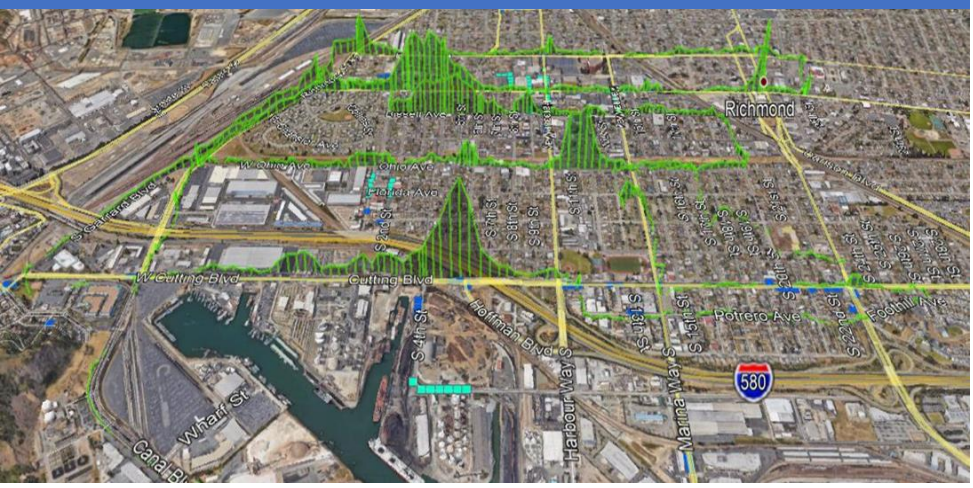
2020

Characterization of Air Toxics and GHG Emission Sources and their Impacts on Community Scale Air Quality Levels in Disadvantaged Communities



FluxSense

FINAL REPORT

March 2021

Original submission: 20 April 2020

Updated: 20 February 2021, 1 December 2020, 4 September 2020, 24 August 2020.

Final submission: 8 March 2021

Title: Characterization of Air Toxics and GHG Emission Sources and their Impacts on Community Scale Air Quality Levels in Disadvantaged Communities

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CARB contract no. 17RD021
Principal Investigator: Johan Mellqvist,
Project period: July 2018 through April 2020
Prepared for the California Air Resources Board

[Cover: SOF measurement of alkane plumes in Richmond, California. Image mapped on Google Earth © 2019.]

DISCLAIMER

Acknowledgement

This Report was submitted in fulfillment of CARB contract 17RD021 “Characterization of Air Toxics and GHG Emission Sources and their Impacts on Community-Scale Air Quality Levels in Disadvantaged Communities” by FluxSense Inc under the sponsorship of the California Air Resources Board. Work was completed as of 30 April 2020.

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Abstract

The emissions of several air pollutants and greenhouse gases have been studied from industrial and agricultural activity on behalf of the California Air Resources Board (CARB). Unique optical techniques and a methodology combining gas column measurements by remote sensing and concentration measurements on a mobile platform were applied. The methodology was developed for remote quantification and characterization of point and diffuse emission sources.

This approach makes it possible to capture facility level emissions, measure co-pollutant emissions, and capture larger spatially extensive or distributed operations with diffuse emissions. These measurements allow better understanding of real-world emissions of complex sources and will aid in developing better emission control strategies.

This was an extensive study demonstrating a variety of measurement methods and targeted gas emissions, with diverse sources and applications, focused on screening many specific sources rather than investigating a few sources with comprehensive statistics.

The target gases were methane which impacts climate, non-methane volatile organic compounds (NMVOCs, used interchangeably for alkanes here) and NO_2, which contribute to the formation of ground level ozone, and ammonia and SO_2 which causes the formation of particulate matter. Several of these species are of major health concern and have a direct health impact on surrounding communities.

The main results are:

- 5 refinery areas and one port in the Bay Area had combined emissions of 1 ton/h alkanes, 0.4 ton/h methane, 0.1 ton/h BTEX, 0.4 ton/h NO_2 and 0.4 ton/h SO_2.
- The major oil and gas fields surveyed in the San Joaquin valley emitted about 8 ton/h NMVOCs and 8 ton/h methane.
- Large dairies in the San Joaquin valley had average site emissions of 0.4 ton/h methane and 0.1 ton/h ammonia. Average emission factors obtained were 12 g NH_3/head/h and 50 g CH_4/head/h.
- Methane and alkane emissions from multiple landfills were measured in the San Francisco Bay, South Coast and San Diego County Air Basins. Emissions from the Potrero Hills Landfill (Suisun City) averaged 0.9 ton/h methane and 0.08 ton/h alkanes.
- A 10-day source screening study in the South Coast and San Diego County Air Basins showed major emission sources that were related to oil and gas production, fuel storage and landfills, several in close proximity to residential communities. Emissions of about 1 ton/h alkanes and 2 ton/h methane were identified from these sources. Measurements in San Diego showed significant NO_2 and SO_2 emissions, 688 kg/h and 265 kg/h, respectively, which appeared to originate from the port activity.
- Community measurements were performed during all the field campaigns with the most resources allocated to measurements in the Richmond area. Ground level concentrations of BTEX were on average low in all studies. The measurements in the Richmond community showed NMVOC concentrations varying between 0-500 µg/m^3, dominated by alkanes from the port area rather than the refinery.

Emission measurements were conducted during the daytime which may bias the results toward higher emissions than annualized emission inventories or models. Other important parameters for emissions are the average wind and temperature during the measurement period, which may differ from the annual average climatology. Measurements were conducted over a period of days or weeks within a single season which may bias results either positively or negatively when extrapolated and compared to annualized values. That stated, measurements indicated significantly higher emissions than inventories or modeled values in several instances:

- Bay Area refinery and port NMVOC emissions were around 2.5 times higher than reported. Here we estimate, assuming a typical refinery, that only a minor part of the discrepancy is caused by diurnal effects and varying meteorological conditions.
- Oil and gas field methane and NMVOC emissions were 2 and 10 times higher than production-based emission factors, respectively.
- Methane and ammonia emissions from dairies were 50 % and 100 % higher than emission factor models, respectively. In the latter case this is likely an effect of diurnal variations.

Executive summary

BACKGROUND

The emissions of several air pollutants and greenhouse gases have been studied from industrial and agricultural activity. The target gases are methane which impacts climate, non-methane volatile organic compounds (NMVOC, used interchangeably for alkanes here) and NO_2 which contribute to the formation of ground level ozone, and ammonia and SO_2 which causes the formation of particulate matter. Ozone and particulate matter are both of major health concern. Facilities emitting significant amounts of NMVOCs may also emit BTEX and other air toxics that have a direct health impact on surrounding communities.

A two-year study has been carried out on behalf of the California Air Resources Board (CARB) measuring emissions of atmospheric pollutants and climate gases from a wide variety of emission sources and their community impact. 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. The focus was on screening many specific sources of different gaseous compounds rather than investigating a few sources with comprehensive statistics.

The study is based on four field surveys conducted in California:

- Bay Area in October 2018
- San Joaquin Valley in October 2018
- San Joaquin Valley in May 2019
- South Coast Air Basin and San Diego Air Basin in October 2019.

OBJECTIVES AND METHODS

The aim was to investigate emissions from various sources and to understand their community impact. The sources were comprised of refineries, petrochemical facilities, oil storage, port activities, landfills, oil and gas production and dairy farms. Emissions of alkanes, ammonia (NH_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and formaldehyde (H_2CO) were quantified from gas flux measurements using Solar Occultation Flux (SOF) and mobile SkyDOAS (Differential Optical Absorption Spectroscopy). Ground level concentrations around facility fence-lines and in selected adjacent disadvantaged communities were measured using MWDOAS (Mobile White Cell DOAS) and MeFTIR (Mobile extractive Fourier Transform Infrared) techniques of the following species, i.e. alkanes, benzene (C_6H_6), BTEX (sum of benzene, toluene, ethylbenzene and xylenes), methane (CH_4) and ammonia. The emissions of methane and BTEX were indirectly obtained from the SOF alkane emission rate and the ground-level concentration ratio of methane or BTEX to alkanes.

Emission measurements were conducted during the daytime which may bias the results toward higher emissions than annualized emission inventories or models. Other important parameters for emissions are the average wind and temperature during the measurement period, which may differ from the annual average climatology. Measurements were conducted over a period of days

or weeks within a single season which may bias results either positively or negatively compared to annualized values.

RESULTS

Oil & Gas

Tables E.1 and E.2 show the main results from two surveys in 2018 and 2019, respectively, which focused on studying NMVOC and methane emissions from eight oil and gas fields in Kern County, San Joaquin Valley, California. The cumulative emissions from the fields amount to about 7600 kg/h NMVOCs and 8000 kg/h methane. Inventory data for methane and production-based emission factor calculations show 20 % and 50 % lower values than the survey measurements, respectively. For NMVOCs the emission factor-based calculations show an order of magnitude lower values than the alkane measurements in this survey. Community monitoring, targeting BTEX, alkanes, and methane, was carried out at various sites close to the oil and gas fields. For alkanes several hotspots, i.e. locations with repeatedly measured ground level concentrations significantly higher than background, were found while for aromatic VOCs the concentrations were low but measurable in some locations.

The average wind speed during the measurement period was 25 % higher than the annual one, possibly causing a positive bias in the SOF data, while the ambient temperature during the campaign was the same as the annual one. The SOF measurements are positively biased by the fact that SOF measurements are only carried out on sunny days. This effect has been studied using the API (American Petroleum Institute) model for various tanks (Johansson 2014) and for a typical refinery this may increase the emissions by 30-40 %.

Table E.1. NMVOC emissions from oil and gas fields in the San Joaquin valley from SOF. CI 95% is the 95% confidence interval for the mean. D is the number of measurements days, N is the number of measurement transects.

Area (fields and associated facilities)	**D**	**N**	**NMVOC** kg/h	**CI 95%,** kg/h
Elk Hills	8	13	3470	2980 – 3970
Poso Creek & Kern Front	3	5	440	210 – 680
Coles Levee North	3	5	250	200 – 300
Cymric & McKittrick	3	7	1230	790 – 1680
Lost Hills	4	6	780	460 – 1110
Belridge	2	4	1480	800 – 1970
McKittrick	3	4	320	130 – 500

Table E.2. Methane emissions from oil and gas fields in the San Joaquin valley from SOF and MeFTIR measurements. Indirect emissions calculated from median ratio and SOF NMVOC flux therefore interquartile range (IQR) is given instead of CI.

Area (fields and associated facilities)	**D**	**N**	**CH_4/NMVOC mass ratio**		**CH_4** kg/h
			Median	IQR	
Elk Hills	2	4	1.35	1.25 – 1.49	4820
Poso Creek & Kern Front	3	4	1.08	0.71 – 1.42	470
Coles Levee North	Not Available				
Cymric & McKittrick	5	10	1.25	1.06 – 1.35	1470
Lost Hills	2	4	0.42	0.38 – 0.46	330
Belridge	3	3	0.53	0.43 – 0.71	860
McKittrick	Not Available				

Industrial emissions in Bay Area

Tables E.3 and E.4 summarize measurements from 5 refinery areas and one port in the Bay Area October 2018. NMVOC emissions amounted to 1153 kg/h and methane emissions to 442 kg/h. BTEX emissions were about 109 kg/h of which benzene constituted 12%. A comparison of these values to the CARB 2016 emission inventory (annual values converted to emission rates in kg/h) shows that the average VOC and CH_4 emissions are 2.5 and 2.9 times higher than the reported ones, respectively, varying between 1.36 to 6.2 for individual refineries.

Although meteorology can impact emissions, wind speeds during the measurement period were lower than annual average and temperatures only slighter higher than average (16.1 °C/ 14.7 °C). Similar to emissions from oil and gas production, as discussed above, the emissions are affected by diurnal factors such as solar forcing and operational activities (vacuum trucks, loading, etc).

In a recent study by AQMD (Pikelnaya 2019) long term, seasonal measurements were conducted using SOF on a single refinery in southern California. Here 7 separate measurement campaigns were carried out during different seasons from fall 2015 to summer 2018. The overall variability was 20 % with poor correlation (r^2=0.27) to season. From this study and the one by Johansson (2014) we estimate that only a minor part (1/5) of the discrepancies observed is caused by diurnal effects and varying meteorological conditions.

Table E.3. Gas emissions in the Bay Area from refinery areas and Port of Richmond measured by SOF and SkyDOAS. *D and N for SO_2 retrievals. NO_2 and H_2CO have similar number of measurement days (D) and number of measurements (N).

Source	**D**	**N**	**NMVOC** kg/h	**CI 95%** kg/h	**D***	**N***	**SO_2** kg/h	**CI 95%** kg/h	**NO_2** kg/h	**CI 95%** kg/h	**H_2CO** kg/h
Martinez E refinery	3	8	151	140 – 161	3	11	60	30 – 90	69	60 – 79	<5
Richmond refinery	4	16	291	248 – 335	3	9	105	34 – 175	113	83 – 142	<5
Rodeo refinery	2	17	143	118 – 168	2	9	11	8 – 14	34	19 – 49	<5
Martinez W refinery	4	15	334	249 – 419	3	14	200	159 – 240	104	85 – 122	<10
Benicia refinery	4	20	144	124 – 165	3	13	20	15 – 25	84	66 – 102	<5
Sum Refineries			**1063**				**395**		**404**		**-**
Richmond port	5	40	90	78 – 102	2	7	4	1.5 – 6	33	22 – 44	<5

Table E.4. Gas emissions in the Bay Area from refinery areas and Port of Richmond measured by SOF, MeFTIR, MWDOAS. *Limited number of measurements. D is the number of measurement days, N is the number of measurement transects.

Refinery Area	**D**	**N**	**CH_4/ NMVOC**		**CH_4** kg/h	**D**	**N**	**BTEX/ NMVOC**	**BTEX** kg/h	**C_6H_6/ NMVOC**	**C_6H_6** kg/h
			Med	**IQR**							
Martinez E	3	6	0.36	0.32 – 0.53	54	Not available					
Richmond	4	10	0.36	0.27 – 0.50	105	2	2	0.14	40*	0.017	6.1*
Rodeo	4	17	0.31	0.20 – 0.56	44	1	2	0.12	17*	0.014	2.0*
Martinez W	5	17	0.47	0.37 – 0.58	157	3	7	0.092	31	0.010	3.3
Benicia	3	16	0.48	0.39 – 0.61	69	2	6	0.82	12	0.07	1.0
Sum Refineries					**430**				**100**		**12.4**
Richmond port area	6	33	0.13	0.094 – 0.26	12	3	10	0.097	9	0.07	0.6

CAFOs

Table E.5. summarizes the results from methane and ammonia measurements at 16 dairy farms (Concentrated Animal Feeding Operations-CAFOs) in the Bakersfield, Tulare and Merced areas in San Joaquin Valley in May 2019. Overall ammonia emissions of 1653 kg/h and methane emissions of 6626 kg/h were measured, with corresponding CAFO averages of 103 and 414 kg/h respectively, although with large variability among the CAFOs. Average emission factors obtained were 11.7 g NH_3/head/h and 49.9 g CH_4/head/h. The methane numbers correlated reasonably well with airborne methane emission measurements at the same facilities in other periods of the year, given differences in the average wind and temperature. Additionally, a comparison of the measured methane and ammonia emissions to inventory models showed that the measurements were 50 % and 100 % higher, respectively.

The ammonia and methane emissions are affected by ambient temperature, wind conditions, solar insolation and diurnal patterns of the animal activity. The measurements in this study were performed in sunny conditions during the month of May. An analysis showed that both the ambient temperature and wind speeds during the measurements campaign were relatively close to the annual average ones, hence causing relatively small biases on the results. However, due to lower nighttime emissions, the daytime measured emissions are estimated to be 70% higher than the diurnal average emissions, reasonably in line with the 50-100% inventory discrepancy discussed above.

Table E.5. Ammonia and methane emissions measured at 16 CAFOs in San Joaquin Valley in May 2019. For ammonia D is the number of measurements days and N is the number of measurement transects for the direct flux NH_3 measurements. For methane, D and N represents number of days and transects for the CH_4 to NH_3 concentration ratio measurements, respectively.

CAFO	**NH_3 (kg/h)**				**CH_4 (kg/h)**			
	D	**N**	**Average**	**CI 95%**	**D**	**N**	**Average**	**CI 95%**
SB02	3	7	107	68 – 146	1	3	548	0 – 1110
SB03	3	9	120	73 – 167	1	3	385	0 – 890
SB04	3	10	61	42 – 80	3	9	214	100 – 330
SB05	2	8	114	80 – 152	2	9	514	280 – 740
NB01	2	7	70	17 – 122	2	5	392	0 – 860
NB02	2	9	104	61 – 147	1	4	675	0 – 1400
WT01	3	14	71	48 – 93	4	14	196	100 – 290
WT03	3	9	158	121 – 193	3	11	389	260 – 520
WT04	2	7	192	120 – 263	2	7	483	270 – 700
WT05	3	6	70	29 – 111	3	8	304	140 – 460
WT06	1	6	121	57 – 185	1	6	260	60 – 460
WT07	3	8	67	51 – 83	4	10	415	270 – 560
ET01	3	7	32	20 – 43	3	11	188	100 – 270
ET08	1	7	60	48 – 72	1	7	293	170 – 420
SM01	1	7	166	127 – 204	1	6	527	380 – 670
SM02	2	13	142	104 – 180	2	13	845	570 – 1120
Sum CAFOS			**1653**				**6626**	
Average			103				414	
Median			105				390	

- The CAFOs were designated according to their geographic location in San Joaquin Valley. "SB" stands for South Bakersfield, "NB" for North Bakersfield, "WT" West Tulare, "ET" East Tulare, and "SM" for South Merced.

Landfills

Methane and alkane emissions from landfills were measured during the Bay Area and the South Coast surveys of the study. Emissions from the Potrero Hills Landfill (Suisun City) averaged 860 kg/h methane and 76 kg/h alkanes. The Sunshine Canyon Landfill in Los Angeles, the Frank Bowerman and Coyote Canyon Landfills in Orange County, and the Otay and Miramar Landfills in San Diego were also measured. Methane emissions for Frank Bowerman and Otay averaged over 500 kg/h, respectively, and Miramar (including the airfield) averaged around 90 kg/h. Results for Coyote Canyon and Sunshine Canyon were inconclusive.

South Coast and San Diego

During a 10-day source screening study in the South Coast Air Basin and San Diego County Air Basin in October 2019, multiple sources were studied, including oil and gas production, gas/fuel storage, breweries, landfills, port and facilities, and an airport. The major emission sources were related to oil and gas production, fuel storage and landfills, several in close proximity to residential communities. Emissions of about 800 kg/h alkanes and 1900 kg/h methane were identified from these sources. Measurements in San Diego showed significant NO_2 and SO_2 emissions, 688 kg/h and 265 kg/h, respectively, which appeared to originate from the port activity. Community monitoring of VOCs in Huntington Beach and Newport revealed several hotspots related to active oil wells. The main emissions from these were methane and other alkanes while the emissions of aromatic VOCs were low.

Community Measurements

Community measurements were performed during all the field campaigns with the most resources allocated to measurements in the Richmond AB617 area (Survey A). In Richmond, community monitoring was carried out in the entire Richmond AB617 area. Measurements were focused on the near vicinity to larger stationary sources i.e. Port of Richmond, Iron Triangle, Central Richmond, North Richmond and Marina Bay with few measurements in the I-80 corridor and Hilltop areas. The measurements were either done on preselected locations or by tracking identified emission plumes in the community. The emissions from the port area affected the community more than the refinery during the time period, since the former is located in the prevalent upwind direction from the community. This is also consistent with the annual wind climatology. The VOC concentration varied between 0-500 $\mu g/m^3$ and was dominated by alkanes.

Within Richmond AB617 area, the consistently highest ground level concentrations of BTEX were adjacent to the port area (Figure E1). For Richmond, as well as within the other surveys (Surveys B & D), ground level concentrations of BTEX at refinery fencelines were low on average, presumably due to the distance of sources from the perimeter roads and potential plume lift effects. These measurements were, however, limited to few sampling occasions. Other transient plumes were encountered during the surveys but due to their short-lived nature, no source could be identified.

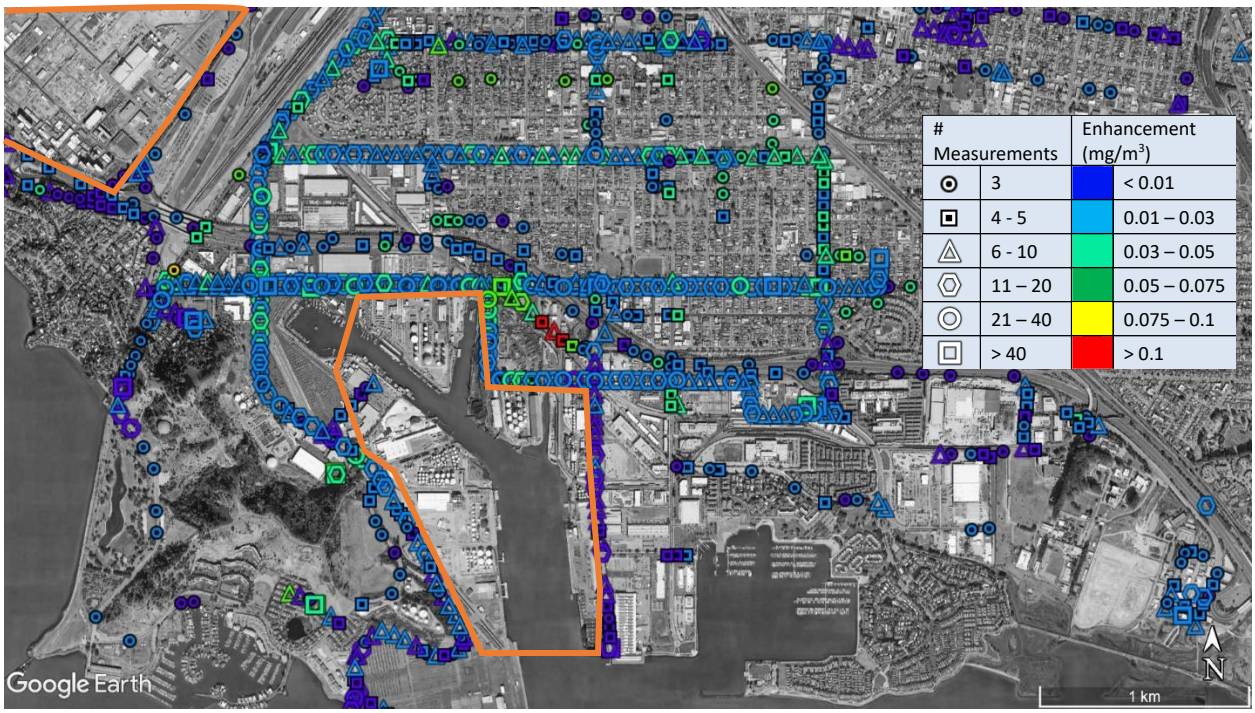

Figure E1. Concentration map of BTEX in Richmond (survey A), number of measurements (min. 3) within an approximately 50 x 50 m grid cell and mean BTEX enhancement within the cell. Oct, 2018. Highlighted areas show approximate boundaries for the refinery (northwest) and port (south) areas.

CONCLUSIONS

Emissions from a multitude of sources and source types have been successfully surveyed in four focused campaigns around California using a set of optical remote sensing techniques operated from a mobile lab vehicle. The measurement data provide regulators with an actionable data set that allows for more targeted emission reduction efforts. Large scale emissions from vast oil- and gas production fields down to individual sources such as single CAFOs, landfills, oil wells and tank farms have been covered. In terms of greenhouse gas emissions, sources totaling 17 tons/h CH_4 and on the order of 10 tons/h NMVOC have been identified. CAFOs were measured to have significant emissions of both methane and ammonia, on average 414 kg/h/CAFO for methane and 103 kg/h/CAFO for ammonia. This study indicates that the emissions from the measurements are larger than the emission inventories for many of the NMVOC sources, when accounting for the annual variability, while they are more comparable for CH_4 and NH_3. Future community monitoring of air toxics based on a combination of mobile and fixed continuous measurements would improve understanding of the impact of intermittent sources on adjacent populated areas. Given the considerable emissions of methane, ammonia and VOCs found here and source variability further measurements extending spatial and temporal coverage are recommended.

1. INTRODUCTION

The emissions of several air pollutants and greenhouse gases have been studied from industrial and agricultural activity on behalf of the California Air Resources Board (CARB). The studied species includes volatile organic compounds (VOCs), SO_2, NO_2 and NH_3.

VOCs correspond to a large number of species which in turn can be categorized into different chemical groups such as: alkanes (e.g. methane, propane, butane etc.), alcohols (e.g. ethanol and propanol, alkenes (e.g. ethene and propene), aromatic hydrocarbons (e.g. benzene and toluene) and aldehydes (e.g. formaldehyde and acetaldehyde). VOCs contributes to the formation of ground level ozone, which is formed through atmospheric chemical reactions of volatile organic compounds and nitrogen oxides (NO_x) in the presence of sunlight. Elevated ozone concentrations are known to reduce crop yields and constitute a public health concern. Larger metropolitan areas in the US have trouble meeting ozone standards since anthropogenic sources tend to be concentrated in urban areas, including both mobile and stationary sources. For instance, to meet current and future more stringent ozone standards in Los Angeles, reductions in VOC emissions are foreseen [Downey et. al. 2015]. Stationary sources such as refineries, storage depots, petrochemical facilities and oil production activities are significant point sources of VOCs. The emissions are typically dominated by evaporative losses from storage tanks and process equipment, so-called diffuse emissions. Several VOCs are also toxic with direct impact on health such as benzene and formaldehyde. Methane is a strong climate gas and is emitted from oil related sources (production and processing) and enteric fermentation and anaerobic breakdown of feces in livestock, e.g. from Concentrated Animal Feeding Operations (CAFOs). The species NH_3 is emitted from feces and urine from livestock and causes secondary production of fine particulate matter (PM2.5), which is of great health concern.

In 2015, the California Legislature approved Assembly Bill 1496 (AB 1496), which requires the California Air Resources Board (CARB) to monitor and measure high methane emission hotspots within the state using the best available scientific and technical methods. In order to meet the requirements under AB 1496, CARB, in conjunction with the California Energy Commission (CEC), has funded a large-scale statewide aerial methane survey conducted by NASA Jet Propulsion Laboratory (JPL) to detect and identify methane super emitters which may be a large contributor to the regional methane hotspots. CARB has also funded Scientific Aviation to quantify emission fluxes from various methane sources (including super emitters) with airborne measurements. There are several other relevant California bills such as AB32 and SB32, requiring a reduction in greenhouse gases of 40% by 2030 and SB1383 requiring a 40% reduction in methane and a 75% reduction in organic waste disposal from 2014 levels by 2025.

Furthermore, certain emissions from oil and gas facilities, which are also major methane emitters, are known to have potential adverse health effects. Oil and gas operations are located across California, including densely populated areas and in proximity of disadvantaged communities. In order to meet CARB's mission to protect the public from harmful effects of air pollution, there have been efforts to enhance the community monitoring for air toxics and methane, particularly in the communities near oil and gas facilities, which are primarily disadvantaged communities. The CARB Program Study of Neighborhood Air Near Petroleum Sources (SNAPS) is one such project. The recently approved AB 617 will also require air districts to develop community monitoring plans to identify disadvantaged communities for community monitoring deployment. It will also require CARB to develop a cumulative impact state strategy to identify communities with high cumulative risk so air districts can develop Community Action Plans.

The mapping of the above-mentioned emissions is generally difficult to carry out since they correspond to diffuse emissions from numerous sources and activities. In this project we used unique mobile optical techniques and a measurement methodology that has been developed for real time remote quantification and characterization of point and diffuse emission sources. This has made it possible to capture facility level emissions, measure co-pollutant emissions, and capture large, spatially extensive or distributed operations with diffuse emissions. These measurements allow better understanding of real-world emissions of complex sources, and will aid in developing better emission control strategies.

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 MWDOAS (Mobile White cell DOAS). The emissions measurement methodology is described in the subsections below. The instrument systems are detailed more fully in Appendix A. 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. MeFTIR and MWDOAS both measure ground level concentrations (vehicle roof height, approx. 2 m) of alkanes and BTEX (benzene, toluene, ethylbenzene, and xylene) respectively.

Both concentrations and 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.r

Accurate wind data is necessary in order to compute gas emission fluxes. 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 setup and Figure 2 shows the mobile lab.

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 MWDOAS are then used to indirectly estimate the emissions for methane and BTEX.

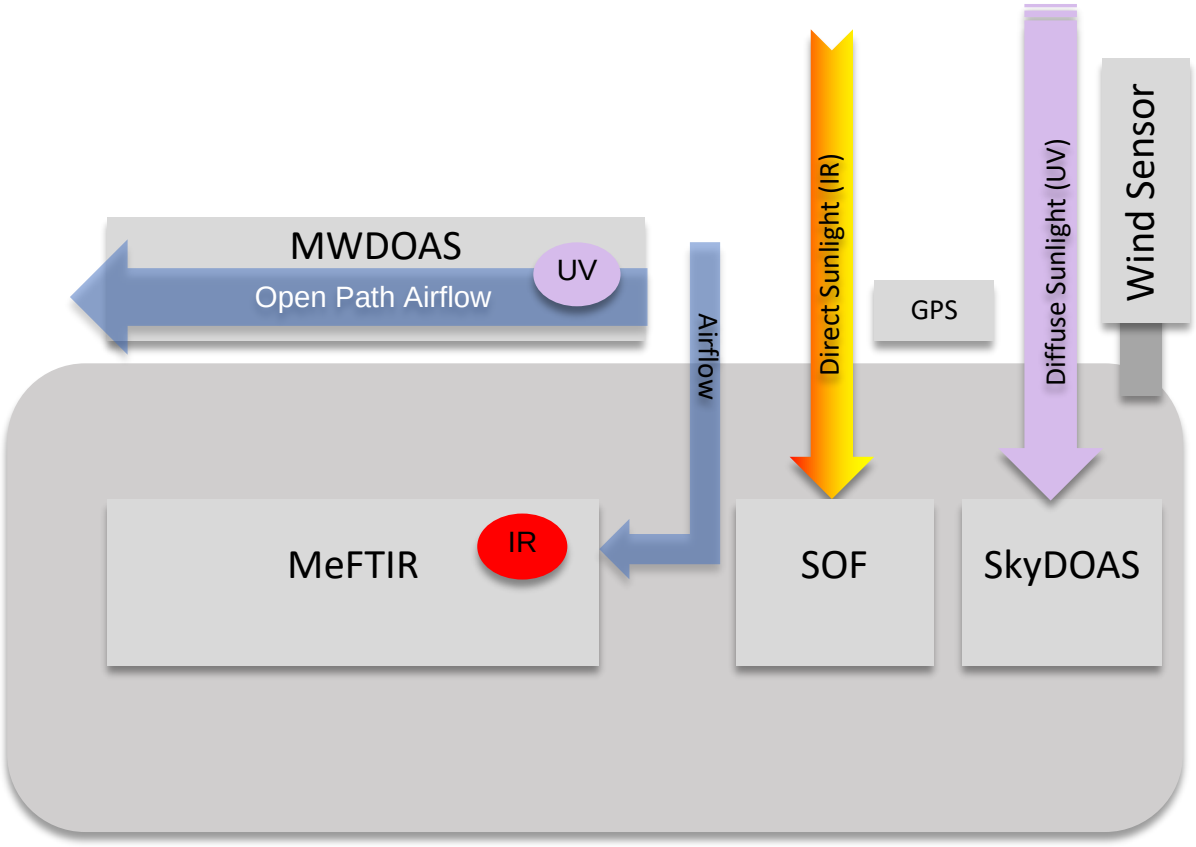

Figure 1. Overview of the mobile lab main instruments; SOF, MeFTIR, MWDOAS and SkyDOAS. SOF and SkyDOAS are column integrating passive techniques using the sun as the light source while MeFTIR and MWDOAS measure near ground-level concentrations using active internal light sources.

Figure 2. Internal and external view of the mobile lab.

Table 1. Summary of gas measurement techniques. *For typical wind conditions at an optimal distance from the source.

Method	SOF	Sky DOAS	MeFTIR	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 N_2O or C_2H_2 (tracer)	BTEX
Detection limit column	0.1-5 mg/m^2	0.1-5 mg/m^2	1-10 ppbv	0.5-3 ppbv
Detection limit Flux*	0.2-1 kg/h	1 kg/h	0.2-2 kg/h	0.2-2 kg/h
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 BTEX and methane fluxes are measured indirectly from MWDOAS/MeFTIR gas mass ratios.

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):

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

Where,

$\bar{v}_T$ = 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 or "boxed", 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/MWDOAS measurements. The indirect mass flux ($\hat{Q}^i$) for species (*i*) are calculated from MeFTIR and/or MWDOAS ground level gas ratios integrated over the plume (*P*) along path (*l*) are given by (units in brackets):

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

$\bar{Q}^j$ = 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 MWDOAS 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.

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.

Measurement Parameter	Analysis Method	Total Uncertainty
SOF column concentrations alkanes, alkenes, NH_3	SOF spectral retrieval	±10%
SkyDOAS column concentrations: NO_2, SO_2, H_2CO	DOAS spectral retrieval	±10%
MeFTIR concentrations: CH_4, VOC, NH_3, N_2O	SOF spectral retrieval	±10%
MWDOAS concentrations: BTEX, Benzene	MWDOAS spectral retrieval	±10%
SOF mass flux: Alkanes, alkenes, NH_3	**SOF flux calculations**	**±30%-40%**
SkyDOAS mass flux: NO_2, SO_2, H_2CO	**SkyDOAS flux calculations**	**±30%**
Indirect mass flux (e.g. BTEX, 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, diurnally and seasonal differences may bias this estimate and these biases are addressed in the relevant sections as these potential biases differ depending on the source.

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 to 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).

2.5 Field survey setups

2.5.1 Survey A – Bay Area

Mobile measurements with SOF, SkyDOAS, MWDOAS, and MeFTIR were carried out during 18 measurement days between Oct 4 and Oct 24, 2018 in the Bay Area, California (Figure 3). The focus was on industrial VOC emissions from refineries, petrochemical industry, oil storage, port activities and landfills. It also included investigating the impact of various sources on the concentration levels in Richmond.

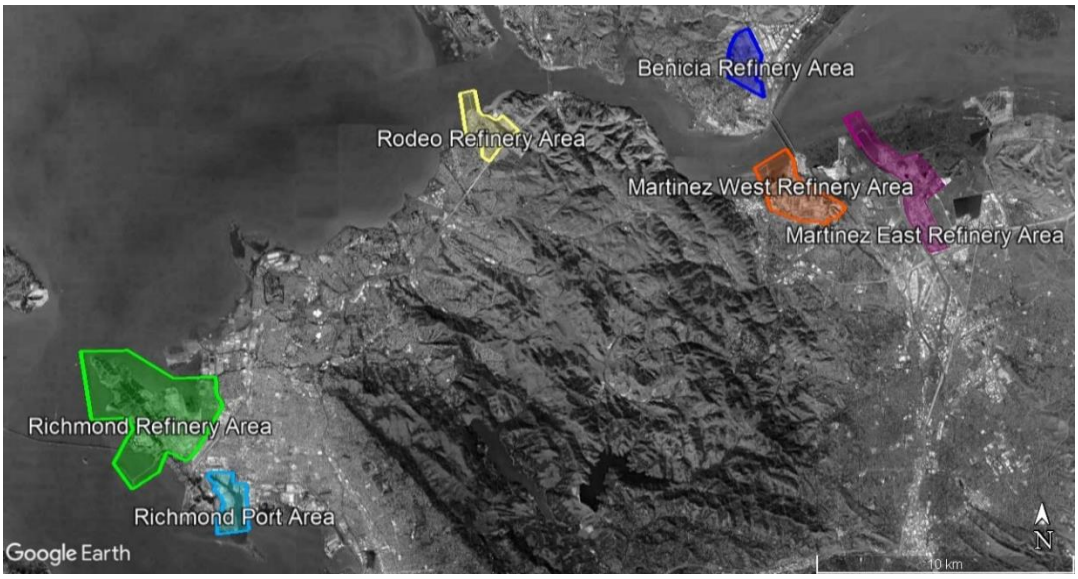

Figure 3. The primary sites in the Bay Area that were studied in the emissions survey A during Oct, 2018. Refinery areas typically included additional industries that were inseparable from the primary refinery source during the emissions survey.

2.5.2 Survey B – San Joaquin Valley, oil and gas production

Mobile measurements with SOF, SkyDOAS, MWDOAS, and MeFTIR were carried out during 4 measurements days in 2018 (Sep 30 - Oct 2 and Oct 25 - Oct 26) and 18 measurement days in 2019 (Apr 27 - May 19) in Kern County, California (Figure 4). 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. Two additional days (May 26-27, 2019) measurement of industrial sources were made within the Port of Stockton.

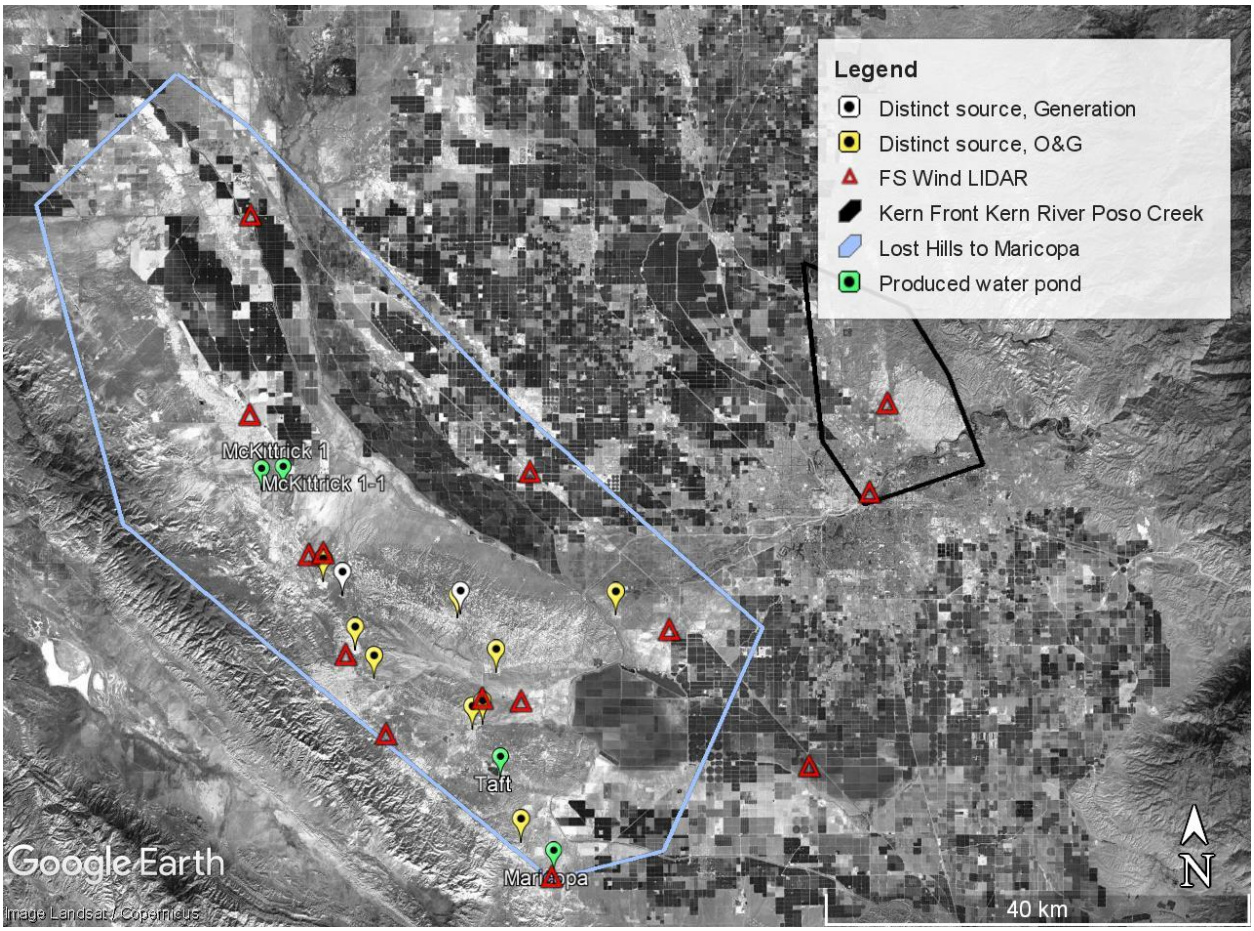

Figure 4. The primary oil and gas areas in the San Joaquin Valley that were studied in the emissions survey B during May 2019 and October 2018. The polygon to the left incorporates the fields of Lost Hills, Belridge, Cymric, McKittrick, Elk Hills, Midway-Sunset and Buena Vista. The polygon to the right incorporates Poso Creek, Kern Front, Kern River, Round Mountain and Mount Poso. In addition to the fields themselves, processing facilities and power generation facilities were also surveyed.

2.5.3 Survey C – San Joaquin Valley, dairy farms

Dairy farm measurements were made with SOF and MeFTIR on 12 days in May 2019 in the southern half of San Joaquin Valley around Bakersfield, Tulare and Merced. Complementary measurements with MWDOAS and SkyDOAS were made on a total of 4 and 6 days, respectively.

The dairies were divided into three main regions: Bakersfield, Tulare, and Merced (Figure 5). Nine (9) dairies were studied in the Bakersfield area, 11 in the Tulare region and 3 in Merced, representing more than 150,000 animal units (AU, mature animals represent 1 AU, heifers 0.75 AU and calves 0.17 AU). The number of animals was obtained from the San Joaquin Valley Air Pollution Control District (ValleyAir, Personal communication, 2019), corresponding to mature cows, replacement heifers and calves.

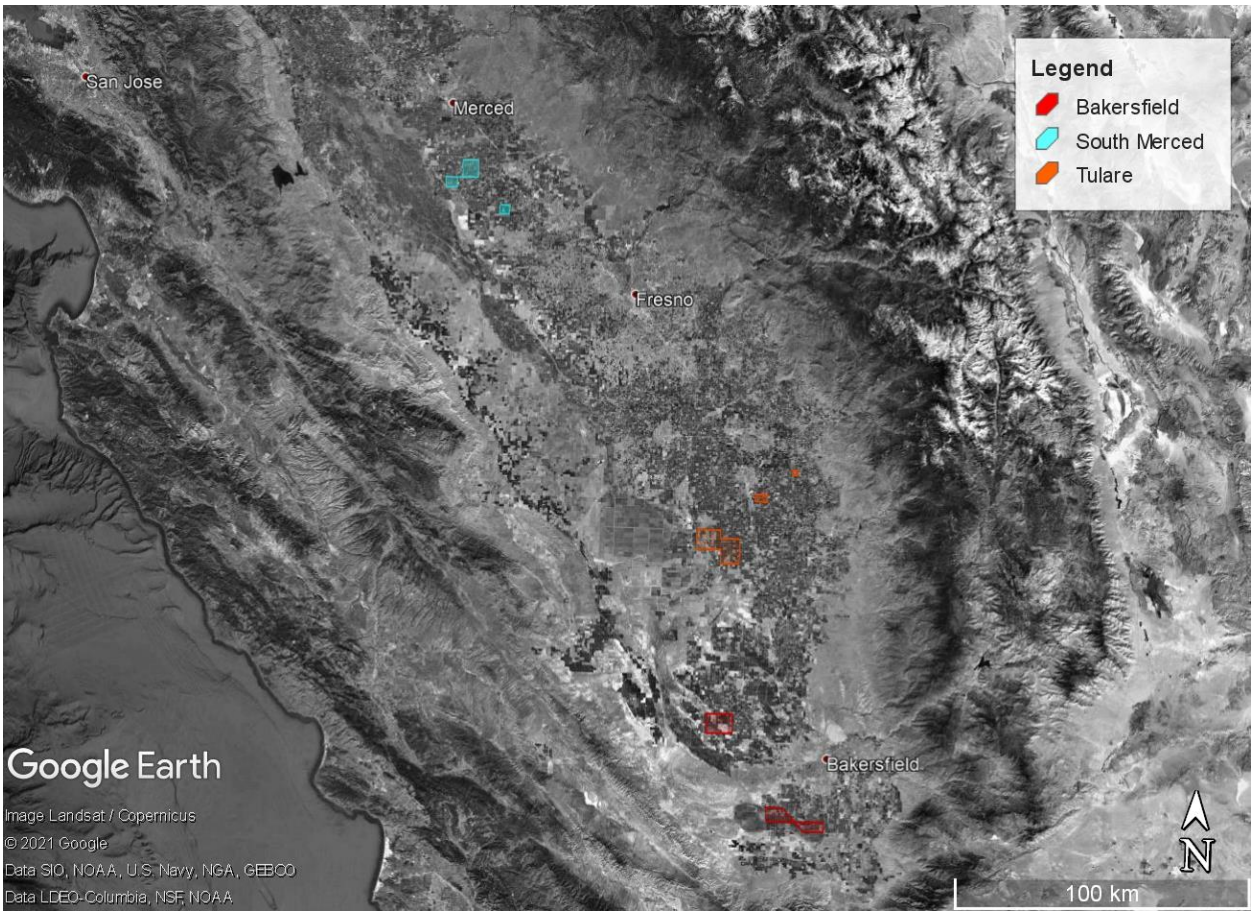

Figure 5. Three dairy farm measurement areas in the San Joaquin Valley during survey C. Map from Google Earth™, 2021.

2.5.4 Survey D – South Coast Air Basin and San Diego Air Basin

Mobile measurements with SOF, SkyDOAS, MWDOAS, and MeFTIR were carried out during 10 measurements days in 2019 (Oct 22 to Oct 31) in three different regions:

1. San Diego Air Basin, see Figure 6.
2. South part of South Coast Air Basin, see Figure 7.
3. North part of South Coast Air Basin, see Figure 8.

A variety of sources were studied, including oil and gas production, gas/liquid fuel storage, breweries and landfills. In addition, emissions from the port and airport were measured.

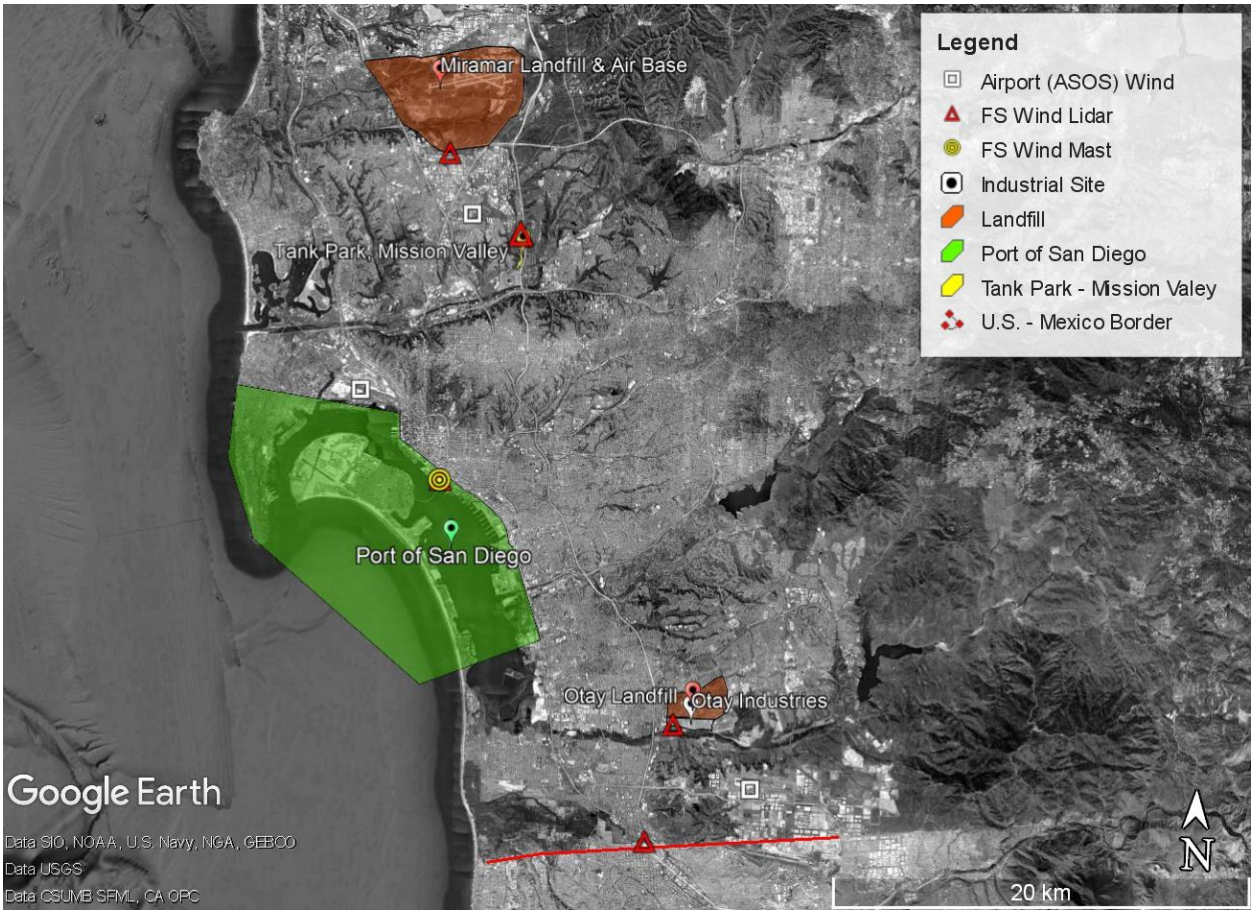

Figure 6. Measured areas in the San Diego Air Basin during survey D, Oct, 2019. Map from Google Earth™, 2020.

Figure 7. Measured areas in the south part of the South Coast Air Basin during survey D, Oct 2019. Map from Google Earth™, 2020.

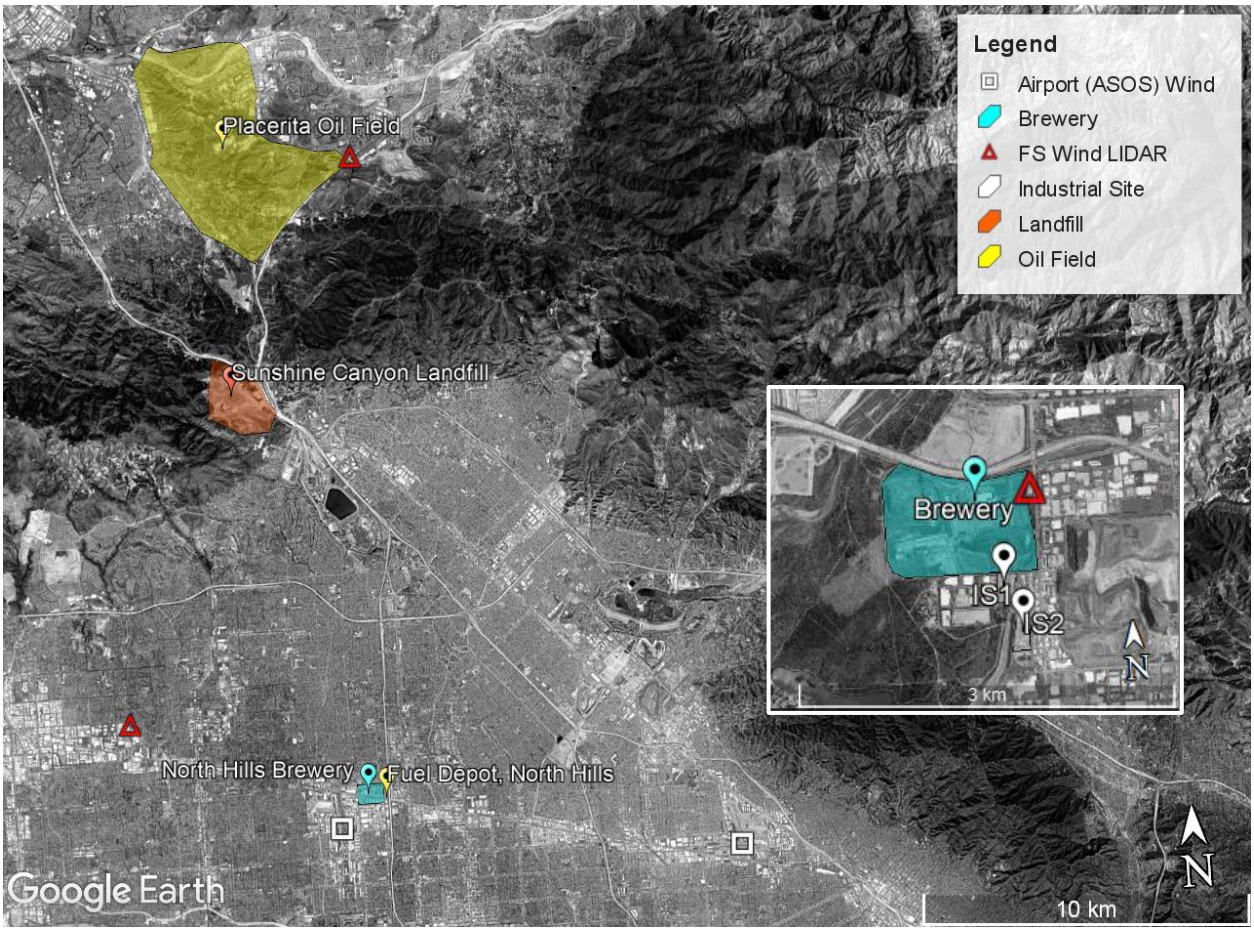

Figure 8. Measured areas in the north part of the South Coast Air Basin during survey D, Oct 2019. Inset Irwindale industrial sites (IS) and brewery. Map from Google Earth™, 2020.

3 RESULTS

The field campaigns were conducted over 3 periods from 2018 to 2019. Summary results are presented according to the geographical areas and/or source types (refineries, oil and gas production, dairy farms) for the sub-projects within the study in their respective sections. Complete results are presented in the individual sub-project reports included as appendices to this document.

3.1 VOC Emissions and VOC concentration mapping in the Bay Area (survey A)

Measurements were made over a period of 4 weeks in October 2018 with 18 days of measurements primarily focused on refineries and the city of Richmond. An additional 5 days during this period were allocated to measurements in the San Joaquin Valley.

3.1.1 VOC and methane emissions from refineries and the Port of Richmond (survey A)

VOC and methane emissions were measured from the 5 largest refineries in the area and the Port of Richmond. These sites were the primary focus of the emissions measurement portion of the sub-project. Measurements for each site encompassed between 2 to 5 days of total facility emissions for alkanes, SO_2, NO_2, H_2CO, BTEX and CH_4. An example of a SOF measurement is shown in Figure 9.

Figure 9. Example of a SOF measurement of alkane emissions at the Rodeo refinery area, survey A, Oct 12, 2018, 2 PM. The apparent height of the blue overlay is proportional to the alkane column. Wind direction during the measurement shown with a white arrow. Map from Google Earth™ 2021.

Results from the direct emission measurements are shown in Table 3. Aggregated average NMVOC emissions for the 5 major refineries were more than 1000 kg/h. Results of the indirect measurements are shown in Table 4. Benzene and BTEX emissions for the refineries and port areas totaled 13 and 109 kg/h, respectively. Methane emissions from these sources were approximately 440 kg/h.

Table 3. Results of the SOF and SkyDOAS emission measurements for the 5 refineries in the Bay Area and Port of Richmond (survey A). *D and N for SO_2 retrievals. NO_2 and H_2CO have similar number of days (D) and measurements (N).

Source	**D**	**N**	**NMVOC** kg/h	**CI 95%** kg/h	**D**	**N**	**SO_2** kg/h	**CI 95%** kg/h	**NO_2** kg/h	**CI 95%** kg/h	**H_2CO** kg/h
Martinez E refinery	3	8	151	140 – 161	3	11	60	30 – 90	69	60 – 79	<5
Richmond refinery	4	16	291	248 – 335	3	9	105	34 – 175	113	83 – 142	<5
Rodeo refinery	2	17	143	118 – 168	2	9	11	8 – 14	34	19 – 49	<5
Martinez W refinery	4	15	334	249 – 419	3	14	200	159 – 240	104	85 – 122	<10
Benicia refinery	4	20	144	124 – 165	3	13	20	15 – 25	84	66 – 102	<5
Sum Refineries			**1063**				**395**		**404**		**-**
Richmond port	5	40	90	78 – 102	2	7	4	1.5 – 6	33	22 – 44	<5

Table 4. Results of the indirect emission measurements based on SOF, SkyDOAS, MeFTIR and MWDOAS for the 5 refineries in the Bay Area and Port of Richmond (survey A).*Limited number of measurements.

Refinery Area	**D**	**N**	**CH_4/ NMVOC**		**CH_4** kg/h	**D**	**N**	**BTEX/ NMVOC**	**BTEX** kg/h	**C_6H_6/ NMVOC**	**C_6H_6** kg/h
			Med	**IQR**							
Martinez E	3	6	0.36	0.32 – 0.53	54	Not available					
Richmond	4	10	0.36	0.27 – 0.50	105	2	2	0.14	40*	0.017	6.1*
Rodeo	4	17	0.31	0.20 – 0.56	44	1	2	0.12	17*	0.014	2.0*
Martinez W	5	17	0.47	0.37 – 0.58	157	3	7	0.092	31	0.010	3.3
Benicia	3	16	0.48	0.39 – 0.61	69	2	6	0.82	12	0.07	1.0
Sum Refineries					**430**				**100**		**12.4**
Richmond port area	6	33	0.13	0.094 – 0.26	12	3	10	0.097	9	0.07	0.6

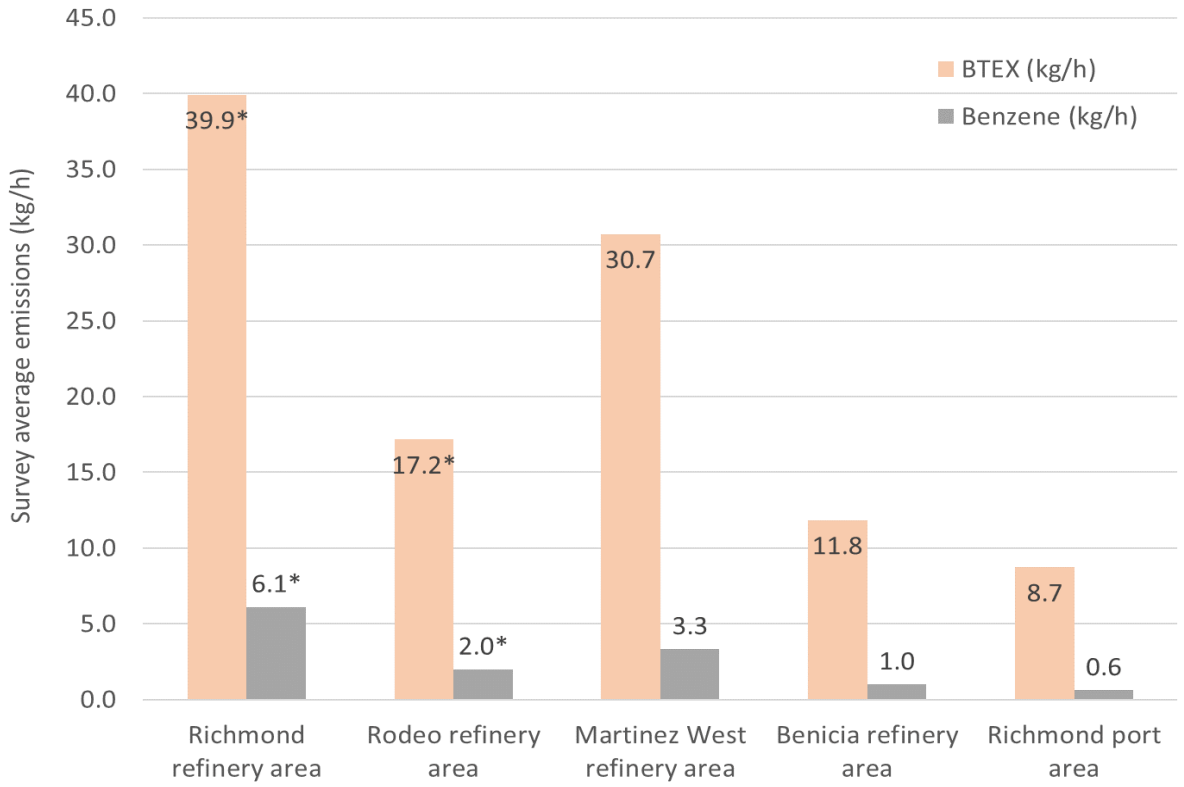

Figure 10. BTEX and benzene emissions for the Bay Area survey A measured indirectly from the ground-level ratio of BTEX (benzene, toluene, ethylbenzene and xylene) to alkanes and benzene to alkanes multiplied by the SOF alkane flux. *Limited number of samples.

3.1.2 VOC and methane emissions from other area and point sources in the Bay Area (survey A)

As part of the screening process, many other smaller area and point sources such as terminals, depots, and oil and gas storage, were also measured although with a lower repeat frequency or on a single day for remote sites. The remote sites included the Port of Stockton, McDonald Island and the Potrero Hills Landfill. The Port of Stockton was revisited in 2019. The survey also included a propane facility in Richmond, various terminal sites, and a sulfuric acid recovery plant. Emission results are summarized in Table 5. In addition to the normally targeted gases, ethanol emissions from an ethanol producer in Stockton were also measured.

Table 5. Summary of emission screening results from other select areas and point sources measured during the Bay Area survey A. Insufficient statistics for aromatic emissions and NO_2, SO_2, and H_2CO were not evaluated for some sites (blank). *Insufficient statistics. ** Indicative of significant emissions but no quantification due to wind direction.

Source	**N**	**NMVOC** kg/h	**CI 95% NMVOC** kg/h	**N**	**SO_2** kg/h	**CI 95% SO_2** kg/h	**NO_2** kg/h	**CI 95% NO_2** kg/h	**H_2CO** kg/h	**CH_4** kg/h
Port of Stockton	3	84	42 - 130	1	18.5	-	65	-	0.5	*
Gas storage, McDonald Island	4	26	15 - 38	Not Measured						*
Martinez tank farm and terminal	9	86	29 - 143							*
Propane facility, southeast Richmond	5	9.5	1.4 – 18							*
H_2SO_4 regeneration plant, Martinez	-	*	*	5	102	66 - 140	5	3 – 7	-	*
Richmond Long Wharf Terminal	-	**	-	Not Measured						*
Potrero Hills Landfill	7	76	58 - 94							860

3.1.3 Community monitoring and concentration mapping primarily in disadvantaged areas (survey A)

Ground level concentrations of NMVOCs, methane, and aromatics were measured at all the refinery fencelines and extensively within the City of Richmond. Results of the alkane concentrations mapping in Figure 11 show on average highest concentrations in the port, at least partly due to vicinity to the source. However, as can be seen in Figure 12, this plume also affects Richmond in southerly winds. Concentrations at the refinery fencelines were relatively low, both a factor of the meteorology at the time and the distance to the sources, however their total emissions of BTEX are greater than the port. The result of the BTEX mapping for the south of Richmond including the port is shown in Figure 13.

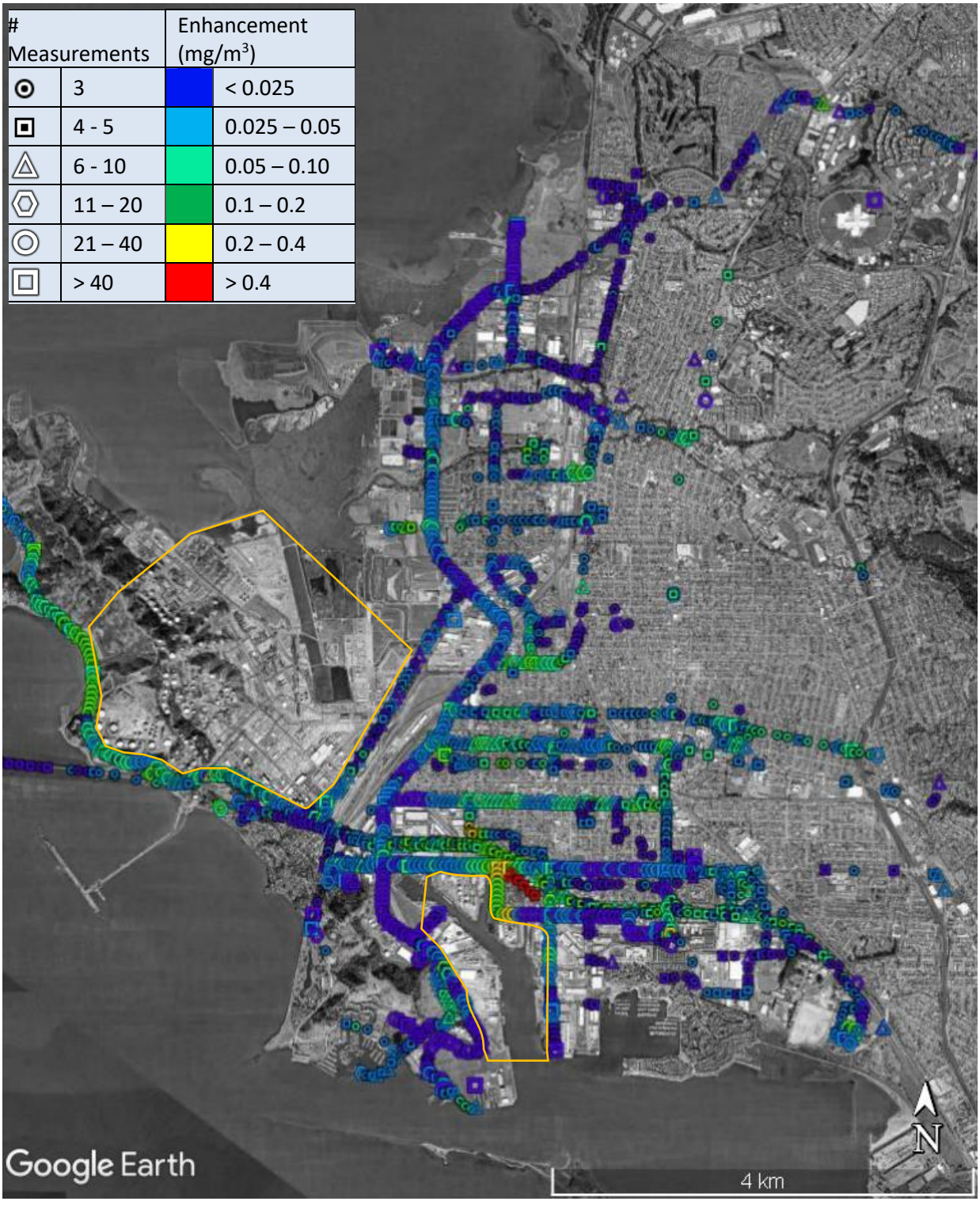

Figure 11. Concentration map of alkanes in Richmond for the Bay Area survey A, October 2018. Number of measurements (min. 3) within an approximately 50 x 50 m grid cell and mean alkane enhancement within the cell. Areas outlined in orange show approximate boundaries for the refinery (northwest) and port (south) areas. Map from Google Earth™, 2018.

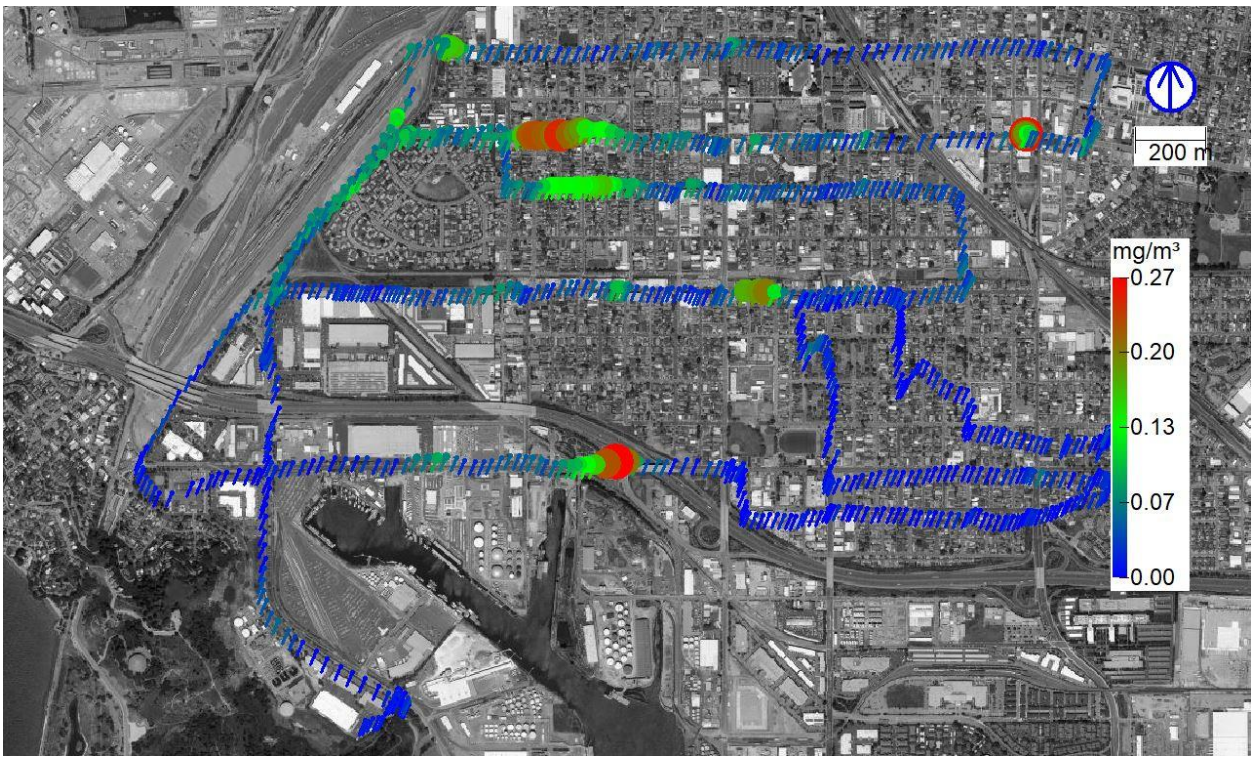

Figure 12. Tracking the VOC (alkane) plume from the Port of Richmond into the Richmond community using MeFTIR (survey A). Marker size and color show concentration with a line point in the upwind direction toward the source. Daytime measurement. October 20, 2018.

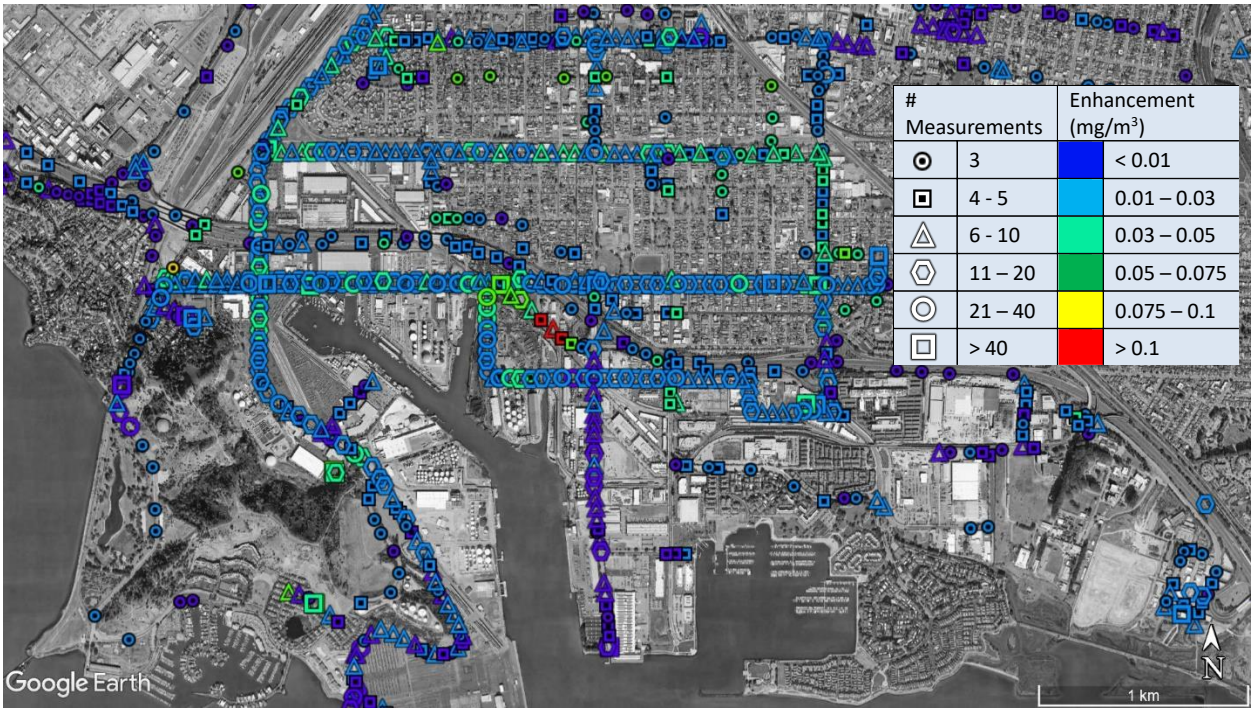

Figure 13. Concentration map of BTEX in Richmond (survey A), number of measurements (min. 3) within an approximately 50 x 50 m grid cell and mean BTEX enhancement within the cell. October 2018. Map from Google Earth™, 2018.

3.2 San Joaquin Valley - oil and gas production (survey B)

Measurements during the 2018 campaign indicated high alkane and methane emissions from the oil and gas fields in the SJV near Bakersfield and these were measured extensively during the second campaign in May 2019, along with community monitoring in disadvantaged areas within the survey. Figure 14 shows a large-scale measurement of alkane emissions from the Elk Hills survey area made during the second campaign. A summary of VOC and methane emissions for the major oil fields in the area is given in Table 6 and Table 7, respectively. Results for several point sources are summarized in Table 8.

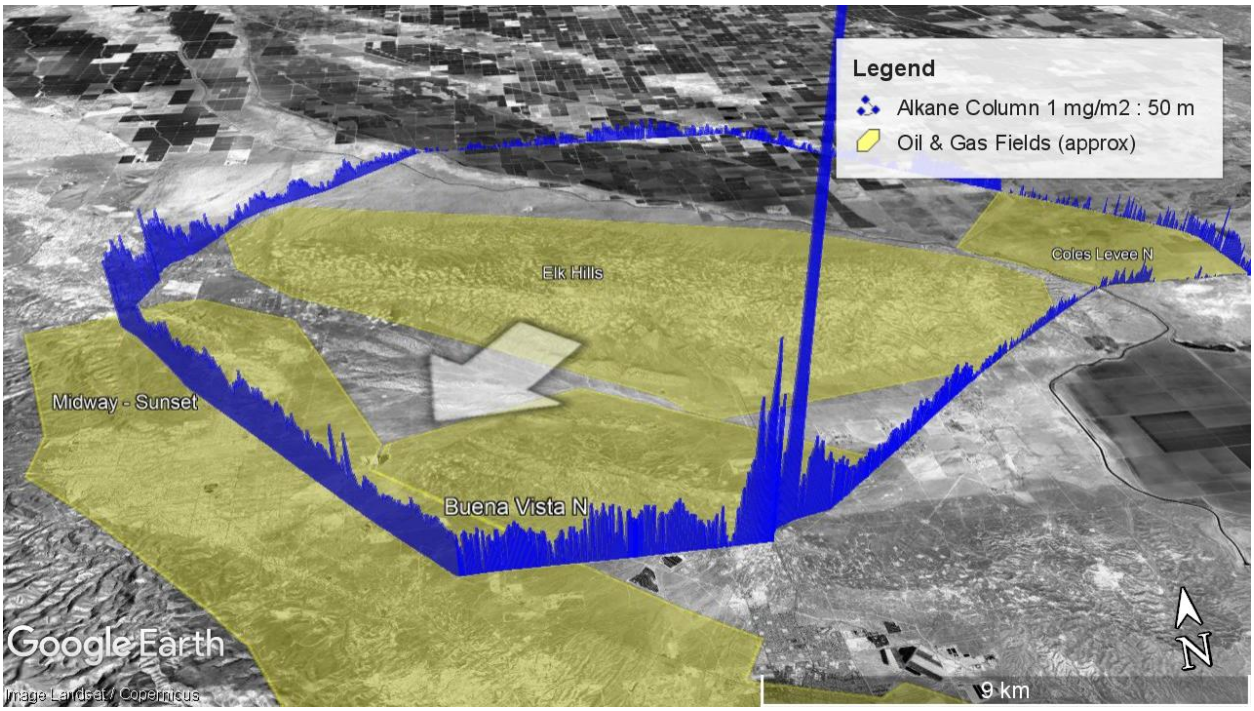

Figure 14. Alkane emission measurement around Elk Hills (survey B) with north-easterly winds, May 1, 2019, 13:35 – 15:14. SOF alkane column (apparent height of blue overlay) had a maximum of 341 mg/m2, near a source in Buena Vista. White arrow shows average wind direction during the measurement. Highlighted areas show approximate field boundaries for Elk Hills, Midway-Sunset, Coles Levee N and the northern portion of Buena Vista. Map from Google Earth™, 2021.

Table 6. Results of the SOF NMVOC emission measurements for oil and gas fields in the SJV (survey B). D is the number of measurement days, N is the number of measurement transects.

Area (fields and associated facilities)	**D**	**N**	**NMVOC** kg/h	**CI 95%,** kg/h
Elk Hills	8	13	3470	2980 – 3970
Poso Creek & Kern Front	3	5	440	210 – 680
Coles Levee North	3	5	250	200 – 300
Cymric & McKittrick	3	7	1230	790 – 1680
Lost Hills	4	6	780	460 – 1110
Belridge	2	4	1480	800 – 1970
McKittrick	3	4	320	130 – 500

Table 7. Methane emissions from oil and gas fields in the San Joaquin valley from SOF and MeFTIR measurements. Indirect emissions calculated from median ratio and SOF NMVOC flux therefore interquartile range (IQR) is given instead of CI. D is the number of measurement days, N is the number of measurements.

Area (fields and associated facilities)	**D**	**N**	**CH_4/NMVOC mass ratio**		**CH_4** kg/h
			Median	IQR	
Elk Hills	2	4	1.35	1.25 – 1.49	4820
Poso Creek & Kern Front	3	4	1.08	0.71 – 1.42	470
Coles Levee North	Not Available				
Cymric & McKittrick	5	10	1.25	1.06 – 1.35	1470
Lost Hills	2	4	0.42	0.38 – 0.46	330
Belridge	3	3	0.53	0.43 – 0.71	860
McKittrick	Not Available				

Table 8. Results of the NMVOC emission measurements for specific sources in the SJV oil and gas field survey B. Note that most of these localized source emissions are also included in the reported overall O&G field emissions. Treatment site refers to unspecified processing/treatment facility.

Area (fields and associated facilities)	**D**	**N**	**NMVOC** kg/h	**CI 95%,** kg/h
Produced water ponds McKittrick 1-1	2	4	14	6-22
Treatment site, Buena Vista, Highway 119	6	23	220	150-290
Treatment site, Elk Hills Road & 119, Elk Hills	2	4	37	0-91
Facilities directly east of Derby Acres (persistent sources)	3	4	319	0-968
Power Generation Elk Hills Road	1	3	69	39-99
Treatment Site, Elk Hills Rd/Skyline Rd	1	3	58	21-95
Refinery, Bakersfield	2	6	36	26-46

Table 9. Results of methane emission measurements for specific sources in the SJV oil and gas field survey B. Note that most of these localized source emissions are also included in the reported overall O&G field emissions. Treatment site refers to unspecified processing/treatment facility. D is the number of measurement days, N is the number of measurements.

Area (fields and associated facilities)	**D**	**N**	**CH_4/NMVOC mass ratio**		**CH_4** kg/h
			Median	IQR	
Produced water ponds McKittrick 1-1	2	7	0.64	0.28 – 0.82	8.7
Treatment site, Buena Vista, Highway 119	7	13	1.5	0.11 – 2.3	470
Treatment site, Elk Hills Road & 119, Elk Hills	Not available				
Facilities directly east of Derby Acres (persistent sources)	6	18	4.3	2.4 – 6.2	1362
Power Generation Elk Hills Road	1	2	1.5	1.4 – 1.5	102
Treatment Site, Elk Hills Rd/Skyline Rd	Not available				
Refinery, Bakersfield	Not available				

3.3 San Joaquin Valley – community monitoring (survey B)

Concentrations measurements of NMVOCs, methane and BTEX were made in 7 different communities over 7 days during the May 2019 campaign (Table 10). Examples of these measurements for Highland Knolls and Meadow View are shown in Figure 15 (BTEX) and Figure 16 (methane and alkanes). Methane measurements indicated a large inflow from the oil fields and there were no corresponding plumes of alkanes or aromatics. No hot spots for BTEX were found during these concentration measurements.

Table 10. Community monitoring of VOCs in the SJV survey B.

Area	**Date (all 2019)**
Highland Knolls and Meadow View, Bakersfield	May 2, May 17
Derby Acres	May 12
Lost Hills	May 14
Alon refinery and adjacent communities Quailwood and Park Stockdale	May 18
Port of Stockton	May 26 and 27
Covanta Stanislaus in Patterson	May 27, unfavorable wind

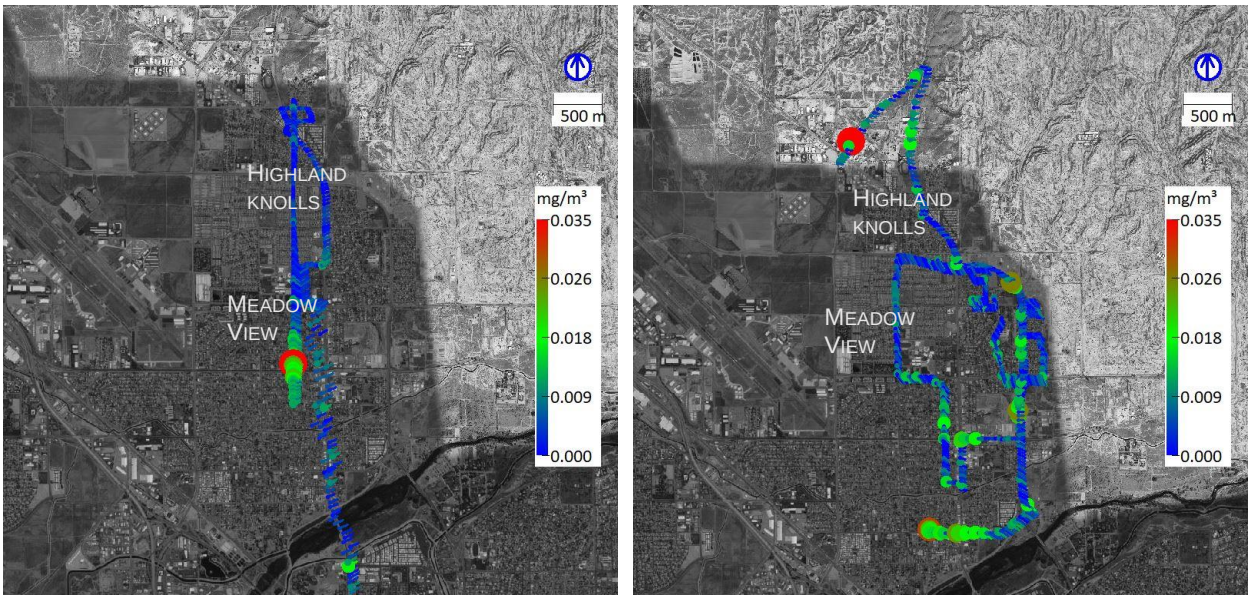

Figure 15. SJV BTEX concentration community monitoring measurements in the Bakersfield communities of Highland Knolls and Meadow View (survey B), May 2, 2019, 22:33 – 23:18 (Left) and 23:31 – May 3, 00:39 (Right). Color scale and point size show BTEX concentrations (mg/m^3) and the lines point in the instantaneous wind direction.

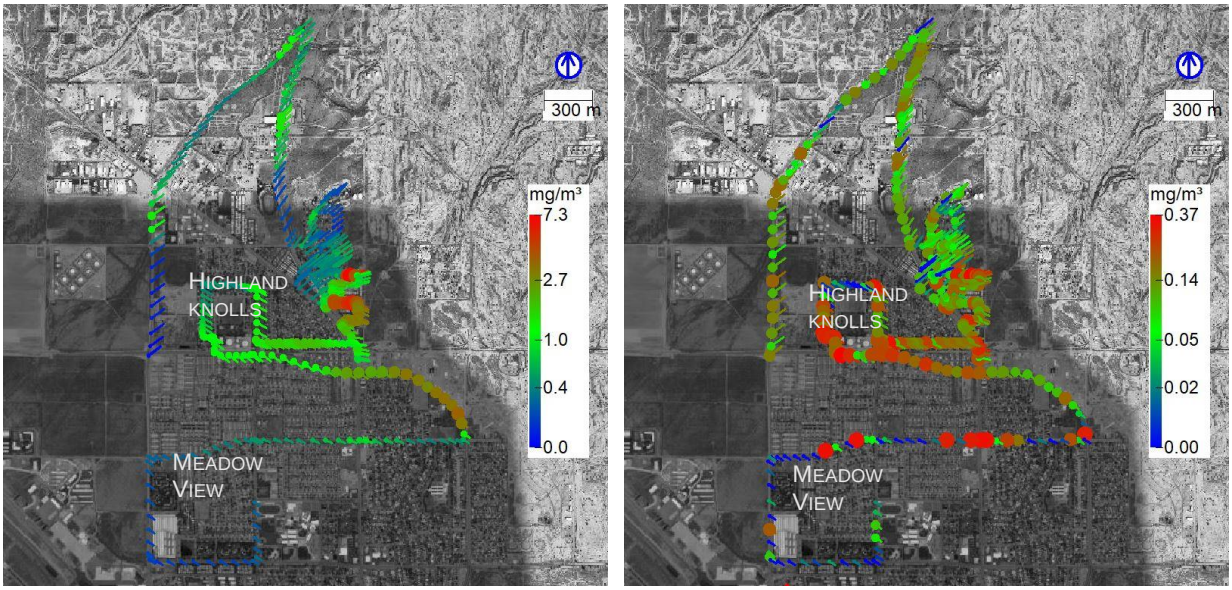

Figure 16. SJV methane and alkane concentration community monitoring measurements in the Bakersfield communities of Highland Knolls and Meadow View (survey B), May 17, 2019, 21:56 – 23:00. Color scale and point size show methane (left) and alkane (right) concentrations (mg/m^3) and the lines point in the instantaneous wind direction. Color scale is logarithmic.

3.4 San Joaquin Valley - gas emissions from CAFOs (survey C)

Ammonia and methane emissions from more than twenty of the San Joaquin Valley's large dairy farms were measured. Table 11 summarizes methane and ammonia emissions measured from 16 dairies located in 3 main regions in the San Joaquin Valley: Bakersfield, Tulare and Merced. The dairy farms are designated according to their location and the order that they were measured. Sites that are excluded from the summary statistics due to an insufficient number of measurements are still found in the report. Overall ammonia emissions of 1650 kg/h and methane emissions of 6630 kg/h were measured, with corresponding dairy averages of 103 and 414 kg/h respectively, although with large variability among the dairies.

Table 12 presents measured emission factors in g $head^{-1}$ h^{-1}, for methane (49.9 g CH_4 $head^{-1}$ h^{-1}) and ammonia (11.7 g NH_3 $head^{-1}$ h^{-1}) by facility calculated from the most recent animal data available for the farms. The number of animals corresponds to mature cows, replacement heifers and calves, and calculated in terms of animal unit (here mature animals correspond to one animal unit, heifers to 0.75 and calves to 0.17). Figure 17 shows the ammonia emission factors along with degree of variability for each facility. In addition to ammonia and methane, emissions of some other species were observed. Enhanced ethanol concentrations were observed at three sites, and acetic acid at one of these dairies. Plume concentrations of ethanol at two of these, WT01 and WT04, averaged about 30 times lower than ammonia (26.7 and 36.2 respectively). The higher ethanol concentrations were correlated with the feeding areas and were only found at facilities where favorable wind conditions and nearby road access allowed for close downwind measurements of this area of the farm(s). Some enhanced concentrations of nitrous oxide were detected from fertilized fields adjacent to the farms. Plumes of NO_2 were found downwind a farm south of Bakersfield. These emissions averaged 23.5 kg/h (CI 95%: 15.7-31.3 kg/h). However, it was not determined whether the emissions originated from a combustion source on site or were of biological origin, due to site access restrictions.

Table 11. Results of the SJV dairy farm emission measurements based on SOF, SkyDOAS, MeFTIR (survey C). For ammonia, D is the number of measurements days and N is the number of measurement transects for the direct flux measurements. For methane, D and N represents number of days and transects for the CH_4 to NH_3 concentration ratio measurements, respectively.

CAFO	**NH_3 (kg/h)**				**CH_4 (kg/h)**			
	D	**N**	**Average**	**CI 95%**	**D**	**N**	**Average**	**CI 95%**
SB02	3	7	107	68 – 146	1	3	548	0 – 1110
SB03	3	9	120	73 – 167	1	3	385	0 – 890
SB04	3	10	61	42 – 80	3	9	214	100 – 330
SB05	2	8	114	80 – 152	2	9	514	280 – 740
NB01	2	7	70	17 – 122	2	5	392	0 – 860
NB02	2	9	104	61 – 147	1	4	675	0 – 1400
WT01	3	14	71	48 – 93	4	14	196	100 – 290
WT03	3	9	158	121 – 193	3	11	389	260 – 520
WT04	2	7	192	120 – 263	2	7	483	270 – 700
WT05	3	6	70	29 – 111	3	8	304	140 – 460
WT06	1	6	121	57 – 185	1	6	260	60 – 460
WT07	3	8	67	51 – 83	4	10	415	270 – 560
ET01	3	7	32	20 – 43	3	11	188	100 – 270
ET08	1	7	60	48 – 72	1	7	293	170 – 420
SM01	1	7	166	127 – 204	1	6	527	380 – 670
SM02	2	13	142	104 – 180	2	13	845	570 – 1120
Sum CAFOs			**1653**				**6626**	
Average			103				414	
Median			105				390	

[1] The dairy farms were designated according to their geographic location in San Joaquin Valley. "SB" stands for South Bakersfield, "NB" for North Bakersfield, "WT" West Tulare, "ET" East Tulare, and “SM" for South Merced.

Table 12. Emission factors for the SJV dairy farm measurements, emission per animal unit[2], by facility (survey C).

CAFO	NH_3 (g/head/h)		CH_4 (g/head/h)	
	Average	**CI 95%**	**Average**	**CI 95%**
SB02	6.0	3.8 – 8.2	30.5	0 – 61.6
SB03[1]	10.5	6.3 – 14.7	33.8	0 – 78.5
SB04	10.2	6.8 – 13.6	37.1	17.3 – 56.9
SB05[1]	18.3	11.7 – 24.9	82.9	45.9 – 119.9
NB01	8.8	2.1 – 15.5	49.3	0 – 108.8
NB02	12.9	7.5 – 18.3	83.6	0 – 173.3
WT01[1]	3.9	2.6 – 5.2	10.9	5.6 – 16.2
WT03	16.7	12.9 – 20.5	41.2	27.4 – 55
WT04	15.9	9.3 – 22.5	41.9	23.4 – 60.4
WT05[1]	12.2	5.2 – 19.2	52.7	24.9 – 80.5
WT06	14.6	6.8 – 22.4	31.3	6.8 – 55.8
WT07[1]	15.3	11.6 – 19	95.0	62.2 – 127.8
ET01	14.0	8.6 – 19.4	88.6	49 – 128.2
ET08[1]	4.1	3.3 – 4.9	20.0	11.5 – 28.5
Average CAFOs	***11.7***		***49.9***	
Median	*12.5*		*41.4*	
CI 95%	*10.4-13.8*		*39.8-81.2*	

[1] Farms with a methane collection cover. San Joaquin Valley region designation: SB – South Bakersfield, NB – North Bakersfield, WT – Western Tulare, ET – Eastern Tulare.

[2] 1 mature animal = animal unit, 1 heifer = 0.75 a.u., 1 calf = 0.17 a.u.

A factor of uncertainty in this study is the number of animals at each farm, used to calculate the emission factors. The animal data were obtained from inspections by the San Joaquin Valley Air Pollution Control District, and the numbers used on this report are from the last inspection 2017-2019, and that inspection did not include Merced farms. Since the number of animals on a particular farm fluctuates during the year the actual number of cows present at each farm in the measurement period is uncertain. In addition, at some farms, emissions upwind or from adjacent crop fields interfered with the measurements, e.g. the measurements at farm SB05. Figure 17 shows a distribution plot of ammonia emission factors obtained from the survey measurements in May 2019.

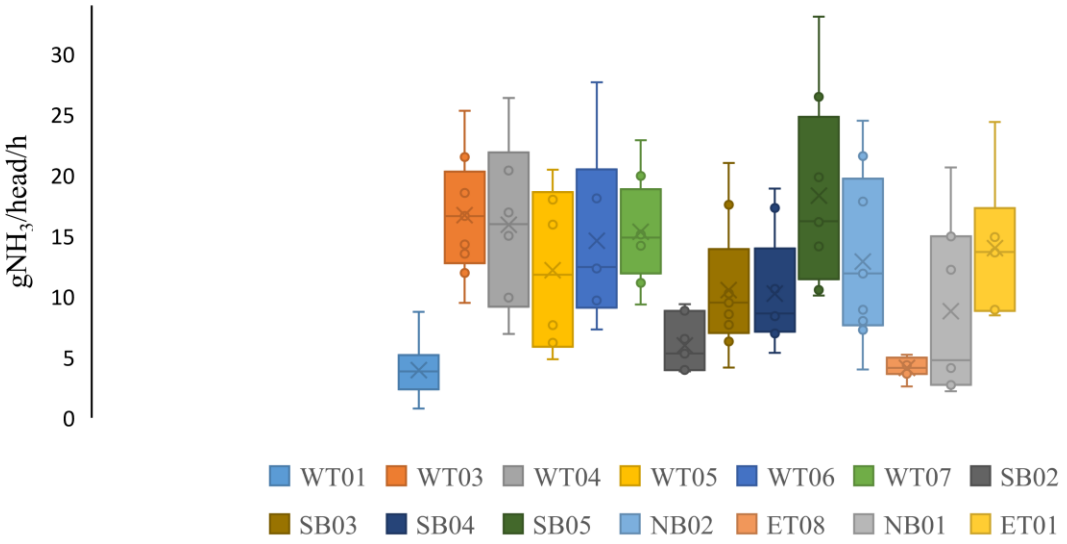

Figure 17. Ammonia emission factors obtained in the SJV dairy farm survey C. Displayed parameters: the minimum value, 25th percentile, median, mean, 75th percentile, maximum and individual values (filled circles).

3.5 VOC emissions measurements and community monitoring in South Coast Air Basin and San Diego Air Basin (survey D)

A summary of the quantitative results of emission measurements of 18 sites/areas in the three regions (San Diego Air Basin, north part of South Coast Air Basin and south part of South Coast Air Basin) is presented in Table 13. In this survey the objective was to screen many sources in several areas over a limited time frame, thus limiting the number of repeats on each site. Because of the limited number of measurements, the median emissions are reported for each site instead of the average.

Table 13 Summary of emissions measurements during the CARB survey D, 2019. Results are reported here as median emissions (Q) of the number (N) qualified transects to reduce sensitivity to outliers, n.d.= no detection. Results based on 3 or fewer measurements, should be considered indicative only. NA = not available.

	NMVOC		**SO_2**		**NO_2**		**CH_4**
San Diego County Region/Site	**N**	**Q** (kg/h)	**N**	**Q** (kg/h)	**N**	**Q** (kg/h)	**Q** (kg/h)
Mission Valley Tank Farm & Depot	7	27	1	n.d.	3	n.d	
Otay Landfill	6	47	Not measured				660
Otay Industry Sites	6	48					135
Miramar Landfill & Airbase	1	135					91
Port of San Diego	4	137	6	265	7	688	92
San Diego Airport	2	5.0	2	34	3	26	NA
South SCAB Region/Site							
Highlands Area Facility	7	31	Not measured				39
Huntington Beach Bolsa Area	11	31					23
Huntington Fuel Depot	5	4.8					0.6
Huntington Toronto Ave Well Site	7	4.3					6.8
Frank Bowerman Landfill	5	46					522
Coyote Canyon Landfill	5	n.d.					NA
North SCAB Region/Site							
North Hills Brewery	1	53	Not measured				NA
Irwindale Brewery	7	7.9					5.3
Irwindale Industrial Site 1	5	7.7					NA
Irwindale Industrial Site 2	4	3.4					NA
Placerita Oil Field	1	216					337
Sum	**805**		**299**		**715**		**1914**

In total, 153 measurement transects were made during 10 separate days. In this survey the objective was to screen many sources in several areas over a limited time frame, thus limiting the number of repeats on each site. The uncertainties are therefore larger than the 30%-40% which is the typical uncertainty for SOF measurements (Table 2). Figure 18 summarizes the alkane and methane emissions measured during survey D in October 2019.

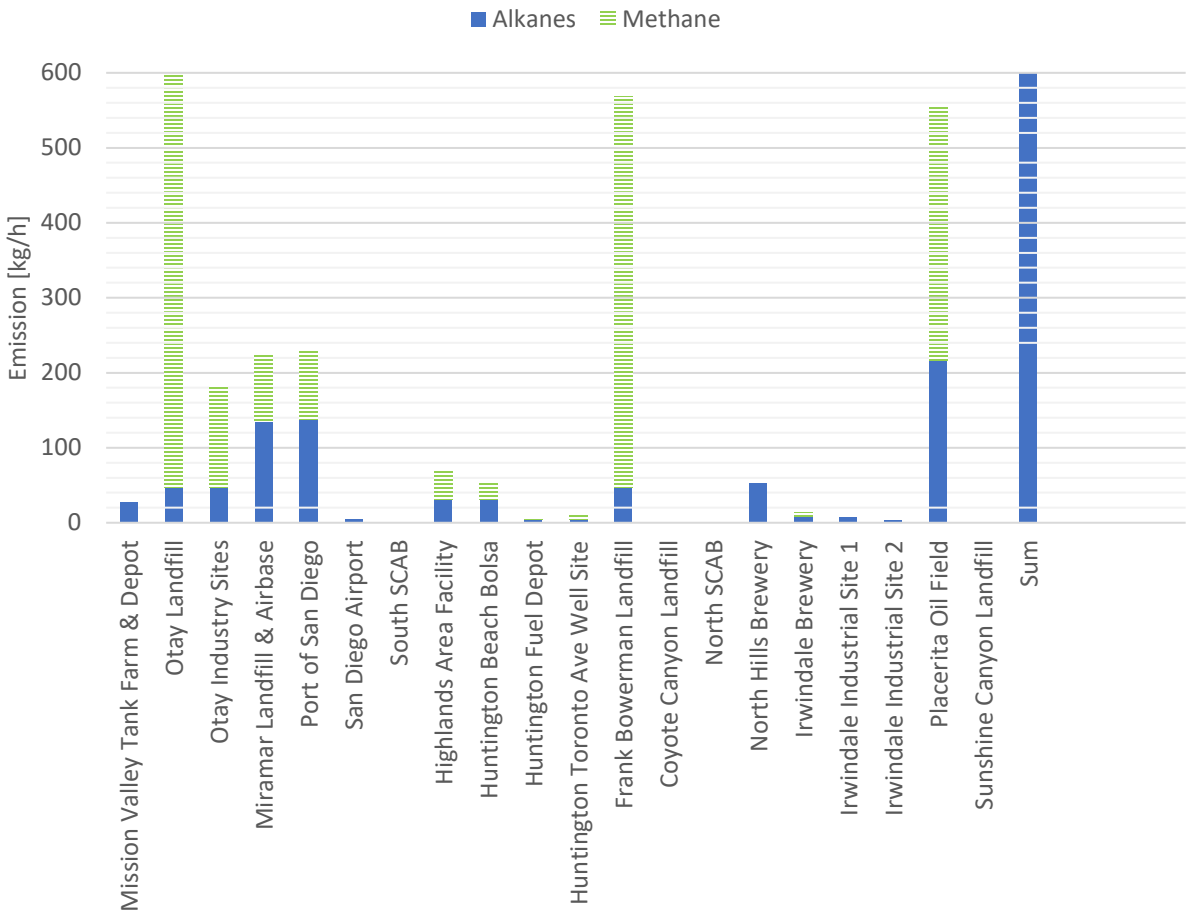

Figure 18. Median values of VOC emissions (alkanes and methane) from the sites during survey D 2019 as measured by the SOF, MWDOAS and MeFTIR instruments. Alkane emissions are measured directly while methane emissions are indirectly measured (IME) from gas ratios.

An example of measurements from this survey is shown for Huntington Beach area in Figure 19, with active wells in the area are indicated in Figure 20. About 90 kg/h of alkanes and 100 kg/h of methane were measured from the Highlands Area Facility.

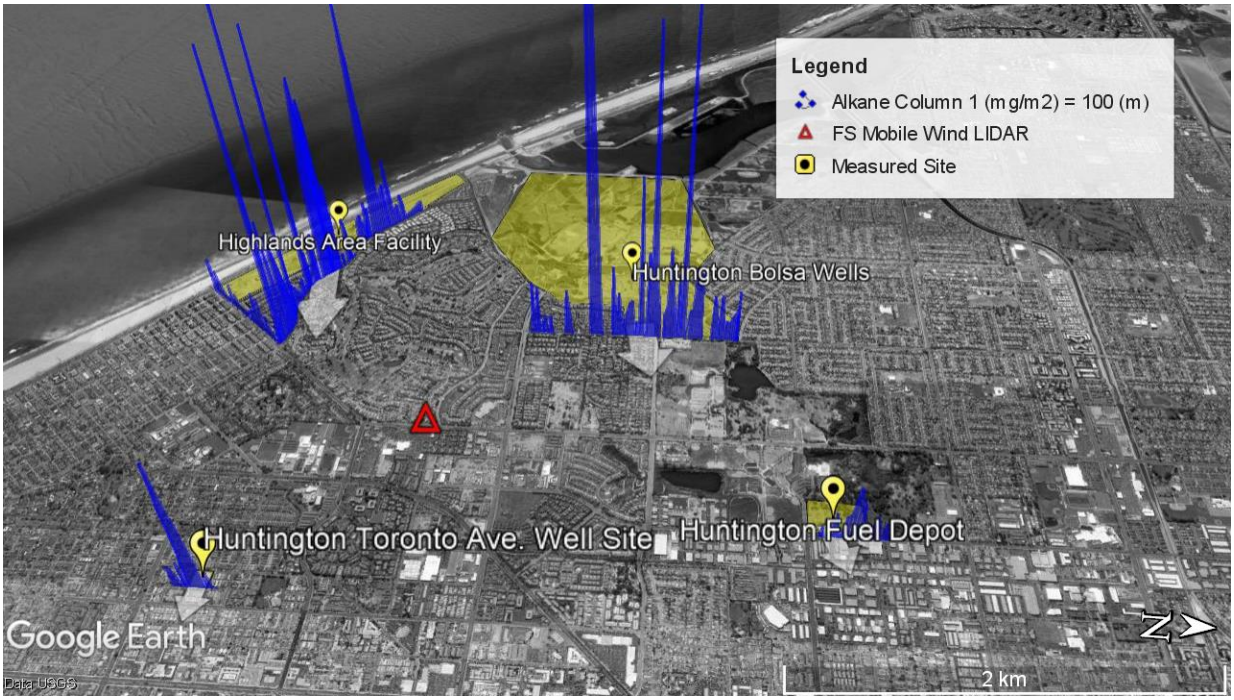

Figure 19. SOF alkane columns (blue overlay) from Huntington Beach sources (survey D), Oct 31, 2019. The figure is a composite of different measurement transects taken between 1:30 pm and 3:30 pm. The wind directions are indicated by the white arrows. Map from Google Earth™, 2020.

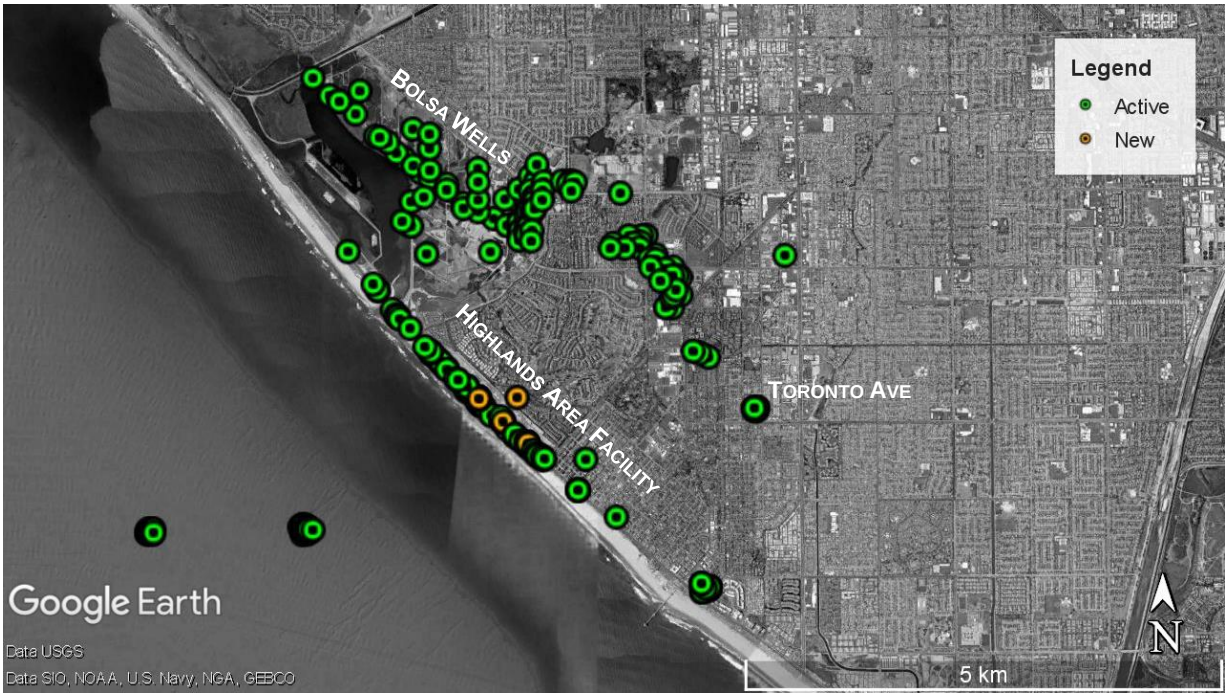

Figure 20. New and active wells in Huntington Beach field (from the CalGEM well finder site, https://maps.conservation.ca.gov/doggr/wellfinder, March 2021).

4 DISCUSSION

Comparison between measured and reported (inventory, calculated) emissions can be the basis for determining performance of a facility (tank park, refinery) if reported emissions are based on idealized tank and process operations and standardized emission factors. Alternatively, the representativeness and validity of measurements conducted over a short time frame can be checked based on comparison with similar surveys, however this requires repeated measurements of the same facility which in reality are few.

Survey A – Bay Area

For this survey, the overall agreement between the CARB 2016 emissions inventory and the measurements is shown in the SUM values in Table 14. The measurements indicate that the measured VOC emissions on average are 2.5 times higher than the reported ones and even higher for the corresponding methane emissions (2.9 times higher). NO_x and SO_2 should likely show better agreement. Both NO_x and SO_2 inventory numbers are in many cases measured by the sites themselves. A notable exception is flaring emissions. The agreement appears to be excellent for NO_x but here it should also be noted that measured NO_2 in this report is compared to NO_x from the inventory. This causes a systematic negative bias in the D_{NOx} factors of around 20 % based on a similar study (Rivera et al., 2010). Note that the inventory corresponds to annual average emission data while the measurements were acquired over 3-4 days during the 4-week campaign. Some of the observed positive discrepancies above can be explained by this, including that the SOF measurements are carried out only during sunny conditions and the fact that the average wind and temperature may differ from the annual average climatology. In a similar study (Johansson et al., 2014) it was shown that such effects could cause a positive bias in the measured emissions of 30-40%, compared to the annual average. In a recent study by AQMD (Pikelnaya 2019) long term, seasonal measurements were conducted using SOF on a single refinery in southern California. Here 7 separate measurement campaigns were carried out during each seasons from fall 2015 to summer 2018. The overall variability was 20% with poor correlation (r^2=0.27) to season. The average ambient temperature in Bay area during the campaign month was close to the yearly average (Oct 2018: 16.1 C; Annual 2017: 14.7 °C) and therefore the measurements were representative for the annual average emissions with regards to this parameter. Slightly lower wind speeds than the annual average was observed in October 2018 which may lead to lower overall emissions from tank storage and open atmospheric sources.

In Table 14, it is also shown that the emissions relative to the refinery capacity varies between 0.016% to 0.037% with an average of 0.022%. These refineries appear to be well operated since the emission factors for industries in Europe and Texas generally span between 0.03% to 0.15% (Mellqvist et al., 2010, Johansson et al., 2014).

Table 14. Crude capacity specific VOC emission factors (EF) and comparison between measurements and CARB 2016 inventory for the Bay Area refineries. (Bay Area survey A, 2018) Here the discrepancy factor D, i.e. ratio of the measurement and inventory, is shown for different species together with the capacity specific VOC emissions obtained from inventory and measurement, respectively. Note that NO_2 for the measurements is compared to NO_x for inventory and methane for the measurements is compared to methane and ethane in inventory. Note also that the inventory values reference only the primary reported REFINERY emissions and the sites contain more emissions sources.

	VOC EF inventory	**VOC EF Survey**	**D_{VOC}**	**D_{NOx}**	**D_{SO2}**	**D_{CH4}**
Martinez E refinery area	0.012%	0.016%	1.36	0.82	1.30	1.26
Richmond refinery area	0.010%	0.021%	1.98	1.41	2.97	2.84
Rodeo refinery area	0.003%	0.021%	6.22	1.55	0.28	4.00
Martinez W refinery area	0.013%	0.037%	2.93	1.06	1.75	4.03
Benicia refinery area	0.004%	0.017%	4.00	0.68	2.50	4.31
SUM	**0.009%**	**0.022%**	**2.47**	**0.99**	**1.64**	**2.93**

For the community concerns, refinery fenceline measurements generally showed relatively low levels of BTEX. Higher ground level concentrations, primarily alkanes, were often found in the vicinity of tank storage and terminal loading operations rather than process or stack emissions which are both elevated and subject to plume lift. There were exceptions to this, for example, see Figure 21, however the source could not be identified at the time.

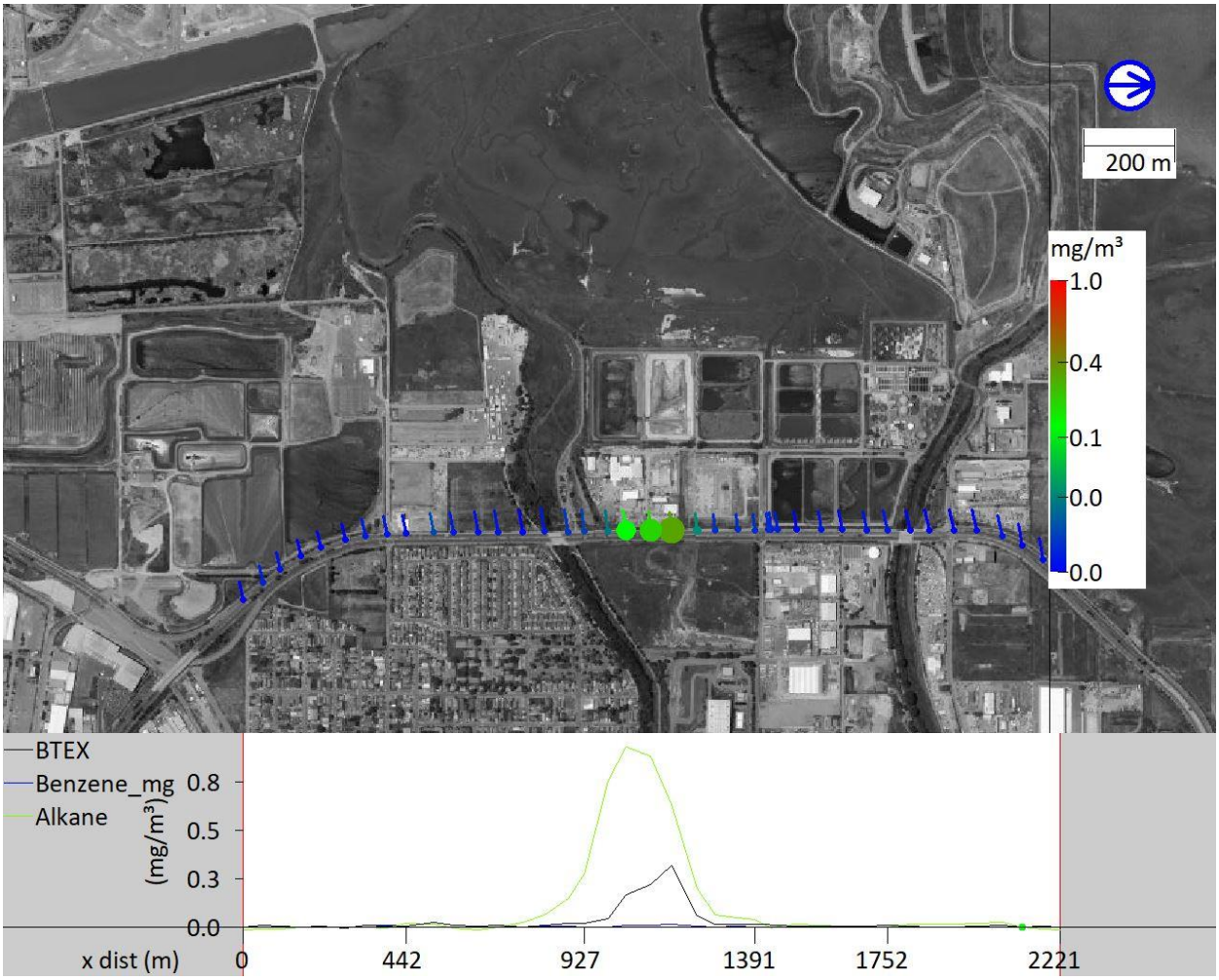

Figure 21. Temporary but unusually large VOC plume from the vicinity of the Pittsburg Ave intersection with Richmond Parkway (Survey A), Oct 23, 2018, 6PM. Image shows total BTEX in logarithmic color scale with lines point upwind in the direction of the source. The plot below the image shows BTEX (0.31 mg/m^3), benzene, and alkane concentrations (1 mg/m^3).

Survey B – SJV oil and gas fields

Survey B in the current study is one of largest diffuse NMVOC emission measurement surveys to date. The area surveyed in this report represents a significant portion of the oil and gas production in California. Cumulative emissions for the fields, wholly or partially measured, amount to 7600 kg/h NMVOCs and 8000 kg/h methane. Measurement data sets for comparison to the measured NMVOC emissions at the scale of this survey report is scarce. However, some methane measurements on this scale have been made. The Jet Propulsion Laboratory (JPL) recently made plume measurements of methane point sources in California and the results have been published on-line (URL https://methane.jpl.nasa.gov/, 13 Dec 2019). Though these represent only measurable plumes and not the sum of all diffuse emissions, the total emissions of the sources in the oil and gas sector in Kern County plus two energy sector sources within the survey area (Figure 22) was 10000 kg/h methane. Scientific Aviation, in measurements conducted on 8 May 2019 concurrently with this study, measured methane emissions from the Elk Hills and Cymric

and McKittrick fields of 6100 kg/h and 3000 kg/h, respectively. Emissions measured in the present study on those days were 4700 kg/h from Elk Hills and 1400 kg/h from Cymric and McKittrick. For the airborne measurements some discrepancy is expected due to uncertainty in field boundaries and possibly not measuring identical areas. Uncertainty is also induced in our methane emissions by measuring concentration ratios at the fenceline over these very large areas.

One can also compare measurements with estimated emission inventories. Total methane emissions as reported in the latest greenhouse gas emissions inventory summary from CARB (2000 – 2017, Last Updated: 11/06/2019) from the industrial oil & gas production and processing sector was 8800 kg/h, of which Kern County and the survey area should account for about 70% of this, or around 6200 kg/h. Table 15 presents the most recent production data from the fields within the survey area and estimated emissions based on standard emissions factors for Oil & Gas Production as a whole. This is a less rigorous methodology than the CARB data but it is applied to field level data. Based on the emission factors from IPCC, methane emissions for the survey area are projected to be 4600 kg/h. While methane emissions appear to be slightly higher than reported, measured NMVOC emissions from the area may be an order of magnitude higher.

Figure 22. JPL measured methane plumes within the current survey area (B and C), colored by estimate emission. Source: Methane Source Finder (https://methane.jpl.nasa.gov/, Dec 13, 2019).

Table 15. 2018 Production and Calculated Emissions derived from standard emission factors, Kern County Oil and Gas Fields. (SJV survey B, 2019) Emission factor sources: *EMEP/EEA air pollutant emission inventory guidebook 2019. **IPCC (Picard, David. 2019. “Fugitive Emissions from Oil and Natural Gas Activities” in Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories).

Field	**Production**			**Calculated Emissions**					
	Oil and Cond. (10^6 m^3)	**Gas** (10^6 m^3)	**Ratio CH_4: NMVOC**	**NMVOC** (kg/h)*			**CH_4** (kg/h)**		
			Vol/Vol	**Oil**	**Gas**	**Total**	**Oil**	**Gas**	**Tot**
Asphalto	0.03	126.8	7.20	0.5	1.4	2.0	5	36	41
Belridge, North	0.28	64.7	0.35	5.6	0.7	6.3	58	18	76
Belridge, South	3.33	230.0	0.10	66.3	2.6	68.9	683	65	749
Buena Vista	0.21	408.0	2.96	4.1	4.7	8.8	42	116	158
Coles Levee, North	0.01	2.9	0.33	0.3	0.0	0.3	3	1	4
Coles Levee, South	0.01	13.2	2.42	0.2	0.2	0.3	2	4	5
Cymric	2.06	67.3	0.05	41.1	0.8	41.9	424	19	443
Elk Hills	1.36	2526	2.78	27.1	28.8	56.0	280	718	998
Kern Bluff	0.01	0.0	0.00	0.1	0.0	0.1	1	0	1
Kern Front	0.55	1.8	0.00	11.0	0.0	11.0	113	1	114
Kern River	2.61	12.9	0.01	51.9	0.1	52.1	535	4	539
Lost Hills	1.54	146.6	0.14	30.6	1.7	32.3	316	42	357
McKittrick	0.42	31.1	0.11	8.3	0.4	8.7	86	9	94
Midway-Sunset	3.28	121.7	0.06	65.5	1.4	66.8	675	35	709
Mount Poso	0.26	1.0	0.01	5.1	0.0	5.1	53	0	53
Poso Creek	0.82	26.1	0.05	16.3	0.3	16.6	168	7	175
Round Mountain	0.41	8.1	0.03	8.1	0.1	8.2	84	2	86
Sum Fields	**17.2**	**3788.1**	0.33	**342.1**	**43.2**	**385.3**	**3527**	**1077**	**4604**

Survey C – SJV dairy farms

The measured emission factors in this study, 11.7 gNH_3 $head^{-1}$ h^{-1} and 49.9 gCH_4 $head^{-1}$ h^{-1} are generally in line with other studies, although notably higher for methane in one case. Bjorneberg found 10.4 gNH_3 $head^{-1}$ h^{-1} and 23 gCH_4 $head^{-1}$ h^{-1} (Bjorneberg *et al.*, 2009), Leytem found 6.25 gNH_3 $head^{-1}$ h^{-1} and 58 gCH_4 $head^{-1}$ h^{-1} (Leytem *et al.* 2011) and Kille found 11.8 gNH_3 $head^{-1}$ h^{-1} (Kille *et al.*, 2017). The methane emissions measurements are well correlated with previous airborne measurements performed by Scientific Aviation of the same facilities, although made in other periods of the year (Table 16).

It should be noted that the ammonia and methane emissions are affected by ambient temperature, wind conditions, solar insolation and diurnal patterns of animal activity (Leytem et al. 2011; Miller et al. 2015). The measurements in this study were performed during daytime in sunny conditions in the month of May. The average ambient temperature in San Joaquin valley during this month is close to the yearly average (May: 20°C; Annual: 19.4 °C) and therefore the measurements were representative for the annual average emissions with regards to this parameter. The SOF measurements were performed during daytime (9:00 to 18:00). According to modelling by Zhu et al. (2015) this would cause 70 % higher NH_3 emissions compared to the average emissions over a 24 h period. For methane the diurnal effects are considerably smaller (Bjorneberg et al, 2009). The wind speeds during the campaign were generally close to the annual average wind speed of 3 m/s, with exceptions for the farms WT06, SM02, NB02, and NB01 for which the wind speeds were twice the average, which potentially increased the measured emissions here. To summarize, a comparison of the measured methane and ammonia emissions to inventory models showed that the measurements were 50 % and 100 % higher, respectively. Much of this discrepancy can be explained by that a daytime measured emission is estimated to be 70% higher than a diurnal average emission. A factor of uncertainty in this study is the number of animals at each farm, used to calculate the emission factors and model the emissions. The animal data were obtained from inspections by the San Joaquin Valley Air Pollution District carried out over several years, and the numbers used on this report are from the last inspection 2017-2019. Since the number of animals can fluctuate during the year, the exact number of cows at each farm in the measured period is uncertain. In addition, at some farms, emissions upwind or from adjacent crop fields interfered with the measurements, e.g. the measurements at farm SB05.

Table 16. Comparison with methane emissions obtained from airborne concentration measurements (SJV survey C 2019) by Scientific Aviation in 2018 and methane obtained from combined SOF and MeFTIR measurements in the SJV dairy farm survey 2019.

Dairy	**Scientific Aviation** (kg/h)	**This survey** (kg/h)	**This survey CI 95%** (kg/h)
WT01	240	196	100 – 290
WT04	670	483	270 – 700
ET08	541	293	170 – 420
SM01	727	527	380 – 670
SM02	560	845	570 – 1120

Additionally, measured and inventory estimated methane emissions were compared (Table 17). The inventory calculations ('Documentation of California's 2000-2017 GHG Inventory – Index') were divided into enteric and manure contributions. For the first, emissions factors were applied

according to the animal life stages and for the latter according the different manure managements for the dairy cows and heifers in California. This estimation was only possible due to the knowledge on the number of animals in each specific facility reported here. Inventory estimated methane emissions were approximately 30% less than measured emissions. It is important to highlight that the facilities studied here have more animals than an average farm in these counties (Monson *et al.*, 2017) and larger CAFOs might emit more methane on an animal basis than smaller farms (Thoma *et al.*, 2013).

For ammonia inventory emissions were estimated by multiplying the emission factor found in literature (84 lbs/cow/year, US EPA, 2004) by the number of animal units on site. The NH_3 inventory estimated emissions were about 50% less than measured emissions.

Table 17. Comparison of measured and inventory emissions[1] dairy methane emission estimates (SJV survey C, 2019).

Dairy	**Measured**		**Inventory[1] estimate**
	CH_4 (kg/h)	**CI 95% (kg/h)**	**CH_4 (kg/h)**
SB02	548	0 – 1110	431
SB03	385	0 – 890	216
SB04	214	100 – 330	186
SB05	514	280 – 740	132
NB01	392	0 – 860	255
NB02	675	0 – 1400	295
WT01	196	100 – 290	354
WT03	389	260 – 520	387
WT04	483	270 – 700	437
WT05	304	140 – 460	109
WT06	260	60 – 460	240
WT07	415	270 – 560	87
ET01	188	100 – 270	67
ET08	293	170 – 420	308

[1]'Documentation of California's 2000-2017 GHG Inventory - Index'. Available at: https://ww3.arb.ca.gov/cc/inventory/doc/doc_index.php.

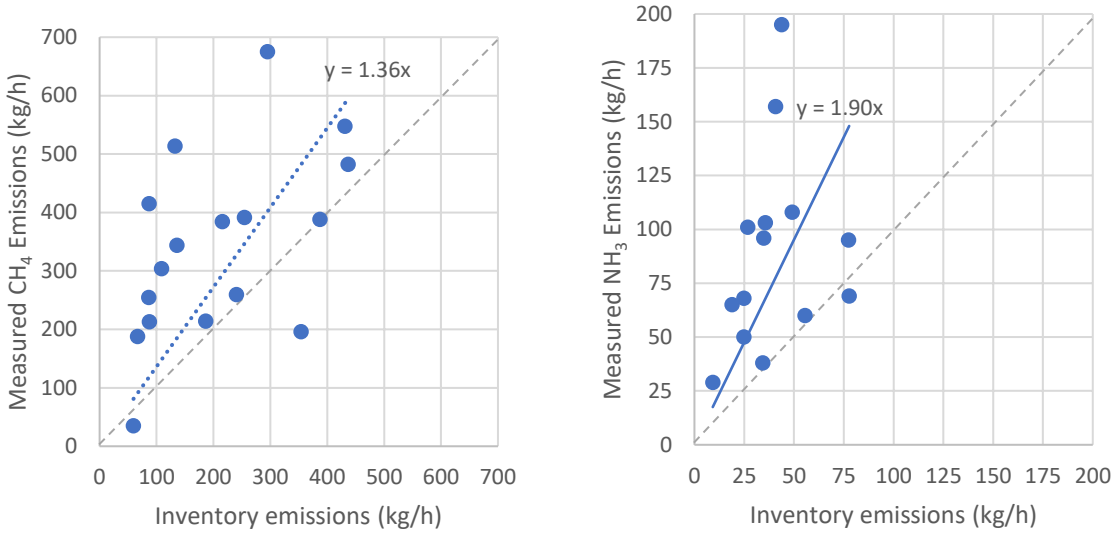

Figure 23. Relationship between measured and inventoried emissions, 1:1 and linear least squares fit plotted: (left) methane (right) ammonia.

Table 18. Comparison of measured and inventory[2] ammonia emissions from animal feedlots for the SJV dairy farm survey C.

Dairy	**NH_3 kg/h**		
	Measured		**Inventory[1] estimate**
	Average	**CI 95 %**	
SB02	107	68 – 146	77
SB03	120	73 – 167	49
SB04	61	42 – 80	25
SB05	114	80 – 152	27
NB01	70	17 – 122	34
NB02	104	61 – 147	35
WT01	71	48 – 93	78
WT03	158	121 – 193	41
WT04	192	120 – 263	44
WT05	70	29 – 111	25
WT06	121	57 – 185	36
WT07	67	51 – 83	19
ET01	32	20 – 43	9
ET08	60	48 – 72	56

[1] Using a constant EF for dairy cows of 84 lbs/cow/year obtained from 'The National emission inventory - ammonia emissions from animal husbandry operations', (EPA, 2004).

Survey D – South Coast Air Basin and San Diego Air Basin

During a 10-day source screening study in South Coast Air Basin and San Diego Air Basin in October 2019, emissions of about 800 kg/h alkanes and 1900 kg/h methane were identified. A multitude of sources were studied covering oil and gas production, gas/fuel storage, a port, landfills, breweries, an airport and general smaller industries. The major emission sources were related to oil and gas production, fuel storage and landfills, several in close proximity to residential communities.

Measurements in San Diego showed significant NO_2 and SO_2 emissions, 688 kg/h and 265 kg/h, respectively, which appeared to originate from the port activity, with ship emissions being a possible source due to a national security exemption for military vessels. Community monitoring of VOCs in Huntington Beach and Newport revealed several hotspots related to active oil wells. The main emissions from these were methane and other alkanes while the emissions of aromatic VOCs were relatively low.

Two of the landfills showed significant methane emissions of over 500 kg/h, Otay in San Diego and Frank Bowerman in Orange County. Few qualified measurements were possible for the other landfills investigated, for example, Miramar Landfill indicated lower emissions, on the order of 100 kg/h methane.

5 SUMMARY AND CONCLUSIONS

A two-year study has been carried out on behalf of California Air Resources Board (CARB). The objective was to provide ground-based flux and concentration measurements from various sources, e.g. refineries, petrochemical facilities, oil storage, port activities, landfills, oil and gas production and dairy farms. Emissions from this multitude of sources and source types have been successfully surveyed in four focused surveys around California using a set of optical remote sensing techniques operated from a mobile lab vehicle.

Stationary source emissions from five large refinery areas in the Bay Area were quantified during 4 weeks in October 2018. Alkane emissions of 1063 kg/h were measured, ranging from 143 – 334 kg/h among the individual refinery areas. In addition, SO_2 emissions of 395 kg/h and NO_2 emissions of 404 kg/h were observed. Obtained BTEX, benzene and methane emissions were 100 kg/h, 12 kg/h and 430 kg/h respectively. Formaldehyde emissions were below 5 kg/h for most refineries. The port area included in the study comprised both tank storage as well as distribution operations. Alkane emissions were most prominent here, with on average 90 kg/h, and associated BTEX emissions were measured to 9 kg/h of which benzene 0.6 kg/h.

This project measured methane and NMVOC emissions from more than 70% of California's oil and gas production and over 40% of its refining capacity. Measurements suggest that emissions from these sectors are still greatly underestimated in inventories. For the oil and gas production fields, comparable methane emission measurements from the same sites within the SJV (ARB and Scientific Aviation, JPL) support this. For methane, emissions were underreported by about half, for NMVOCs less than a tenth of emissions were reported compared to measurements.

Ammonia and methane emissions from more than twenty of the San Joaquin Valleys large dairy farms were measured. Emissions per head were within the range of values reported in the literature, however, total emissions much greater than currently reported. Note that emissions reporting for this sector is limited. A wide variation in management could lead to varying emissions and be problematic for the reliability of standardized emission factors.

Relatively few occurrences of high ground level aromatic concentrations were encountered during the surveys.

Under the period of the survey, the refineries in the Richmond area did not have a broad impact on nearby communities in terms of BTEX concentrations. While the refineries had much larger emissions of BTEX than the port, the distance to nearby residential areas under the prevailing winds was favorable for air quality. For the communities near oil fields in sub project B, this survey was too limited in time and covers at best only a few days for most investigated communities so no aggregated data could be presented or analyzed.

Wildfires occur regularly in California and have a large impact on air quality and contribute significantly to overall toxic emissions even if an individual wildfire is short-lived. During the course of the survey we measured VOC, SO_2, NO_2, H_2CO, NH_3 and other gaseous emissions from wildfires in Central (brush) and Southern California (scrub forest). Unfortunately, time (or scope) was not available during the campaigns to explore these in depth, but it could be seen that these emissions are significant in relation to most stationary sources when they occur.

6 RECOMMENDATIONS

Mobile optical remote sensing techniques have proven to be a versatile tool to screen and quantify and identify emissions from a multitude of sources and a broad range of gases including methane, NMVOCs, ammonia, BTEX, benzene, SO_2, NO_2 and formaldehyde. The scale and extent of sources can vary from very small industries to oil fields. Large scale measurements of O&G are favorable and effective due to the within field variability in activities and the capability to include many installations in an aggregate emission measurement. This in combination with on-site screening measurements for hot spots can rapidly identify the best targets for reducing emissions and facilitate a tool to verify if emissions have been effectively mitigated in subsequent surveys. Aerial and satellite remote sensing measurements can be effective in identifying and locating big emitters although they generally cannot measure diffuse emissions. Care needs to be taken to differentiate temporary emissions, such as activity related, and continuous ones. For all these measurements, accurate determination of emissions relies on establishing the plume speed. This is not always straight forward, or is generally a large source of uncertainty, but given advances in LIDAR and drone measurements of winds, wind parameters can now be directly measured within the plume.

Improving understanding of source variabilities and decreasing uncertainties in the emission estimates by covering a larger fraction of the sources and allowing for more repetitions including different seasons would be a general recommendation for future work. This also applies to the task of community impact monitoring.

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GLOSSARY OF TERMS, ABBREVIATIONS AND SYMBOLS

Abbreviations

AB	Assembly Bill
AU	Animal unit (mature animals represent 1 AU, heifers 0.75 AU and calves 0.17 AU)
BPD	Barrels per day
AFO	Animal Feeding Operations
BTEX	Sum of Benzene, Toluene, Ethyl Benzene and Xylene
CH_2O	Formaldehyde
C_2H_4	Ethylene
C_3H_6	Propylene
C_6H_6	Benzene
CARB	California Air Resources Board
CAFO	Concentrated Animal Feeding Operation
CH_4	Methane
CEC	California Energy Commission
CI	Confidence interval
CalGEM	California Geologic Energy Management Division
DOAS	Differential Optical Absorption Spectroscopy
DOGGR	Division of Oil, Gas, and Geothermal Resources
EF	Emission factor
ET	East Tulare
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
JPL	NASA Jet Propulsion Laboratory
LIDAR	Light Detection and Ranging
MWDOAS	Mobile White cell DOAS
MeFTIR	Mobile extractive FTIR
NB	North Bakersfield
NMVOC	Non-methane volatile organic compound, used interchangeably for alkanes here
NO_2	Nitrogen dioxide
PCBTF	ParaChloroBenzoTriFluoride
QA	Quality Asssurance
QC	Quality Control
ROG	Reactive Organic Gases
SB	South Bakersfield
SCAB	South Coast Air Basin
SM	South Merced
SD	Standard deviation
SJV	San Joaquin Valley
SkyDOAS	Scattered Skylight DOAS
SO_2	Sulphur dioxide

SOF	Solar Occultation Flux
VOC	Volatile organic compound, used interchangeably for non-methane VOC
WT	West Tulare

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

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.

Treatment 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

APPENDIX

APPENDIX A, SUBREPORT A – Bay Area

APPENDIX B, SUBREPORT B – San Joaquin Valley, oil and gas production

APPENDIX C, SUBREPORT C - San Joaquin Valley, dairy farms

APPENDIX D, SUBREPORT D – South Coast Air Basin and San Diego Air Basin