities were quantified. Wind data were obtained from a Light Detection and Ranging (LIDAR) instrument that measured the wind profile between 10 to 300 m altitude and from a 10 m mast mounted anemometer. From the combination of the measured column and concentration values, respectively, the height of the plume could be derived to first order.

Emissions measurements and community monitoring

Measurements of emissions were made over the course of 3 weeks in October 2019 with a little more than two weeks spent on Lost Hills and four days for other sources in the SJV. More than half the duration in Lost Hills was devoted to near-field measurements of emissions and identifying large sources or leaks within the fields of two of the major oil producers in the region.

Lost Hills and Other Oil Field Emissions

Total large-scale fugitive NMVOC emissions from Lost Hills oil and gas production area averaged 522 kg/h over the campaign time frame. This is lower than was previously measured in an earlier study conducted by FluxSense (780 +/- 310 kg/h, May 2019) but the difference was not statistically significant. Additionally, activity related factors vary over time. Roughly 50 % of the emissions originate from the area north of Highway 46 with the remainder coming from the southern portion. Most of the emissions in the Lost Hills area are diffuse and do not originate from a few major sources although activity related sources (drilling, work-over, vacuum trucks) were evident.

Measurements were also made of Cymric and McKittrick fields with combined NMVOC emissions averaging over 1300 kg/h. This is very similar to an earlier study (May 2019). There are at least 5 large sources of the emissions within these fields that account for over half of the emissions.

Table S1 lists the emissions measurement results for the oil and gas fields included in the study.

Table S1 Results of the emission measurements from SOF and indirectly measured emissions (IME) from MeFTIR concentration. Days are the number of individual SOF measurement days, N is the number of emission or concentration measurements; Mean and SD are the mean and standard deviation of the SOF emission measurements, respectively; 1Q, Med, 3Q are the 25th, 50th (Median) and 75th percentile of the concentration ratio. The IME for methane is calculated from the SOF Alkane emissions and the median methane to alkane ratio.

Area (fields and associated facilities)	*Days*	*N_{SOF}*	*SOF Alkane Emissions Mean (kg/h)*	*SOF Alkane Emissions SD (kg/h)*	*N_{MEFTIR}*	*MEFTIR CH4 / Alkane 1Q*	*MEFTIR CH4 / Alkane Med*	*MEFTIR CH4 / Alkane 3Q*	*IME CH_4 (kg/h)*
Lost Hills	2	5	522	69	1	-	0.47	-	244
Lost Hills N of 46	3	14	210	85	6	0.24	0.29	0.35	61
Lost Hills S of 46	3	3	214	180	6	0.44	0.76	1.47	163
Cymric & McKittrick	3	10	1380	373	10	1.39	1.77	2.14	2430
Cymric & McKittrick Belridge	2	7	2970	873	N.M.	N.M.	N.M.	N.M.	N.M.

N.M.=Not measurable as an entity

Two of the oil producers in the Lost Hills field agreed to allow daytime access and provided support for emissions measurements and concentration measurements. Access to Operator A's operations were granted for a week and measurements were comprehensive including individual wellhead measurements, investigation of hot spots and thus determination of possible leaks. Several individual wellheads including pumpjack and other associated measurements using tracer gas were also done. Access to Operator B's operations in Lost Hills were more restricted but still allowed for complete geographical coverage of the fields where large leaks could be detected. However optimal leak search and detection and individual well measurements could not be made.

Many of the larger identified point sources for instantaneous emissions detected within the surveyed operators' fields were associated with temporary but continually ongoing activities: workover rigs, drilling rigs and vacuum truck emissions. To the extent that measurements were carried out in the fields only during daytime, this would bias emissions if they are not 24-hour activities. However, these activities represent only a fraction of total field emissions so any bias should be relatively small.

The other larger point sources were separators or gathering lines from areas of the field where we did not have operator access. Gathering sites, separators and de-sulfurization units in the fields had detectable emissions but measurements were not always possible due to access limitations. The most apparent of these, and largest point sources on the fields, were on operator sites to which we did not have access.

None of the individual wellheads measured in the tracer measurements had greater than 1 kg/h emissions of NMVOCs. With more than 5000 active wells within the Lost Hills fields, wells are still expected to be the major contributor to NMVOC and methane emissions. The largest methane leak detected in the Operator A field was from a buried pipeline belonging to a residential gas operator and not Operator A.

While activity related emissions were readily visible and identifiable due to close observations, permanent installations should still be the largest point emission sources on a long term basis. Emissions from Operator A's main facility varied diurnally and throughout the campaign and accounted for 10% of the Lost Hills NMVOC emissions. Operator B facilities' emissions were measured over a much more limited time and included interference from vacuum truck operations. No near-field measurements were made of the other operators' facilities to which we had no access.

BTEX concentrations from fenceline measurements were below detection limits except for a few specific sources. BTEX emissions measured at the water treatment of an O&G production facility were measurable at the fenceline and at a distance downwind comparable with a nearby community. Benzene concentrations in these plumes were less than 3 ppb except for immediately adjacent to the facility.

Community monitoring in Lost Hills and elsewhere

In addition to daily field monitoring, measurements with the mobile laboratory were carried out during 2 mornings/evenings in the Lost Hills community. Targeted measured species included benzene, BTEX, various alkanes, and methane. A few ephemeral residential BTEX sources were observed. Otherwise BTEX levels were not significantly different from the large-scale observations in the surroundings. The focus on the community also allowed the detection and plume tracing to the source of a commercial gas pipeline leak at 800 Aqueduct Road, Lost Hills. Although the leak had been noted earlier in the measurement campaign, it was then assumed that the plume originated from the oil field. It was first during the community monitoring time possible to trace back the plume and the source location became apparent.

Acronyms, Units and Definitions

Acronyms used in this report

BPD	Barrels per day
BTEX	Sum of Benzene, Toluene, Ethyl Benzene and Xylene
CARB	California Air Resources Board
DOAS	Differential Optical Absorption Spectroscopy
CalGEM	California Geologic Energy Management Division
EF	Emission factor
FTIR	Fourier Transform InfraRed
IME	Indirectly Measured Emission, combining direct emission with concentration ratios
LIDAR	Light Detection and Ranging
MWDOAS	Mobile White cell DOAS
MeFTIR	Mobile extractive FTIR
NMVOC	Non-methane volatile organic compound
SkyDOAS	Scattered Skylight DOAS
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
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 (short) ton = 907.2 kg
1 kton/year = 104 kg/h
1 klbs/year=0.052 kg/h

Definitions

Alkane or Alkanes are considered to be all non-methane alkane species.

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1 Objective and Introduction

This summary report consists of measurement results from a campaign in October 2019 carried out in the San Joaquin Valley, CA. 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. This report also includes investigations of other oil and gas production sources in Kern County in support of CARB SNAPS measurements.

2 Survey Setup & Complementary Measurements

Measurements with Solar Occultation Flux (SOF), sky differential optical absorption spectroscopy (SkyDOAS), mobile White cell DOAS (MWDOAS) and mobile extractive Fourier transform infrared (MeFTIR) methods were carried out over 16 measurements days in 2019 (September 30-October 10 and October 13-October 18) in the SJV, California (Figure 1). 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. The gas measurements were combined with wind data, primarily from a mobile wind LIDAR, to calculate fluxes and identify sources.

The objective was to quantify VOC emissions from the Lost Hills oil field and determine larger sources and identify leaks within the field. Areas for emissions quantification are limited by traversable roads and prevailing wind direction. The emissions area for the Lost Hills field is delineated in Figure 1. 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 The Jet Propulsion Laboratory (JPL) from 2016 – 2017 (URL https://methane.jpl.nasa.gov/, 13 Dec 2019). Of these measurements only 4 sources were positively identified by repeated measurements in the Lost Hills field (Figure 1) out of 1105 for the survey across the entire state.

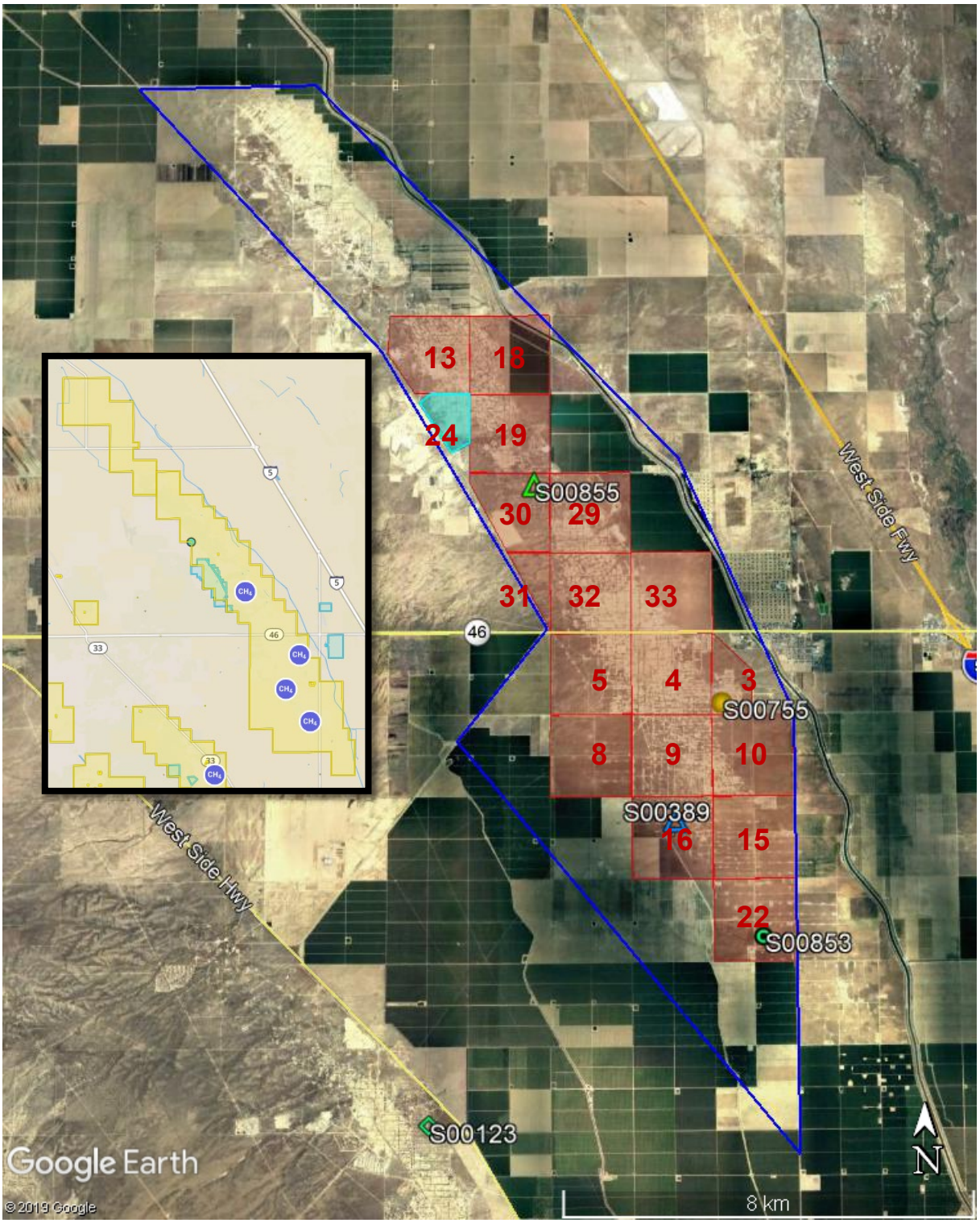


Figure 1. Lost Hills oil field and surroundings. Approximate boundary for total emissions area shown in blue. Areas within the fields that were surveyed completely are shown in red with lines indicating section borders and section numbers. Cyan section indicated area run by an operator outside the current study and was only surveyed from the fenceline. Point markers indicate methane sources within the study area measured by The Jet Propulsion Laboratory (JPL, URL https://methane.jpl.nasa.gov/, 13 Dec 2019). Inset: JPL methane sources and actual field boundary from https://methane.jpl.nasa.gov/

All measurements have been subjected to quality control and assurance. This includes following the standard protocols for SOF, MEFTIR, and MWDOAS, ocular examination of instruments

and data, daily instrument calibration and statistical measures of data quality. The number of accepted measurements varied substantially from day to day and from source to source depending on weather conditions, local measurement conditions (accessibility, state of the roads, obstacles etc.) and time sharing between areas and instruments. Statistical estimates of the flux emissions (kg/h) from the various sources were computed for each measurement day and for the entire survey, including the statistical error.

2.1 Sites – Lost Hills and other Oil and Gas Fields

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 2 to Figure 4. In 2019 there were over 5000 new or active wells within the Lost Hills fields (CalGEM 2019). Belridge was not measured in its entirety independently during the campaign but was measured in part and in combination with Cymric-McKittrick.

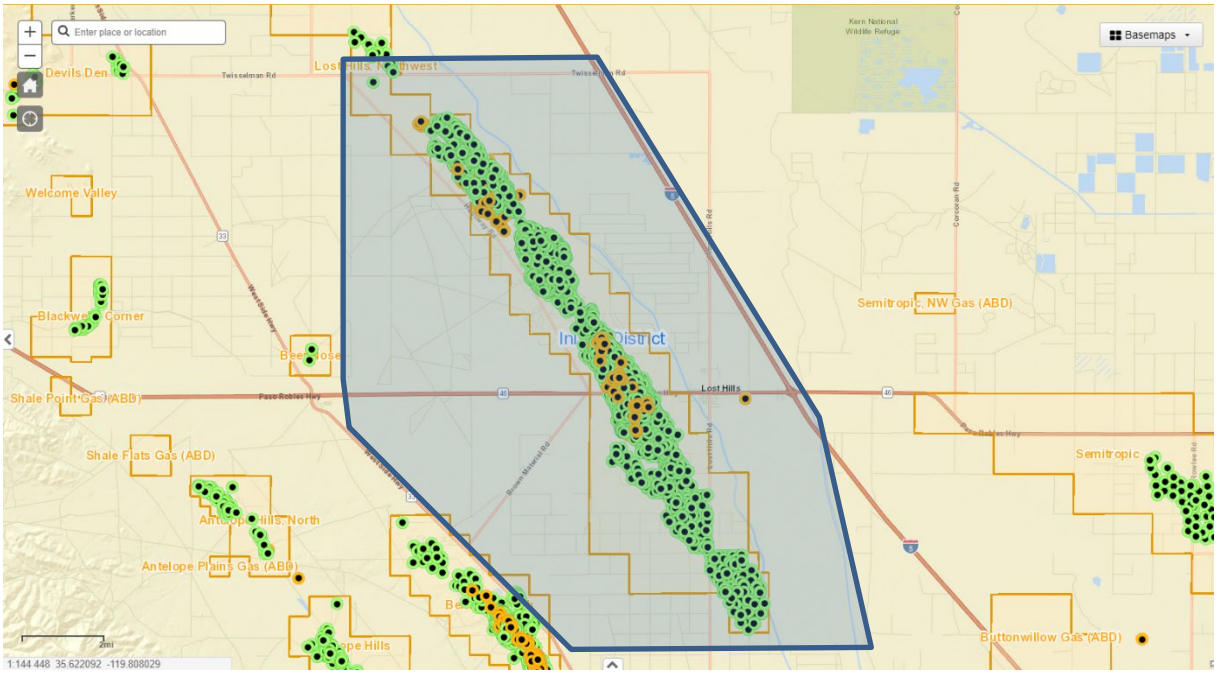


Figure 2. SOF measurement box in blue defining the measurement area for the Lost Hills region. The figure also shows new (orange) and active wells (green) (CalGEM, 2019).

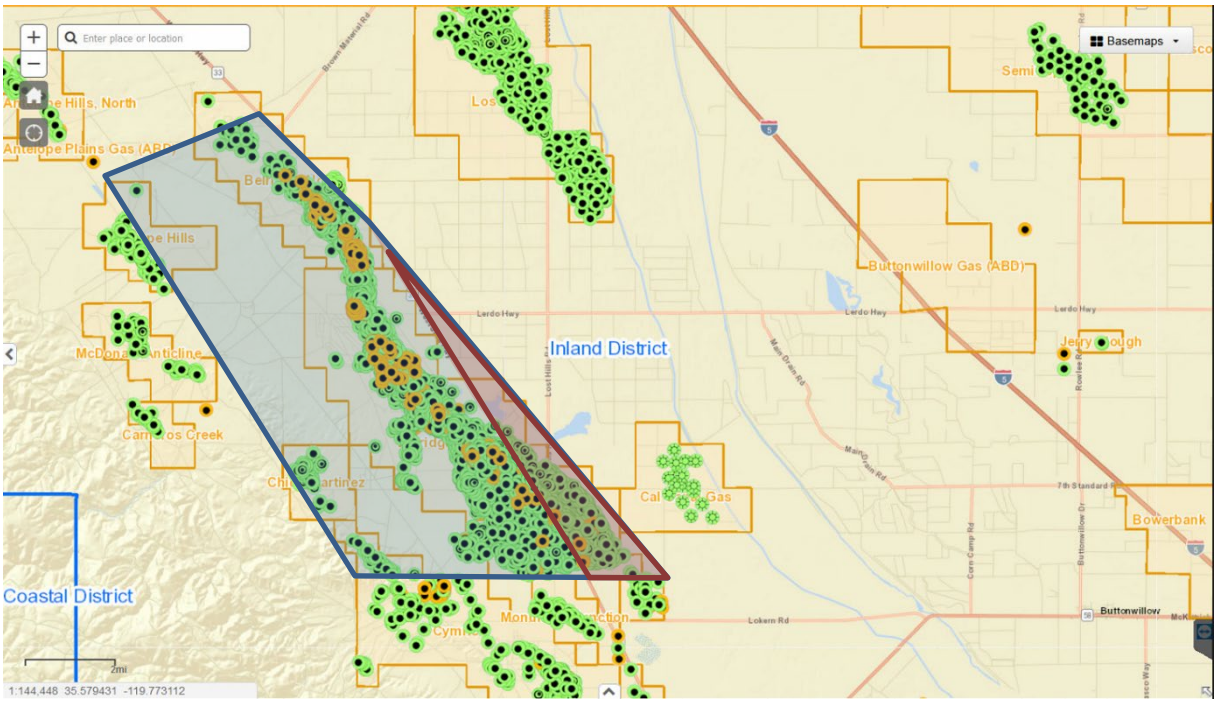


Figure 3. SOF measurement box in blue defining the measurement area for the Belridge North and South area. The figure also shows new (orange) and active wells (green) (CalGEM, 2019). Note that wells in Belridge South east of Highway 33 (highlight in red) have been included occasionally.

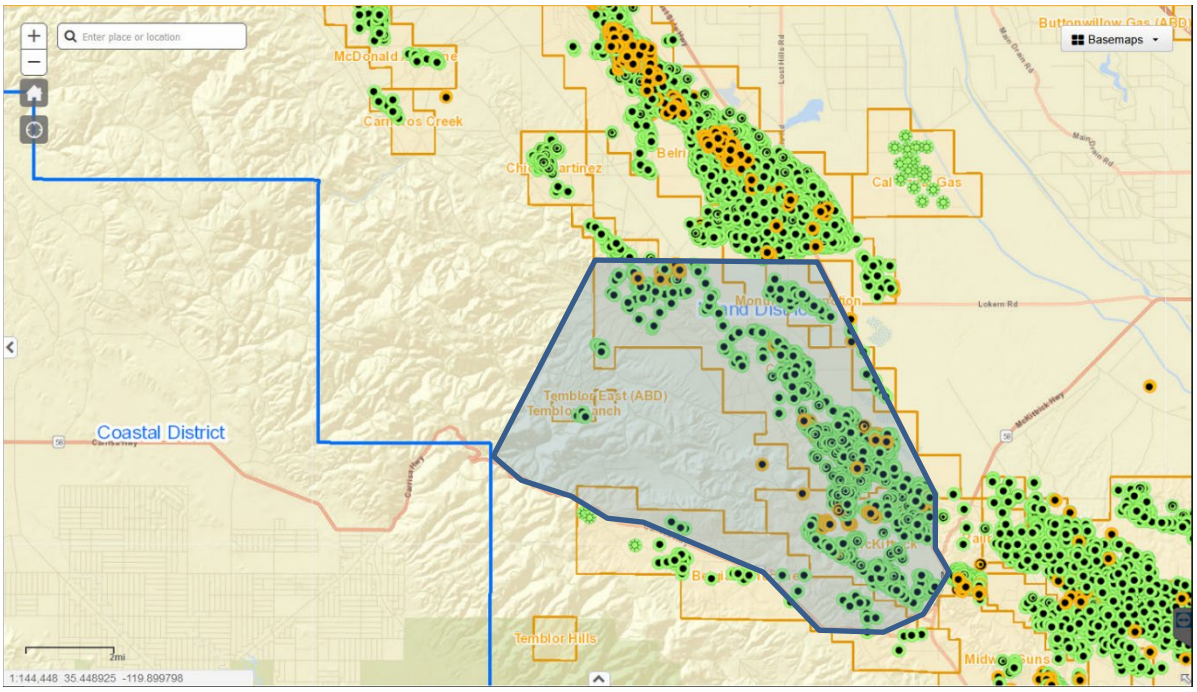


Figure 4. SOF measurement box in blue defining the measurement area for the fields Cymric-McKittrick is highlighted. The figure also shows new (orange) and active wells (green) (CalGEM, 2019)

Table 1 shows the days that measurements were carried out during the campaign.

Table 1. Measurements carried out during the campaign.

Date	*Lidar Location*	*Emissions and Concentration Measurements*	*Community Monitoring*
30-Sep-2019	Wonderful Park	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

2.2 Plume height

The height of the plume influences which wind speed and direction to apply in the flux calculation. In this study 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, 0 – 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, 0 – 100m winds were used. Because the 100 m and 300m winds are very similar this had little impact on the measured emissions. A more complete analysis of winds will be made in a following report.

An example of applied plume height estimation is shown in Figure 5. 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 2. 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.

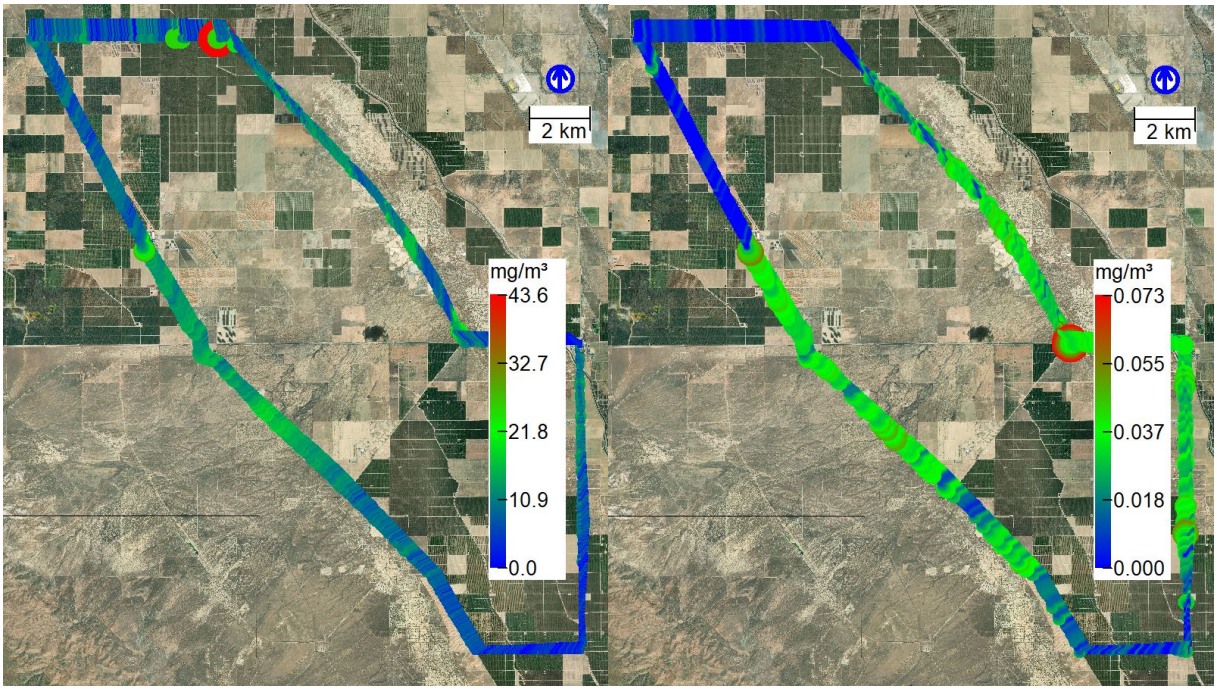


Figure 5 Plume height measurement example showing SOF alkane slant column (left) and MEFTIR alkane concentration (right). Two measurements are shown, one in the near field on Holloway and Highway 46 and the other in the far-field along Highway 33. The first order plume height estimates are 130 and 210 m, respectively.

Table 2 First order plume height from rise time (distance, d, divided by wind speed, U) estimation and measurements (SOF column/MEFTIR concentration).

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 46	1940	747	187	150
Lost Hills S of 46	3779	1774	444	230
Cymric & McKittrick	3011	1187	297	540
Belridge	5073	2169	542	520

3 Results

Quantitative results for the oil field emission measurements in the San Joaquin Valley are presented in section 3.1 and emission measurements of point sources and other distinct sources are presented in section 3.2. Concentration measurements in communities and along oil field 'fencelines' (perimeters) as well as are detailed in Section 3.3 Community monitoring. Section 3.1 includes the results of a small number of measurement days in the San Joaquin Valley from October 2018.

SOF measured direct emissions of alkanes, and SkyDOAS measured direct emissions of SO_2, NO_2 and H_2CO. MeFTIR and MWDOAS were used to measure mass concentration ratios of methane to alkanes and BTEX to alkanes at the site fence-lines. These plume mass ratios were combined with the direct alkane flux from SOF measurements to obtain indirect emission estimates of methane and BTEX, respectively.

3.1 Emission measurements and gas fluxes – Oil and Gas Fields

Table 3 summarizes the results of the measurements of alkane emissions and methane/alkane ratios for methane emissions (IME) for the major oil and gas fields in the survey. Ratio measurements can be influenced by nearby point sources with different compositions than the field, however, care has been taken to include as large an area as possible, to minimize the influence of individual sources. Further details are given under the areas' respective section and in the results for identification and measurement of point sources.

Alkane emissions from Lost Hills averaged 522 kg/h with the emissions about equally distributed between North and South fields (Table 3). Because the measurements were made at different times, the sum of the area emissions does not equal the total for Lost Hills. There is more uncertainty in the emissions from the South field. The nearby fields of Cymric & McKittrick had much greater alkane emissions, averaging 1380 kg/h. The field of Belridge could not be measured separately in its entirety due to wind direction. On the occasions when Belridge was measured in conjunction with Cymric & McKittrick, emissions from Cymric & McKittrick were judged to be significantly higher as well, so the difference between the two measures (2968 to 1380 kg/h) does not solely represent the contribution of Belridge but also the variability of Cymric & McKittrick.

Ratios of methane to alkanes varied between the fields with Cymric & McKittrick having much higher percentages. For the Lost Hills field as a whole, the only qualified measurement gave an integrated plume concentration ratio of 0.47 CH_4/Alkane, which combined with the alkane emissions, produces methane emissions of 244 kg/h. More measurements were available for the fields individually with the South field showing higher methane ratios, 0.76 to 0.29 for the North field.

Table 3 Results of the emission measurements from SOF and indirectly measured emissions (IME) from MeFTIR concentration. Days are the number of individual SOF measurement days, N is the number of emission or concentration measurements; Mean and SD are the mean and standard deviation of the SOF emission measurements, respectively; 1Q, Med, 3Q are the 25th, 50th (Median) and 75th percentile of the concentration ratio. The IME for methane is calculated from the SOF Alkane emissions and the median methane to alkane ratio

Area (fields and associated facilities)	Days	N_{SOF}	Alkane kg/h	SD_{alkane} kg/h	N_{conc}	CH_4 / Alkane 1Q	CH_4 / Alkane Med	CH_4 / Alkane 3Q	CH_4 kg/h
Lost Hills	2	5	522	69	1		0.47		244
Lost Hills N of 46	3	14	210	85	6	0.24	0.29	0.35	61
Lost Hills S of 46	3	3	214	180	6	0.44	0.76	1.47	163
Cymric & McKittrick	3	10	1380	373	10	1.39	1.77	2.14	2430
Cymric & McKittrick Belridge	2	7	2970	873	N.M.	N.M.	N.M.	N.M.	N.M.

N.M.=Not measurable as an entity

SkyDOAS measurements were not a primary focus of the campaign since few combustion sources exist in the fields and distances to the field perimeters and private roads preclude closer access to facilities. There was no evidence of "super emitters" and the large-scale measurements of NO_2, SO_2 and H_2CO were not consistently differentiable from background and/or other interfering sources and as such no results for the fields are reported. BTEX measurements with the exception of point sources are below detectability for fenceline measurements. The point sources measured indicate that BTEX emissions are less than 1% of the total emissions.

3.1.1 Lost Hills

Large scale measurements of the Lost Hills field were made on 2 days. Figure 6 shows one such alkane emission measurement with easterly winds. Alkane emissions averaged 520 kg/h. Ratio measurements were made on two days. Results for the emission measurements are given in Table 4. Due to distance and meteorology, only one of the methane/alkane concentration ratio measurements for Lost Hills in its entirety had sufficiently high concentrations of alkanes to be used for the ratio determination. This had a methane to alkane mass ratio of 0.46 giving total methane emissions of 244 kg/h.

Results for emissions measurements of the Lost Hills areas north and south of Highway 46 are shown in Table 5 and Table 7, respectively. Substantially more measurements of the northern portion were made due to the prevailing north-easterly winds on many days. Methane/alkane concentration ratios are shown in Table 6 and Table 8 for the north and south sections, respectively.

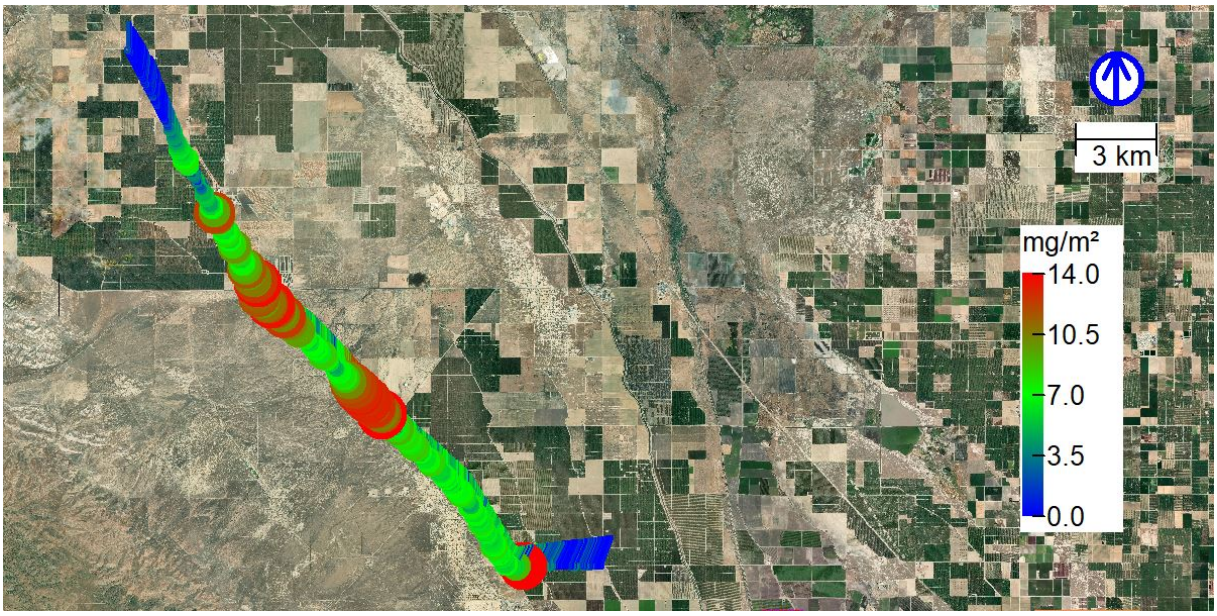


Figure 6. Emission measurement of Lost Hills Area with northeasterly winds. Color scale and point size show the SOF alkane column (mg /m^2) and the lines point in the instantaneous wind direction.

Table 4 Alkane emission measurements of the Lost Hills oil field.

Day [yymmdd] or Summary Statistic	Time Span [hhmmss-hhmmss]	N	Emission Average [kg/h]	Emission SD [kg/h]	Wind Speed Min-Max [m/s]	Wind Direction Span [deg]
191001	151839-155657	1	450	N/A	2.8-2.8	350-350
191015	121110-165351	4	541	63.5	1.6-2.5	2-360
Total number of measurements		**5**				
Median			**503.8**			
IQR			**479.0 - 558.6**			
Mean			**522.6**			
SD			**68.5**			

Table 5 Alkane emission measurements of the Lost Hills N (North of Highway 46).

Day [yymmdd] or Summary Statistic	Time Span [hhmmss-hhmmss]	N	Emission Average [kg/h]	Emission SD [kg/h]	Wind Speed Min-Max [m/s]	Wind Direction Span [deg]
190930	123248-154234	5	174	56.2	2.2-3.2	16-339
191001	095714-164459	6	245	106.7	2.1-3.4	2-360
191005	132303-161818	3	200	66.9	2.3-2.8	334-357
Total number of measurements		**14**				
Median			**204.1**			
IQR			**134.6 - 245.5**			
Mean			**210.2**			
SD			**84.5**			

Table 6 Methane to alkanes concentration ratios for Lost Hills N (North of Highway 46).

Day [yymmdd] or Summary Statistic	Time Span [hhmmss-hhmmss]	N	Mass Ratio Average [%]	Mass Ratio SD [%]	Wind Speed Min-Max [m/s]	Wind Direction Span [deg]
190930	150134-151945	1	27.8	N/A	2.4-2.4	343-343
191001	140851-163039	2	34.8	6.3	1.8-4.0	12-323
191005	144715-164050	2	29.6	10.2	1.3-1.9	313-345
191007	144737-145922	1	16.2	N/A	2.3-2.3	328-328
Total number of measurements		**6**				
Median			**29.1**			
IQR			**23.8 - 35.2**			

Table 7 Alkane emission measurements of the Lost Hills S (South of Highway 46).

Day [yymmdd] or Summary Statistic	Time Span [hhmmss-hhmmss]	N	Emission Average [kg/h]	Emission SD [kg/h]	Wind Speed Min-Max [m/s]	Wind Direction 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 number of measurements		**3**				
Median			**177.0**			
IQR			**116.0 - 292.9**			
Mean			**213.6**			
SD			**179.7**			

Table 8 Methane to alkanes concentration ratios for Lost Hills S (South of Highway 46).

Day [yymmdd] or Summary Statistic	Time Span [hhmmss-hhmmss]	N	Mass Ratio Average [%]	Mass Ratio SD [%]	Wind Speed Min-Max [m/s]	Wind Direction Span [deg]
191001	115953-121050	1	74.4	N/A	3.7-3.7	290-290
191005	172126-173705	2	19.9	19.0	2.8-3.0	240-275
191007	221144-222049	1	78.1	N/A	3.9-3.9	279-279
191015	203938-210827	2	206	50.7	0.7-0.8	227-238
Total number of measurements		**6**				
Median			**76.2**			
IQR			**43.6 - 147.2**			

3.1.1.1 In Field Measurements

Seven days of in field measurements were made within the boundaries of the Lost Hills field. A very large number of measurements were made of both individual wells and oil field sections. No large well head leaks were detected during the survey. The largest leak detected was 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. 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. 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. 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 7 shows an example of the type of digital data from the survey and its usefulness in identifying hotspots.

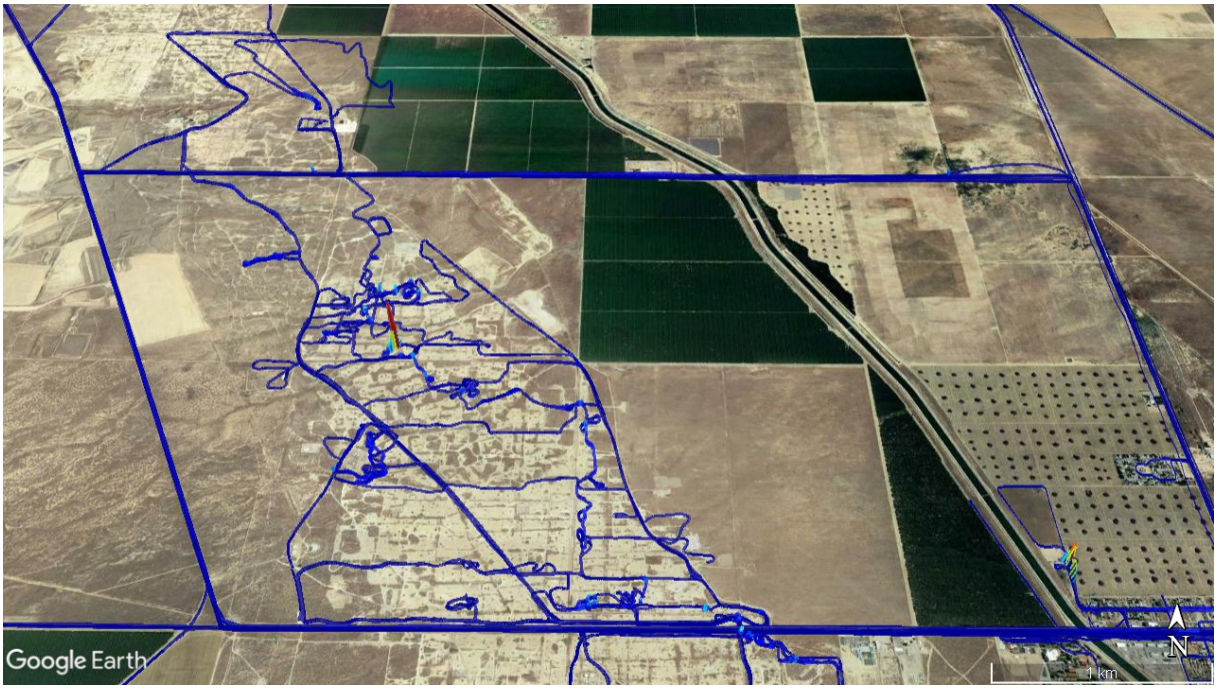


Figure 7 Concentration mapping of alkanes in Lost Hills N. Color and apparent height of curve (m) is proportional to concentration in mg/m^3 x 100. Red > 2 mg/m^3.

Table 9 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.

Table 9 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 with an asterisk (*) in the first column (also underlined) had sufficient measurements to meet the criteria for 30% certainty in emissions, while all others did not. An underscore followed by a direction e.g. West, represents a half (West) or a quarter (NW) section.

Lost Hills Field Half	*Sections*	*Days*	N_{SOF}	*Alkane kg/h*	SD_{alkane} *kg/h*
North	S13+18+19+24	2	2	126	38
North	S19	2	2	21	4
North*	S24	3	6	39	21
North	S32	3	3	30	5
South	S3 - S10	1	2	135	86
South	S4_West	1	2	13	2
South	S4_North	2	3	10	8
South*	S5	2	5	12	7

Table 10 and Table 11 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. For the entirety of the well unit measurements, alkane emissions averaged 0.66 kg/h.

Table 10 Summary of emissions measurements for well units (wellhead and aboveground equipment) in the Lost Hills area made with SOF. Entries with an asterisk (*) in the Unit column (also underlined) had sufficient measurements to meet the criteria for 30% certainty in emissions, while all others did not.

Units (sequentially numbered for anonymization)	*Days*	*N_{SOF}*	*Alkane Emissions 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 11 Summary of emissions measurements for activity related and other equipment emissions in the Lost Hills area made with SOF. All of these locations and activities 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. Table 12 summarizes these measurements. Median emissions from these for alkane were 0.07 kg/h and for methane 0.06 kg/h.

Table 12 Summary of emissions measurements for wells in the Lost Hills area made with MEFTIR and tracer gas.

Well	*Day [yymmdd]*	*Timespan [hhmmss - hhmmss]*	*N*	*Alkane Emissions ±SD (kg/h)*	*Methane Emissions ±SD (kg/h)*	*Wind Speed (m/s)*	*Wind Direction (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

3.1.1.2 Treatment/Processing Facilities

There are at least 5 facilities within the Lost Hills fields of which measurements were made. The largest facility was also the largest emissions source of NMVOC emissions within the Operator A area. The water treatment area for this facility contributes a large but highly variable portion of these emissions. Because of the difference in plume heights between the plant and the water treatment, total emissions are a little less certain. There were very little methane emissions from the water treatment, and even the plant emissions were largely alkanes, with methane emissions only 11% as large as the alkane emissions. To the SW corner of the plant perimeter fenceline there was a parking/handling area for vacuum trucks. Both alkane and methane emissions were measured from this location (SW quadrant of facility) but apparently different sources. As with vacuum trucks in the field, emissions from this area were variable

and suspect highly activity related. The total facility ratio measurements show the influence of this additional methane source. Methane plumes from this facility were noted during two flyovers in September 2017 (JPL, URL https://methane.jpl.nasa.gov/, 13 Dec 2019).).

The other smaller facilities also had measurable emissions, however, many fewer measurements due to restricted access.

Table 13 Summary of alkane emission measurements for facilities in the Lost Hills area made with SOF and MEFTIR. All areas except Facility 1 and its subsections had fewer than the minimum number of measurements required for 30% certainty in emissions.

Area	*Days*	N_{SOF}	*Alkane kg/h*	SD_{alkane} *kg/h*	N_{conc}	CH_4 */ Alkane (%)*	CH_4 *kg/h*
Facility 1 Total	8	27	54	36	13	33*	18
Facility 1 Plant	2	5	27	10	9	11	3
Facility 1 Water Treatment	4	11	32	26	11	1	0
S32_Treatment+Storage	1	2	1	1			
Facility 2	1	2	3	2	2	59	2
Facility 3	1	3	5	2	2	153	7
S19_Unknown	1	3	12	13	11	414	48
S19_Treatment	2	3	4	2	4	194	10

Table 14 Alkane emission measurements of Facility 1.

Day [yymmdd] or Summary Statistic	Time Span [hhmmss-hhmmss]	N	Emission Average [kg/h]	Emission SD [kg/h]	Wind Speed Min-Max [m/s]	Wind Direction Span [deg]
191002	112817-162519	6	64.9	61.1	1.9-2.8	5-356
191003	125807-161938	4	41.6	30.7	2.4-3.0	9-352
191004	103525-112450	3	59.9	13.8	3.0-3.3	341-341
191005	122512-164644	2	69.5	29.9	2.3-2.8	321-356
191007	112458-165708	6	40.4	8.9	1.3-2.8	4-343
191008	123342-132709	3	34.3	9.0	1.4-1.6	104-250
191009	150725-153722	2	54.5	0.2	6.3-6.5	352-353
191010	144046-145016	1	139	N/A	2.3-2.3	360-360
Total number of measurements		**27**				
Median			**48.4**			
IQR			**32.1 - 61.6**			
Mean			**54.4**			
SD			**36.6**			

Table 15 Alkane emission measurements of the Facility 1, plant only.

Day [yymmdd] or Summary Statistic	Time Span [hhmmss-hhmmss]	N	Emission Average [kg/h]	Emission SD [kg/h]	Wind Speed Min-Max [m/s]	Wind Direction Span [deg]
191002	122336-164152	4	26.7	12.0	2.4-2.6	1-340
191007	162033-162713	1	26.8	N/A	1.9-1.9	334-334
Total number of measurements		**5**				
Median			**26.8**			
IQR			**25.2 - 35.6**			
Mean			**26.7**			
SD			**10.4**			

Table 16 Alkane emission measurements of Facility 1, water treatment.

Day [yymmdd] or Summary Statistic	Time Span [hhmmss-hhmmss]	N	Emission Average [kg/h]	Emission SD [kg/h]	Wind Speed Min-Max [m/s]	Wind Direction Span [deg]
191002	114544-121206	6	20.7	8.8	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	22.8	1.0-1.7	85-109
Total number of measurements		**11**				
Median			**25.6**			
IQR			**13.4 - 35.2**			
Mean			**31.7**			
SD			**26.1**			

The water treatment area was the only consistently measurable source of BTEX emissions, Figure 8. Here it can be seen how BTEX concentrations diminish with distance, i.e. toward the north-south road crossing the channel in the image, while the alkane plume is still evident at this distance. This likely indicates much larger and more alkane emissions, which is logical. Benzene concentrations (Figure 9) higher than 5 ppb adjacent to one basin were measured on multiple occasions and likewise diminished with distance to the road.

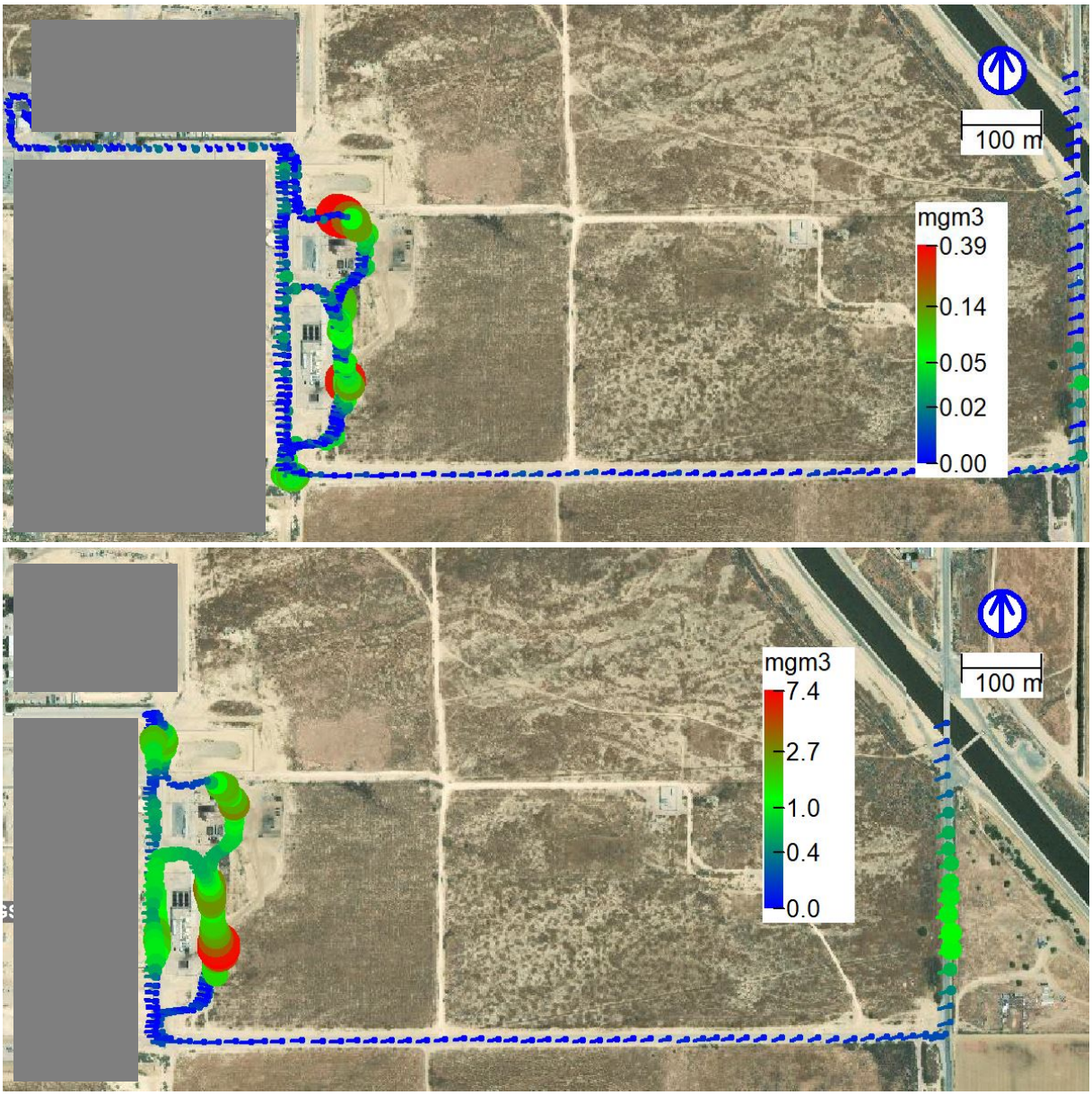


Figure 8. Concentration measurements showing BTEX and alkanes downwind of a water treatment area. Color scale and point size show BTEX (upper figure) and alkane (lower figure) concentrations (mg/m^3) and the lines point in the instantaneous wind direction. Color scale is logarithmic.

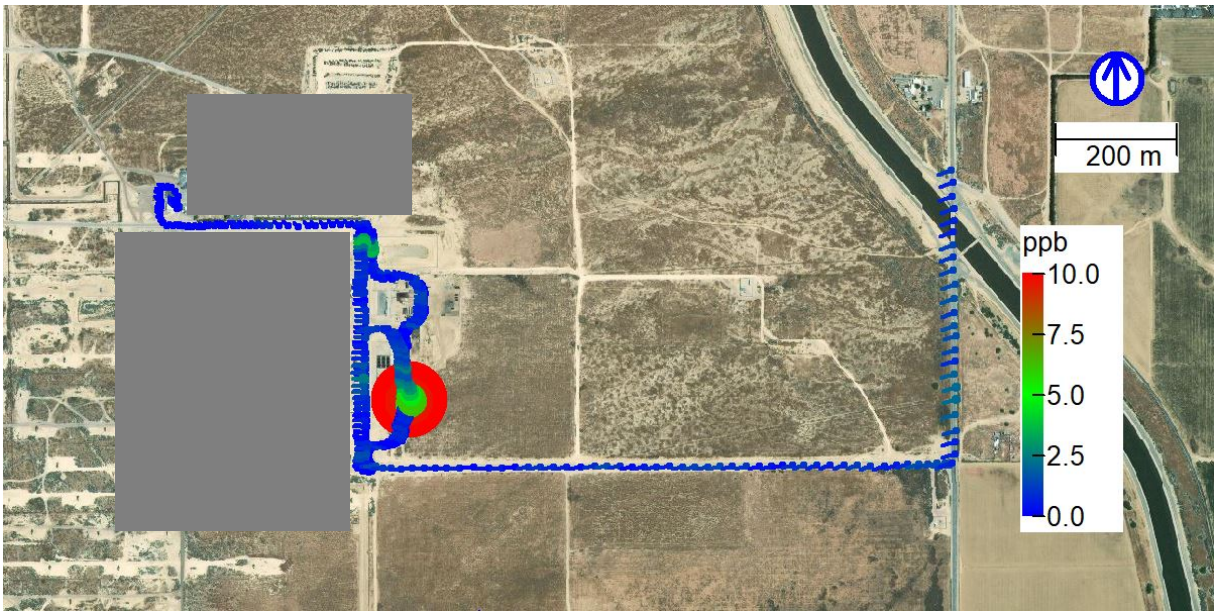


Figure 9. Concentration measurements of benzene. Color scale and point size show benzene concentrations (ppb) and the lines point in the instantaneous wind direction.

3.1.2 Cymric and McKittrick

The area defined here as Cymric and McKittrick includes the named fields and facilities within their boundaries. Measurements were typically made as a partial box of Cymric and McKittrick where the western boundary is formed by the western foothills. An example measurement is shown in Figure 10. A concentration ratio measurement is shown in Figure 11. Several point and area sources are evident in the figure: in the middle of the Cymric field there are several large facilities and clear point source emissions of methane and alkane VOCs. Emissions from these point sources were also quantified with SOF during this survey.

Emissions of alkanes for the Cymric and McKittrick fields were consistently greater than 1000 kg/h. Results are presented in Table 17. Alkane emissions averaged 1380 kg/h over 3 days and 10 measurements. Ratios of methane to alkanes were consistently greater than one, with a median value of 1.8 and hence total methane emissions of 2430 kg/h (Table 3).

Emissions from the major sources in the Cymric and McKittrick fields are summarized in Table 18. None of these sources could be measured repeatedly on different days during the campaign so the results should not be considered indicative of continuous emissions but provide a snapshot of instantaneous emissions.

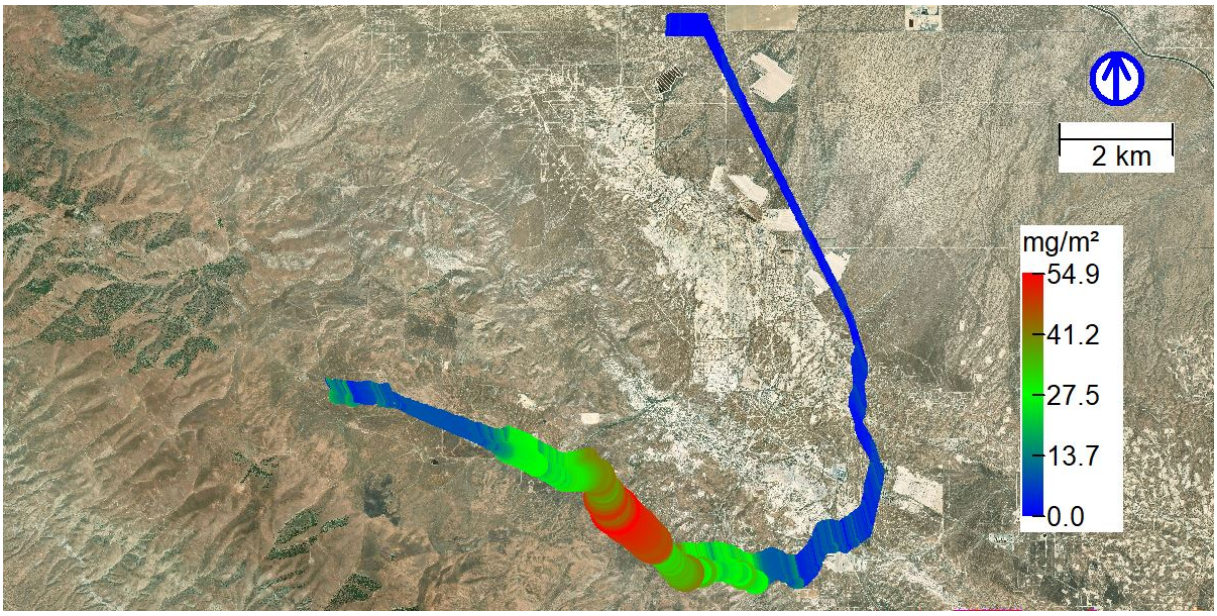


Figure 10. Alkane emission measurement of Cymric and McKittrick Areas with northerly winds. Color scale and point size show the SOF alkane column (mg /m^2) and the line points in the instantaneous wind direction.

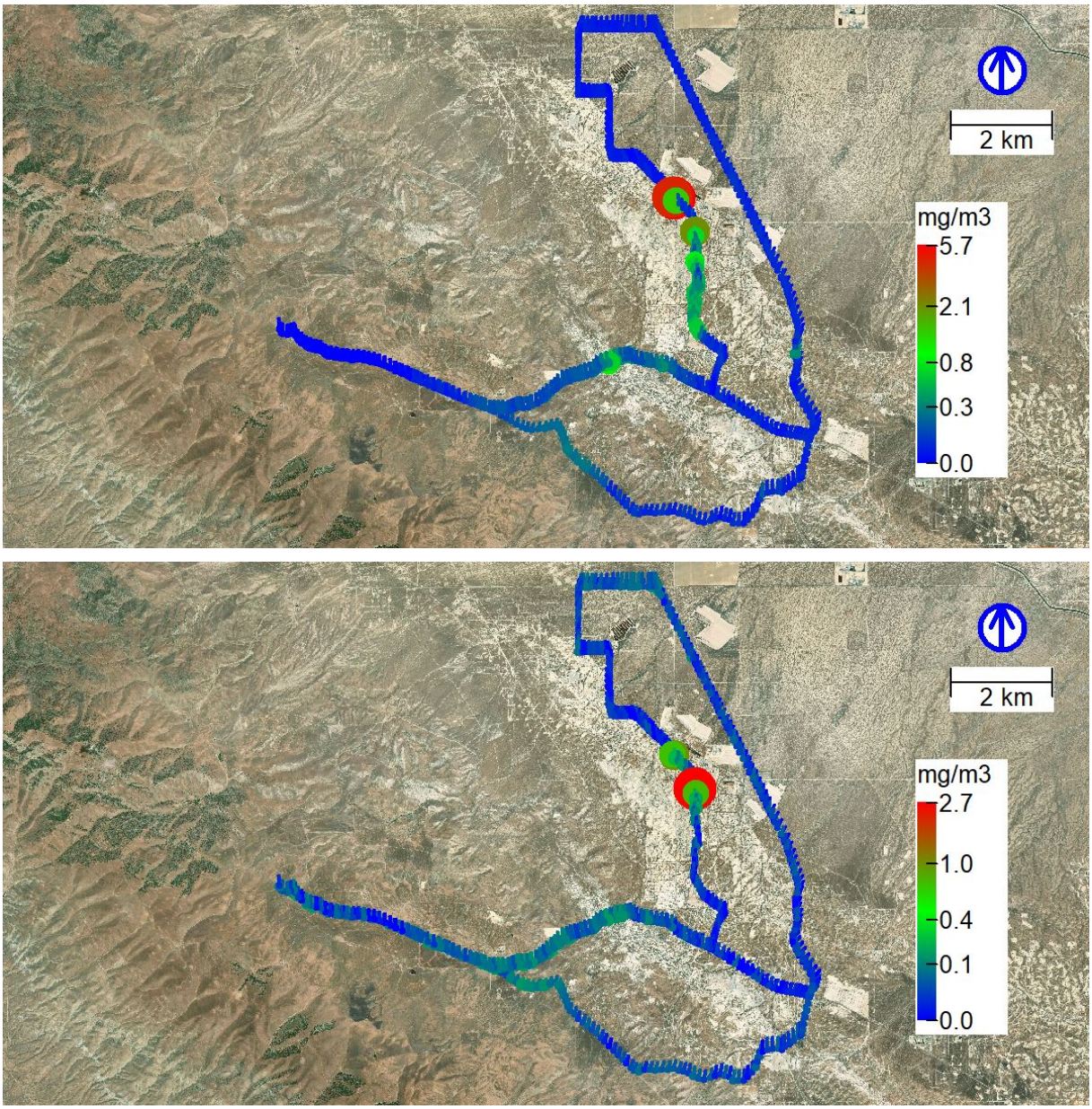


Figure 11. Ratio measurement in and around Cymric and McKittrick fields with northeasterly winds. Color scale and point size show methane (upper figure) and alkane (lower figure) concentrations (mg/m^3) and the lines point in the instantaneous wind direction. Color scale is logarithmic. The typical integrated mass ratio between CH_4 and alkanes was 1.3:1.

Table 17 Alkane emission measurements of Cymric and McKittrick Fields.

Day [yymmdd] or Summary Statistic	Time Span [hhmmss-hhmmss]	N	Emission Average [kg/h]	Emission SD [kg/h]	Wind Speed Min-Max [m/s]	Wind Direction Span [deg]
191006	115747-162159	6	1360	437.9	1.9-2.6	10-359
191013	151955-155628	1	1834	N/A	2.5-2.5	337-337
191018	143502-153414	3	1258	137.6	3.8-4.2	315-321
Total number of measurements		**10**				
Median			**1340.4**			
IQR			**1173.9 - 1478.2**			
Mean			**1376.8**			
SD			**372.6**			

Table 18 Alkane and Methane emissions and Methane/Alkane ratios of the Cymric and McKittrick major sources from SOF and MEFTIR measurements. *Could not be confirmed as the same source.

Area	*Days*	N_{SOF}	*Alkane kg/h*	SD_{alkane} *kg/h*	N_{conc}	CH_4 */ Alkane 1Q (%)*	CH_4 */ Alkane Med (%)*	CH_4 */ Alkane 3Q (%)*	CH_4 *kg/h*
Cymric Facility 1	1	2	289	150	6	426	473	477	1369
Cymric Facility 2	1	2	99	8	8	93	107	158	106
MidField Facility/Gathering	1	1	408	-	3	904	1218	1656	*
Gathering_Hwy58 W	1	2	6	7	2	460	474	488	31

3.1.3 Belridge

Partial emissions measurements of Belridge were made during the current study as these accounted for the inflow to Cymric-McKittrick emission measurements. One such measurement is shown in Figure 12. Alkane emission measurements of this portion of Belridge were made over several days with consistent results over 400 kg/h. No complete measurements of Belridge were possible due to prevailing easterly winds.

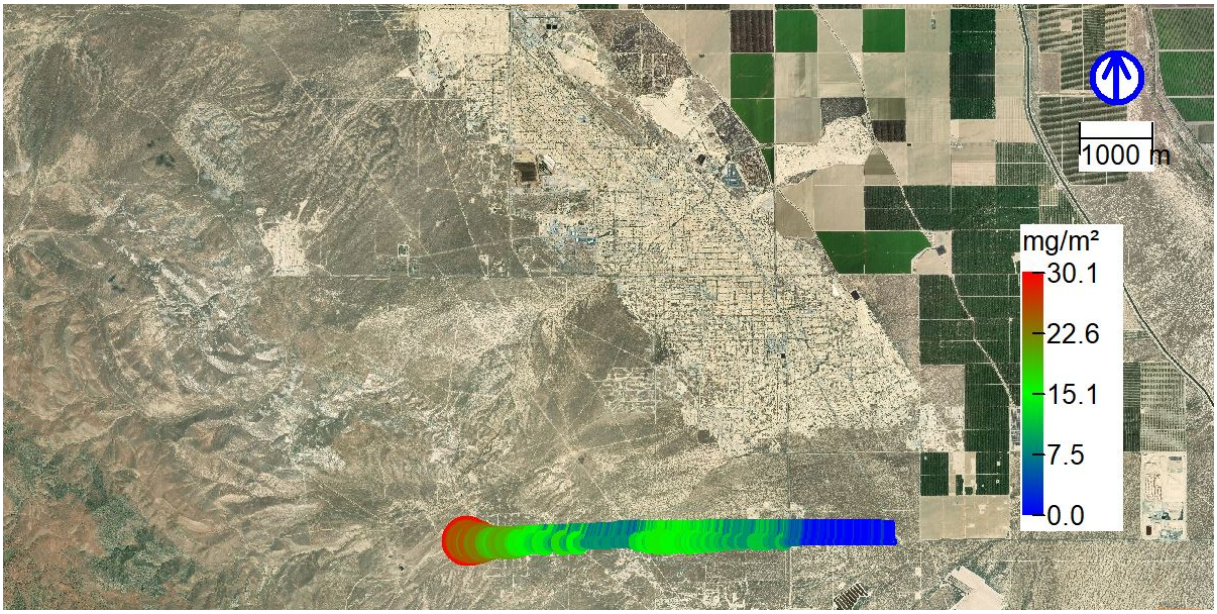


Figure 12. Partial alkane emission measurement of Belridge with northeasterly winds. Color scale and point size show the SOF alkane column (mg /m^2) and the line points in the instantaneous wind direction.

Table 19 Partial emission measurements of Belridge Area.

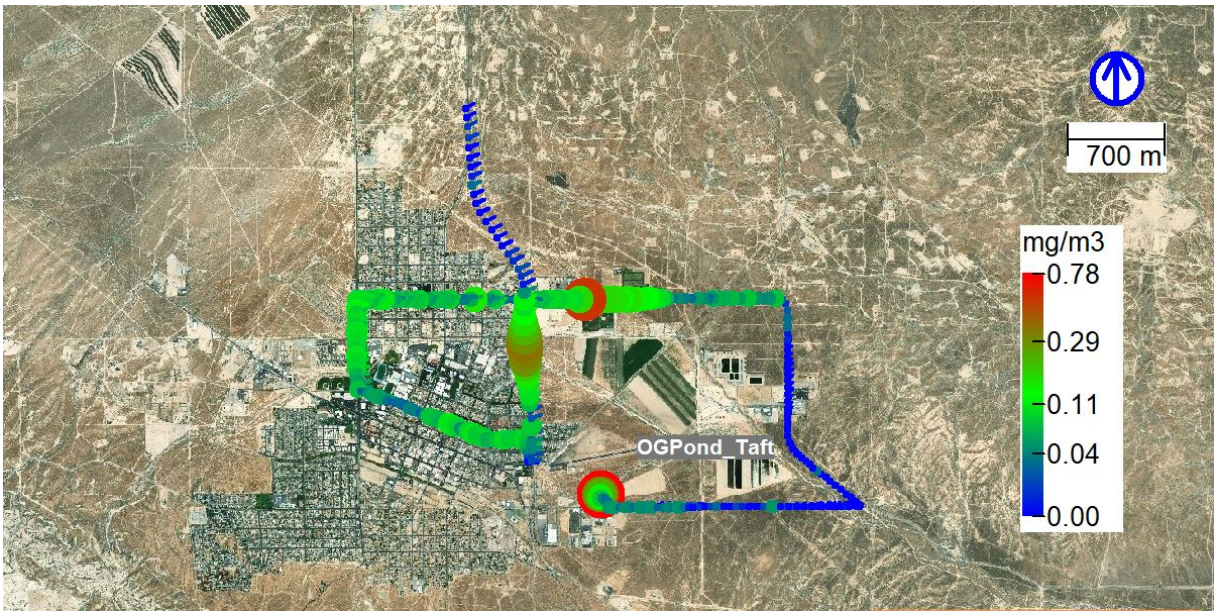
Day [yymmdd] or Summary Statistic	Time Span [hhmmss-hhmmss]	N	Emission Average [kg/h]	Emission SD [kg/h]	Wind Speed Min-Max [m/s]	Wind Direction Span [deg]
191006	111238-132116	4	379	115.7	1.8-2.5	10-355
191013	154315-162512	2	380	63.3	2.3-2.7	333-338
Total measurements		**6**				
Median			**369.5**			
IQR			**311.4 - 419.3**			
Mean			**379.1**			
SD			**94.0**			

3.1.4 Oil and Gas Produced Water 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, isolated emissions measurements with SOF were difficult. 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 other sources than the ponds if they are not evidence of biological activity in the sediment.

Table 20 Alkane and methane emission measurements of O&G produced water ponds. High methane percentages for Cymric and Taft may indicate interfering sources. Cymric 2 had fewer than the minimum number of measurements required for 30% certainty in emissions.

O&G Ponds	Days	N_{SOF}	Alkane kg/h	SD_{alkane} kg/h	N_{conc}	CH_4 / Alkane (%)	CH_4 kg/h
Cymric 1	2	4	10	7	-	-	-
Cymric 2	2	3	7	8	1	60	4
Taft	1	4	17	4	7	241	40



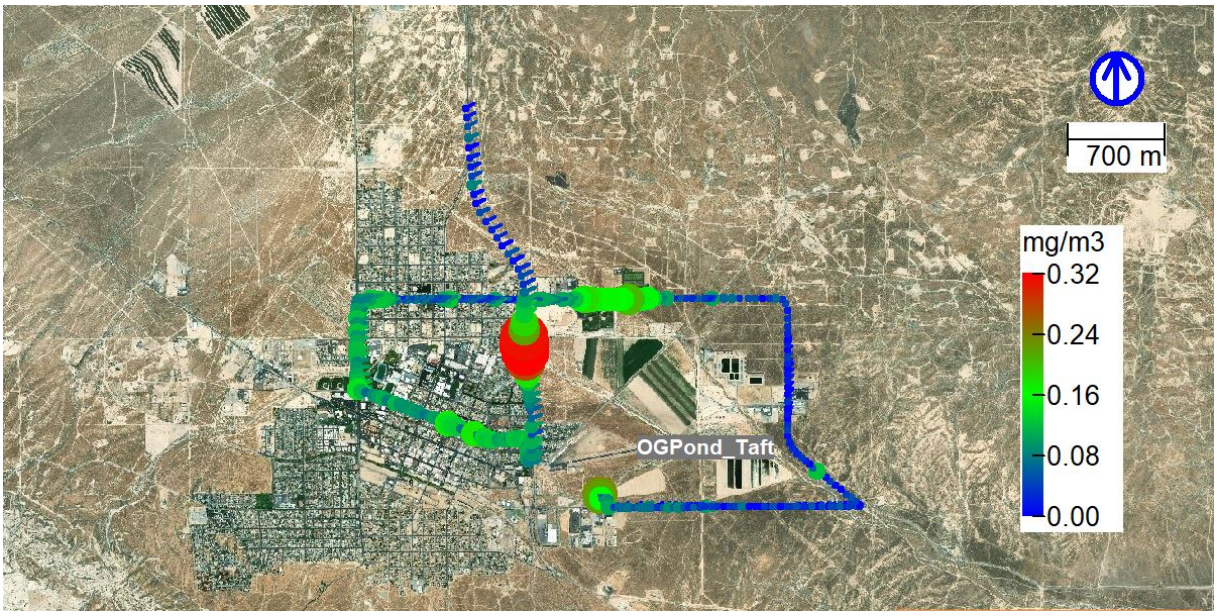


Figure 13. Ratio measurement in and around Taft ponds with northeasterly winds. Color scale and point size show methane (upper figure) and alkane (lower figure) concentrations (mg/m^3) and the lines point in the instantaneous wind direction. Color scale is logarithmic in the upper figure.

3.2 Community monitoring

Community monitoring was performed with simultaneous VOC and aromatic VOC (BTEX) concentration measurements at least one day each in Lost Hills, in and around McKittrick, Derby Acres and Taft (Table 21). Early evening or early morning are the times most favorable for measuring higher concentrations with lower wind speeds and less vertical mixing. In general concentrations were indistinguishable from background.

Table 21. Summary of all days with community monitoring.

Area	Date
Lost Hills	7-Oct (evening), 9-Oct (early morning), 15-Oct (evening)
McKittrick	13-Oct (evening), 17-Oct (evening)
Derby Acres	13-Oct (evening), 17-Oct (evening)
Taft	18-Oct (afternoon)

3.2.1 Lost Hills

Lost Hills is situated just at the eastern edge of the Lost Hills field essentially between Lost Hills 1 and 2 (north and south of Highway 46). Westerly winds should bring oil field plumes in over the community. One oil and gas processing plant is located to the southwest at a distance of approximately 1 km from the edge of the residential area. Measurements were made on two evenings with westerly winds and one morning with north-westerly winds so 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 14).

On 15 October, a residential BTEX plume was observed in the northern residential park and a VOC plume was noted originating from a small fire (Figure 15). Ground concentrations of

Benzene are shown (in ppb) for all 3 measurement occasions in Lost Hills (Figure 16). On the 7th the residential source is obvious, and on the 9th there is apparently a broader plume coming from the west (middle, Figure 16).

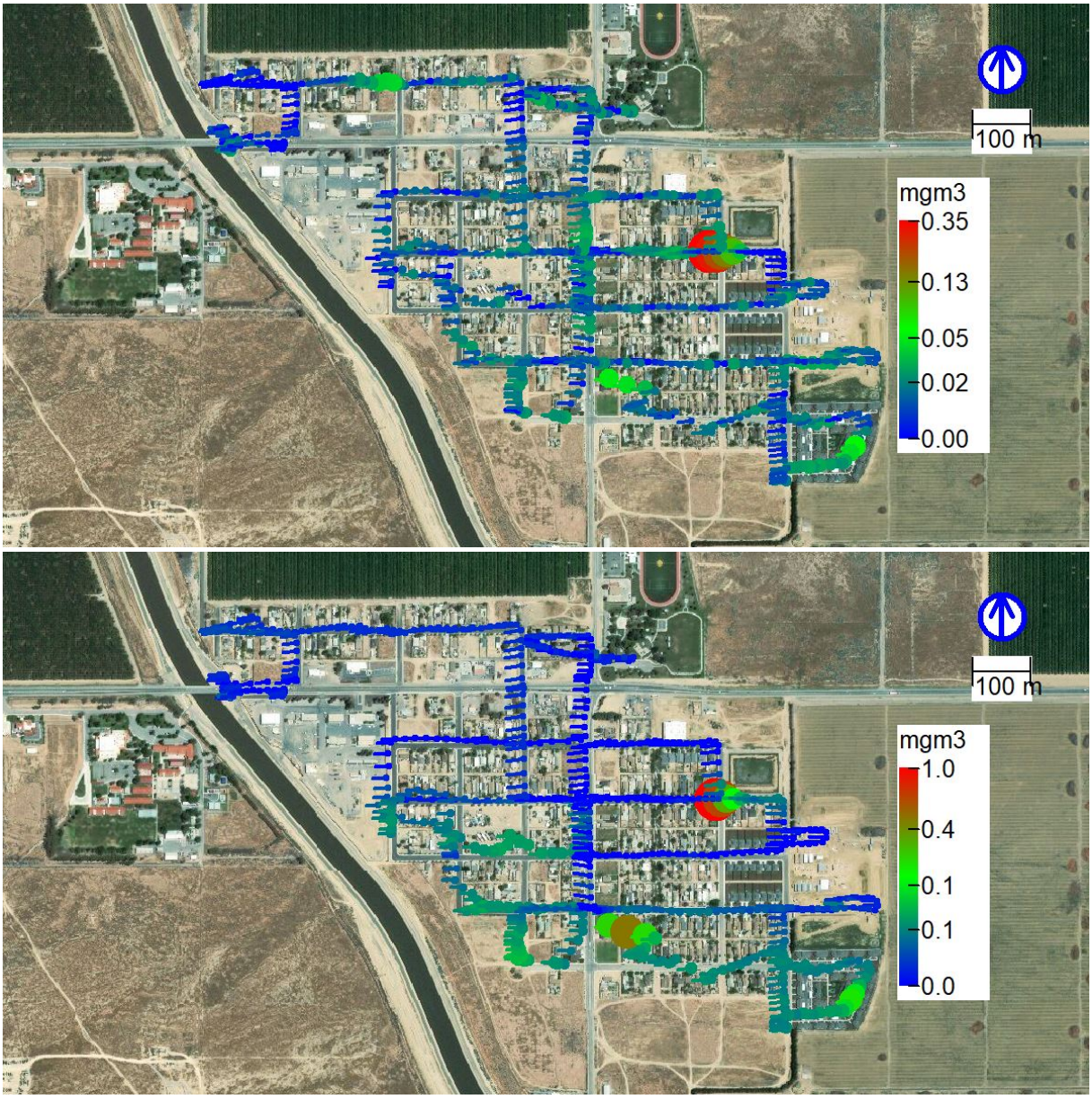


Figure 14. Mobile concentration measurements for community monitoring in Lost Hills 191007 20:33 – 21:39 . Color scale and point size show BTEX concentrations (upper) and alkane concentrations (lower), both in mg/m^3 and the lines point in the instantaneous wind direction. BTEX is plotted with logarithmic color scale.

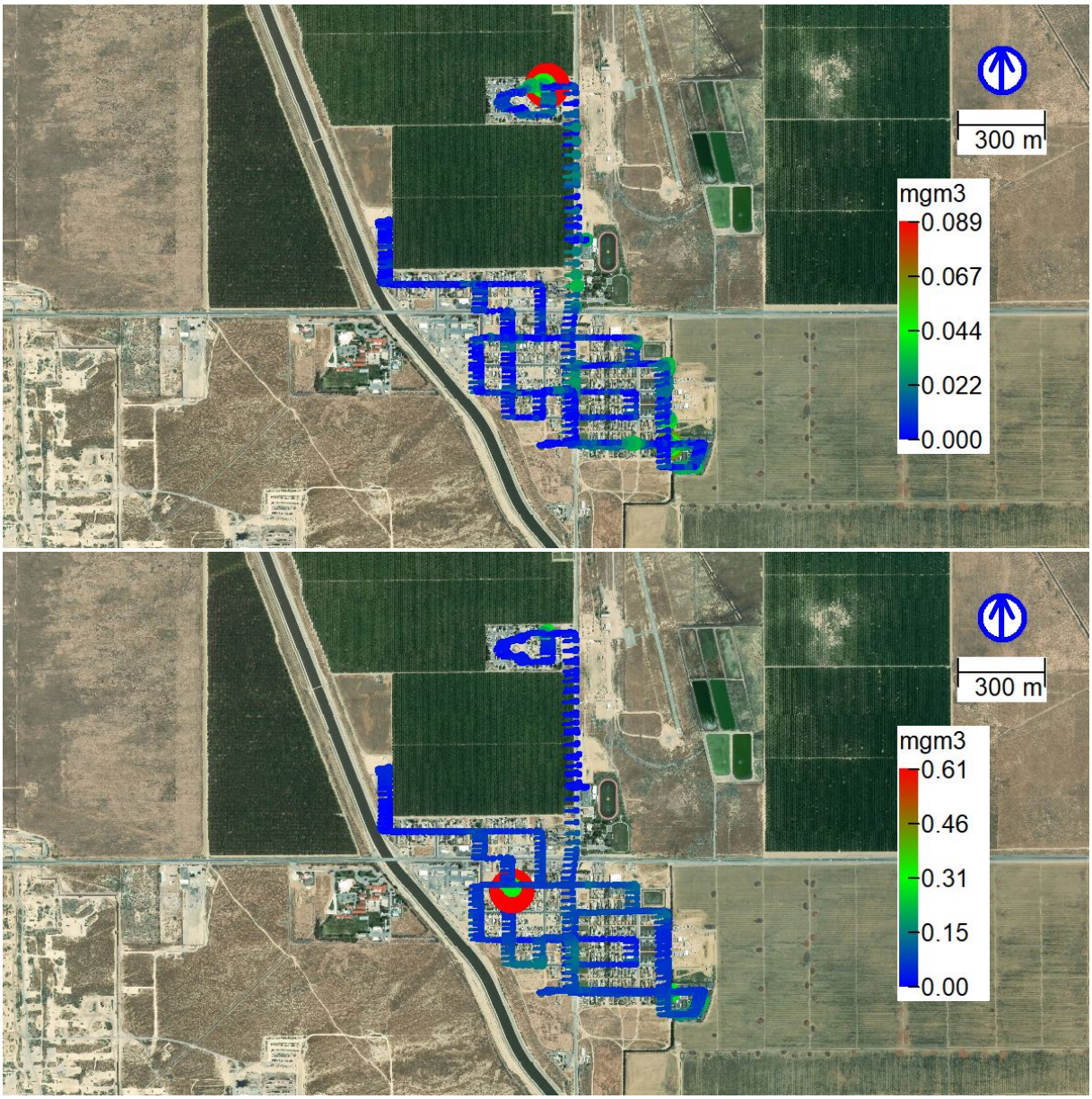


Figure 15. Mobile concentration measurements for community monitoring in Lost Hills 191015 19:30 – 20:35. Color scale and point size show BTEX concentrations (upper) and alkane concentrations (lower), both in mg/m^3 and the lines point in the instantaneous wind direction.

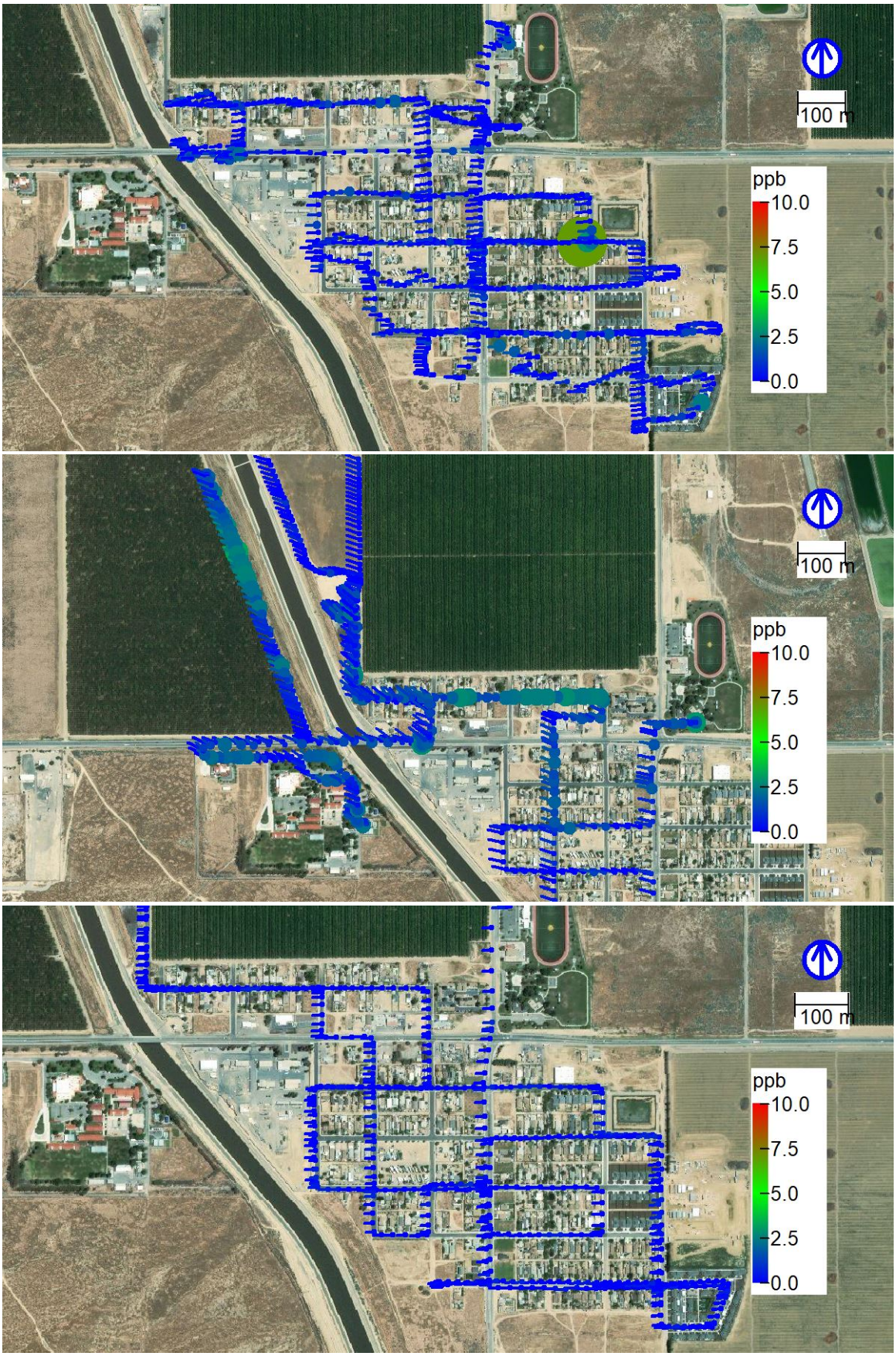


Figure 16. Mobile concentration measurements for community monitoring in Lost Hills 7, 9, and 15 October (top to bottom). Color scale and point size show benzene concentration (ppb) and the lines point in the instantaneous wind direction.

3.2.2 McKittrick, Derby Acres and Taft

With most of the focus of the survey in Lost Hills, only a few evenings were available for measurements further afield including the communities of McKittrick, Derby Acres and Taft. Similar to Lost Hills no notable BTEX plumes from the surrounding oil fields or facilities were noted. Taft showed the highest concentrations despite having daytime (afternoon) measurements.

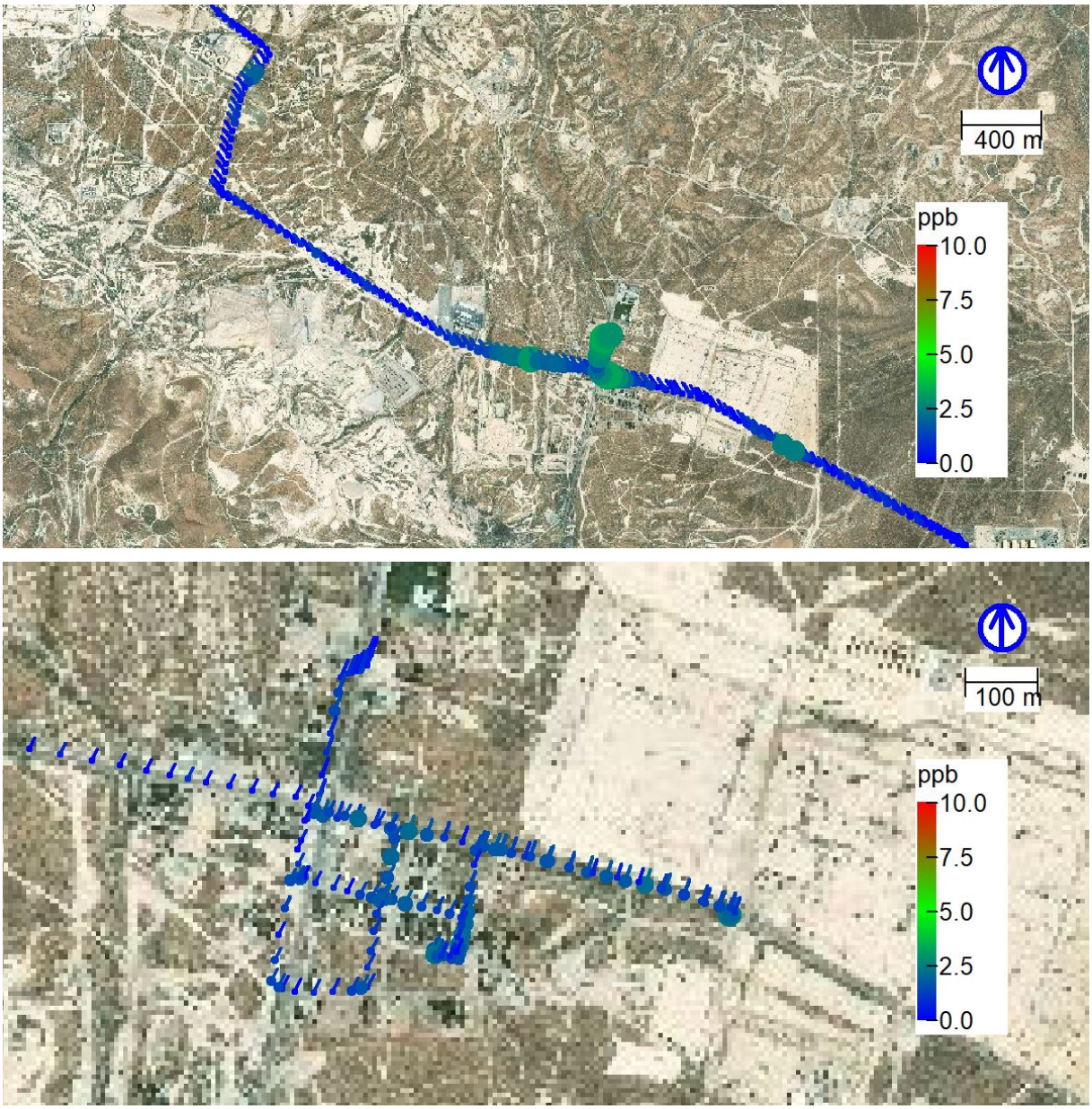


Figure 17. Mobile concentration measurements of benzene in and around the McKittrick, 6 Oct (top) and 13 Oct (bottom). Color scale and point size show benzene (ppb) and the lines point in the instantaneous wind direction.

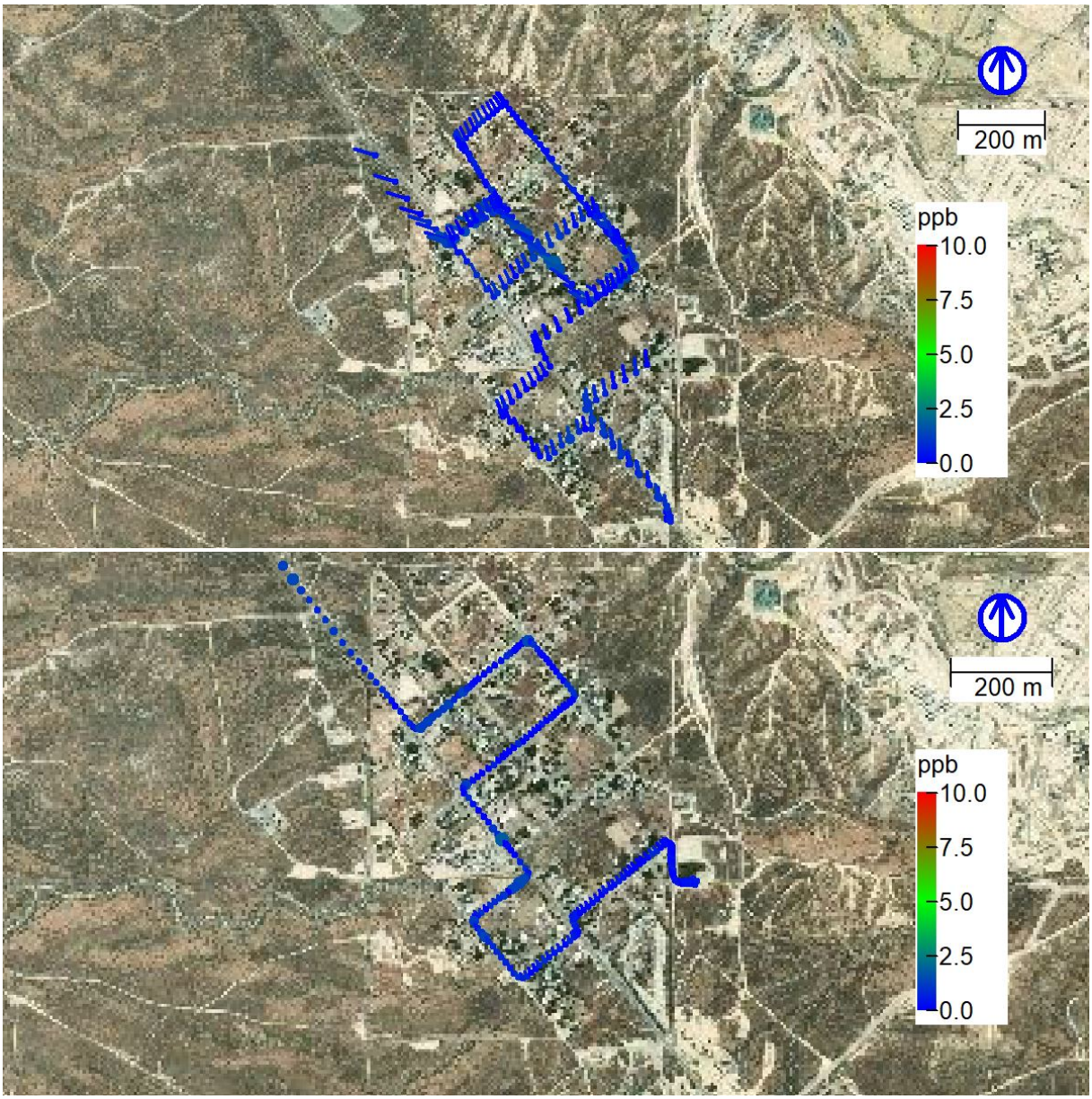


Figure 18. Mobile concentration measurements of benzene in and around the Derby Acres, 13 Oct (top) and 17 Oct (bottom). Color scale and point size show benzene (ppb) and the lines point in the instantaneous wind direction.

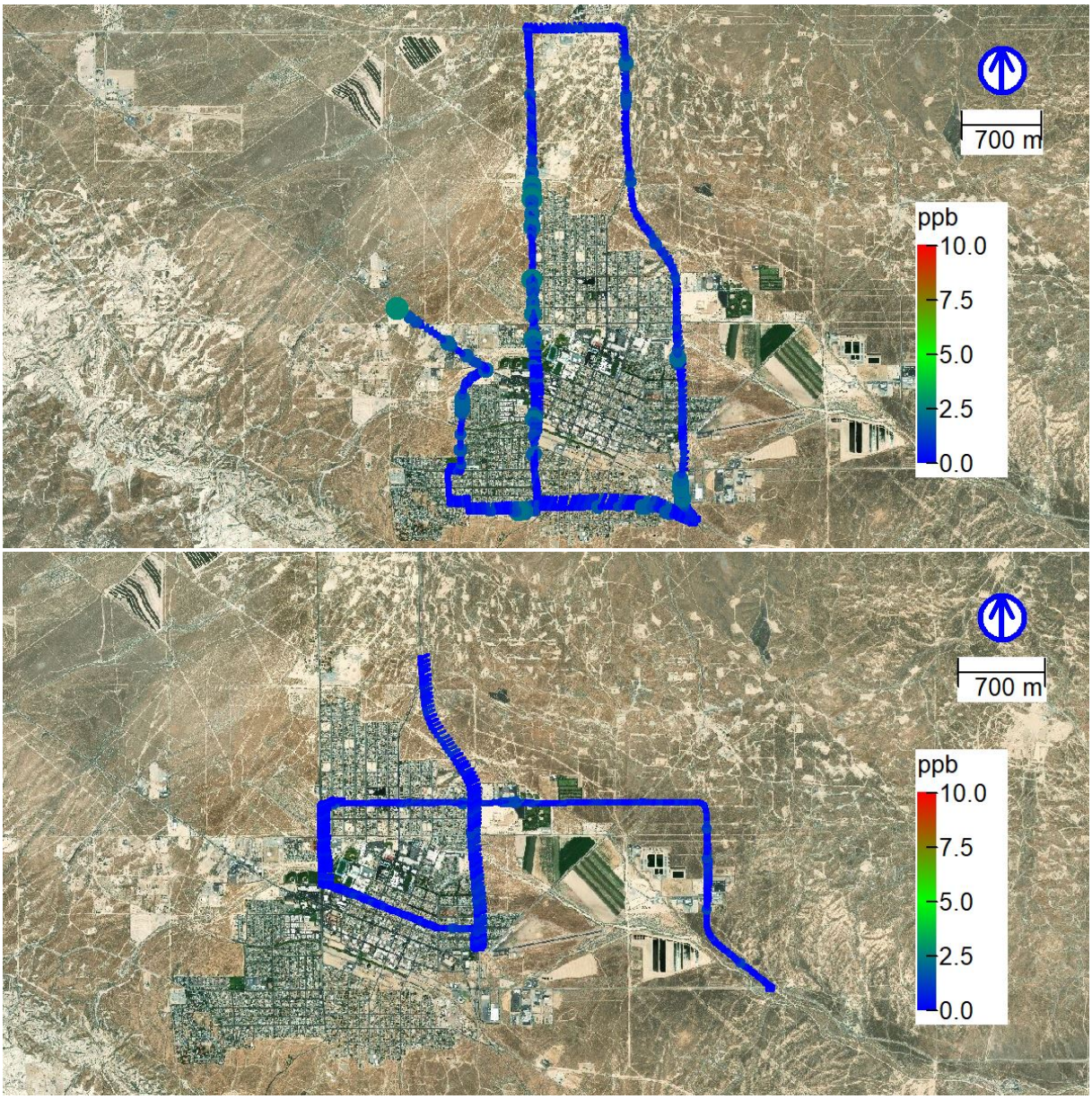


Figure 19. Mobile concentration measurements of benzene in and around the Taft, 16 Oct 2019. Color scale and point size show benzene (ppb) and the lines point in the instantaneous wind direction.

3.3 Plume transport and dispersion

The intention is to use the measurements to follow VOC emission plumes to observe their dispersion with increasing distance from the source. Figure 20 shows one example of an emission plume from the Operator A facility being traced with SOF. This is purely a visual example since the measurements are not contemporaneous. Data analysis of plume transport and dispersion has not been completed at this time.

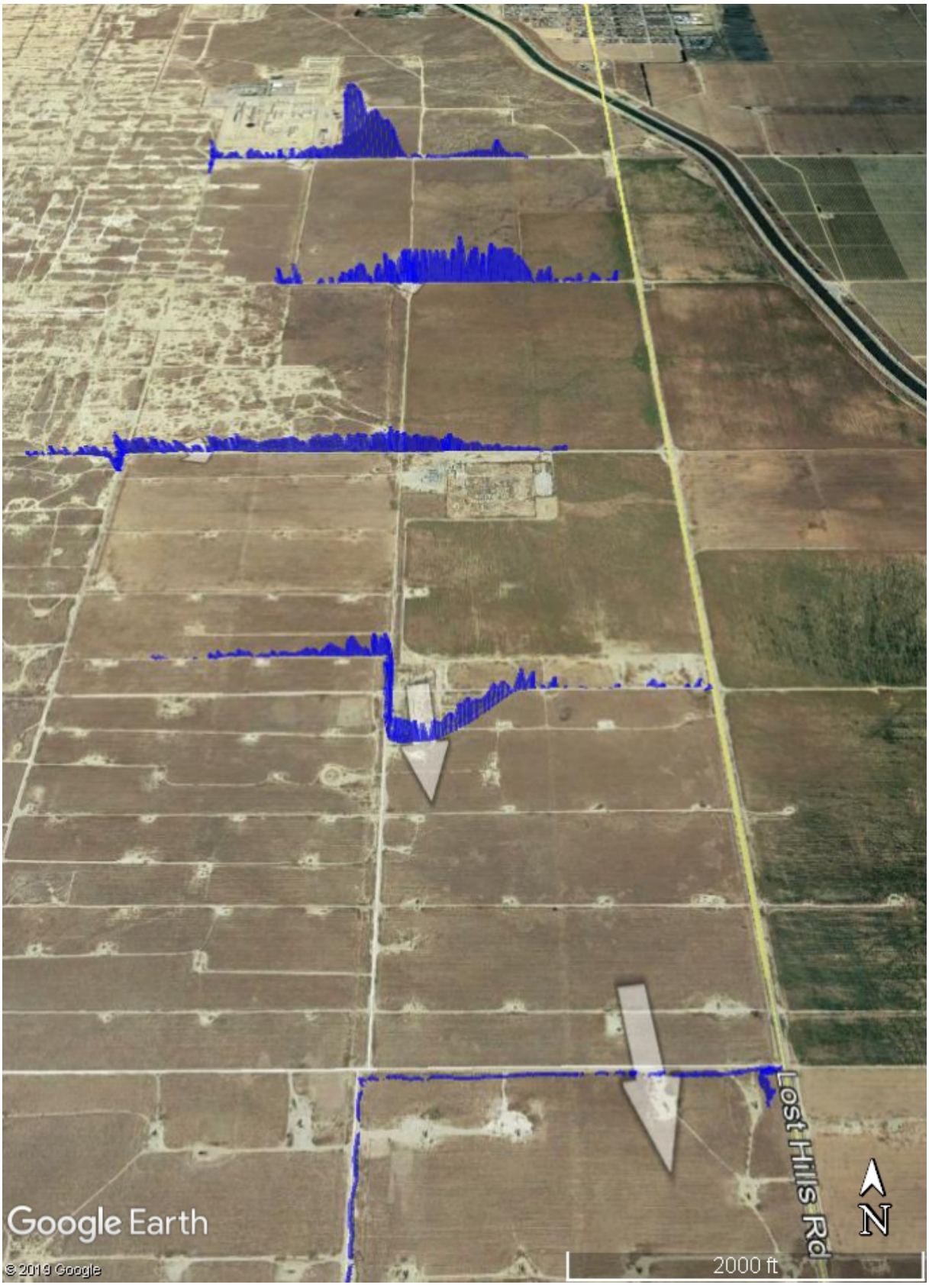


Figure 20 Plume dispersion visualized with SOF measurements with increasing distance from a VOC emission source, daytime convective conditions. The two measurements nearest the bottom of the image were made on a different day.

4 Acknowledgements

We would like to acknowledge the help and participation of Operator A and Operator B for granting both site access and time to this endeavour.

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5 References

Bogumil K., et al, 2003. Measurements of molecular absorption spectra with the SCIAMACHY pre-flight model: instrument characterization and reference data for atmospheric remote-sensing in the 230-2380 nm region, *Journal of Photochemistry and Photobiology A: Chemistry*, 157(2-3):167-184 5/5, 2003.

Burrows J.P., A. Richter, A. Dehn, B. Deters, S. Himmelmann, S. Voigt, and J. Orphal, 1999. "Atmospheric remote-sensing reference data from GOME: Part 2. Temperature-dependent absorption cross-sections of O_3 in the 231-794 nm range," J. Quant. Spectrosc. Radiat. Transfer 61, 509-517, 1999.

Börjesson, G., Samuelsson, J., Chanton, J., Adolfsson, R., Galle, B., Svensson, B.H., 2009. A national landfill methane budget for Sweden based on field measurements, and an evaluation of IPCC models.Tellus B, 61, 424–435.

CalGEM, 2016. Division of Oil, Gas & Geothermal Resources, at Department of Conservation, CA. http://maps.conservation.ca.gov/CalGEM/#close .

CalGEM, 2019, Division of Oil, Gas & Geothermal Resources, at Department of Conservation, CA https://maps.conservation.ca.gov/CalGEM/wellfinder

Downey N., Emery C., Jung J., Sakulyanontvittaya T., Hebert L., Blewitt D., Yarwood G., 2015. Emission reductions and urban ozone responses under more stringent US standards. Atmospheric Environment, 101, pp 209-216, 2015.

Environmental Research & Education Foundation (EREF), 2011. Field comparison of methods for assessment of fugitive emissions from landfills. Available at https://erefdn.org/wp-content/uploads/2015/12/FugitiveEmissions_FinalReport.pdf

Etzkorn T., B. Klotz, S. Sørensen, I.V. Patroescu, I. Barnes, K.H. Becker, and U. Platt, 1999. "Gas-phase absorption cross sections of 24 monocyclic aromatic hydrocarbons in the UV and IR spectral ranges," Atmos. Environ. 33, 525-540, 1999.

European Commission, 2015, Best Available Techniques (BAT) Reference Document for the Refining of Mineral Oil and Gas: Joint Research Centre, Institute for Prospective Technological Studies, ISBN 978-92-79-46198-9 (PDF)ISSN 1831-9424 (online)doi:10.2791/010758, http://eippcb.jrc.ec.europa.eu/reference/BREF/REF_BREF_2015.pdf

Fally S., M. Carleer, and A. C. Vandaele, "UV Fourier transform absorption cross sections of benzene, toluene, meta-, ortho-, and para-xylene," J. Quant. Spectrosc. Radiat. Transfer 110, 766-782, 2009.

Galle, B., J. Samuelsson, B.H. Svensson, G. Börjesson, "Measurements of methane emissions from landfills using a time correlation tracer method based on FTIR absorption spectroscopy." Environ. Sci. Technol. 35: 21–25. 2001.

Griffith D.W.T., Synthetic calibration and quantitative analysis of gas-phase FT-IR spectra. Applied Spectroscopy, 1996. 50(1): p. 59-70.

Johansson, J., et al., 2013a, Quantitative Measurements and Modeling of Industrial Formaldehyde Emissions in the Greater Houston Area during Campaigns in 2009 and 2011, Journal of Geophysical Research – Atmospheres, 2013JD020159R.

Johansson, J., Mellqvist, J., et al., 2013b. Quantification of industrial emissions of VOCs, NO_2 and SO_2 by SOF and Mobile DOAS during DISCOVER-AQ, AQRP project 13-0051, AQRP report, Dec 7 2013.

Johansson, J. K. E., J. Mellqvist, J. Samuelsson, B. Offerle, B. Lefer, B. Rappenglück, J. Flynn, and G. Yarwood, 2014. Emission measurements of alkenes, alkanes, SO_2, and NO_2 from stationary sources in Southeast Texas over a 5 year period using SOF and mobile DOAS, Journal of Geophysical Research, 118, doi:10.1002/2013JD020485.

Kihlman, M., 2005a. Application of solar FTIR spectroscopy for quantifying gas emissions, Technical report No. 4L, ISSN 1652-9103, Department of Radio and Space Science, Chalmers University of Technology, Gothenburg, Sweden.

Kihlman, M., J. Mellqvist, and J. Samuelsson (2005b), Monitoring of VOC emissions from three refineries in Sweden and the Oil harbor of Göteborg using the Solar Occultation Flux method, Technical report, ISSN 1653 333X, Department of Radio and Space, Chalmers University of Technology, Gothenburg, Sweden.

Maul J., James & J. Ostrowski, Philip & A. Ublacker, Gregg & Linclau, Bruno & P. Curran, Dennis. (2008). Benzotrifluoride and Derivatives: Useful Solvents for Organic Synthesis and Fluorous Synthesis. 10.1007/3-540-48664-X_4.

Mellqvist, J., et al. (2013a), Pilot study to quantify industrial emissions of VOCs, NO_2 and SO_2 by SOF and mobile DOAS in the Bay Area, Fluxsense AB, 2013.

Mellqvist, J., et al. (2013b), Pilot study to quantify industrial emissions of VOCs, NO_2 and SO_2 by SOF and mobile DOAS in the Carson Area, Fluxsense AB, 2013.

Mellqvist, J. (1999), Application of infrared and UV-visible remote sensing techniques for studying the stratosphere and for estimating anthropogenic emissions, doktorsavhandling, Chalmers tekniska högskola, Göteborg, Sweden, 1999.

Mellqvist, J., Johansson J., Samuelsson J. And Offerle B. (2008a), Emission Measurements of Volatile Organic Compounds with the SOF method in Normandy 2008. available at www.fluxsense.se

Mellqvist, J., Johansson, J., Samuelsson, J., Rivera, C., Lefer, B. and S. Alvarez (2008b), Comparison of Solar Occultation Flux Measurements to the 2006 TCEQ Emission Inventory and Airborne Measurements for the TexAQS II, Project No. 582-5-64594-FY08-06, TCEQ report., Texas. (available at http://www.tceq.state.tx.us/assets/public/implementation/air/am/contracts/reports/da/20081108-comparison_solar_occultation_flux_measurements.pdf)

Mellqvist, J., et al. (2009), Emission Measurements of Volatile Organic Compounds with the SOF method in the Rotterdam Harbor 2008, available at www.fluxsense.se

Mellqvist, J., J. Samuelsson, J. K. E. Johansson, C. Rivera, B. Lefer, S. Alvarez, and J. Jolly (2010), Measurements of industrial emissions of alkenes in Texas using the solar occultation flux method, Journal of Geophysical Research: Atmospheres, 115(D7), doi:10.1029/2008JD011682.

Rinsland, C. P., R. Zander, and P. Demoulin (1991), Ground-based infrared measurements of HNO_3 total column abundances: long-term trend and variability. *J. Geophys. Res.*, *96*, 9379–9389.

Rivera, C., Mellqvist, J., Samuelsson, J., Lefer, B., Alvarez, S. & Patel, M. (2010) Quantification of NO2 and SO2 emissions from the Houston Ship Channel and Texas City industrial areas during the 2006 Texas Air Quality Study. Journal of Geophysical Research - Atmospheres 115. DOI: 10.1029/2009JD012675.

Rothman et al. (2003), HITRAN 2000, Journal of Quantitative Spectroscopy and Radiative Transfer, vol. 82, pp. 5-44.

Sharpe, S., et al. (2004), Gas-Phase Databases for Quantitative Infrared Spectroscopy, *Applied Optics*, 58(12).