



Air pollution from the Ports of Long Beach and Los Angeles: Volatile Organic Compound Emissions

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Abstract. Ports are a major source of greenhouse gases and air pollution, impacting downwind, typically disadvantaged communities. The Ports of Los Angeles and Long Beach have dramatically improved criterion air pollutants. However, attention has not been on volatile organic compound (VOC) emissions, gases with notable health concerns (this study). Port-area emissions were studied by an evolving mobile air quality laboratory during 10 surveys from 2019 to 2023 including meteorology, aerosols, 18 trace gases, and targeted air samples for laboratory analysis of up to 87 trace gases. A total of 65 cans were collected for this explorative pilot study. Airborne remote sensing data by the thermal infrared imaging spectrometer, Mako, from 21 surveys conducted between 2015 and 2023, identified 37 distinct trace gases in the port area, including VOCs and chlorinated gases. Normalized (to total aromatic or total VOC) trace-gas profiles and trace gas ratios revealed distinct patterns between classes of sources, such as oil production and refineries, and similarities within these classes. For example, the n-butane/iso-butane ratio for Refineries was 0.20, highly distinct from other source classes (1.0-2.2), suggesting different petroleum hydrocarbon source material and maturity.

We demonstrate emissions calculation by fusing discrete air samples with continuous *in situ* methane data for a methane / VOC plume crossing historically disadvantaged communities in West Long Beach with annualized emissions of 0.82 Gg methane and 1.2 Gg total VOC (larger than ethane) including a middle school. Satellite CH₄ indicated plume transport was typical. High-density communities of surround the ports.

Keywords: Ports of Los Angeles, Long Beach, air pollution, emissions, TROPOMI, VOCs, TVOC, aromatic

Highlights:

- Method to fuse air sample data with in situ methane data to derive TVOC emissions.
- Speciated VOC allows for true Total VOC calculation
- Report values for 34 VOC trace gas species from port area sources
- Different port area sources have different VOC species patterns



34 1 Introduction

35 1.1. Air pollution and ports

36 Transportation and industry are important sources of anthropogenic air pollution and greenhouse gases (GHG) that
37 intersect at ports, which typically are surrounded by heavy industry (and their emissions) due to national/international
38 transportation hub access. Ports often are in large urban areas, contributing to air pollution burdens and GHG
39 inventories. Thus, improving urban air quality requires addressing port-area emissions by policies such as the planned
40 electrification of the Ports of Los Angeles and Long Beach (Osenga, 2018) and the development of green shipping
41 corridors (Srivastava, 2007).

42 This study focuses on the Ports of Los Angeles and Long Beach, hereafter the *Ports*, which remain the largest source
43 of air pollution in the metropolitan Los Angeles area, despite air pollution mitigation policies that have achieved
44 significant success. Port area pollution includes criterion pollutants – oxidants like ozone, O₃, volatile organic
45 compounds, VOCs, and particulates. Part 1 showed the Covid19 shutdown led to a significant NO₂ decrease in air
46 quality station data, satellite data, and *in situ* survey data (Leifer et al., 2023). Notably, *in situ* air quality data showed
47 increased ozone, O₃. An inverse relationship between NO₂ and O₃ implies that Ports' O₃ production is VOC-limited,
48 i.e., O₃ production increases from VOC reactions under reduced NO₂ conditions (Sillman et al., 1990). Given the
49 different O₃-forming potential of different VOCs (Derwent et al., 1996), it is important to characterize the atmospheric
50 trace-gas VOC profile.

51 Port-area VOCs arise from a range of sources and activities, each with its unique trace gas profile, that contribute to
52 port-area atmospheric VOC burdens, most strongly in the downwind (diurnally-varying) near-field. Some of these
53 sources and activities will be affected by port electrification, others will not. Thus, it is important to characterize the
54 atmospheric trace gas VOC profiles at the source level.

55 Accurate assessment of the VOC burden is critical for studying ozone formation (Derwent et al., 1996), health impacts
56 (Sect. 4.3), and effective regulation, all of which depend on the VOC composition profile. Common low-cost methods
57 rely on non-selective sensors such as Photo Ion Detectors (PIDs) or metal oxide sensors to measure VOC (see review
58 in Spinelle et al. (2017)). These sensors are typically calibrated against a single gas, such as isobutylene, as the ambient
59 trace gas profile is unknown *a priori*. However, sensor response varies significantly among different trace gases
60 (Khatib and Haick, 2022), making non-selective TVOC measurement a poor, and often inappropriate, proxy for the
61 true atmospheric burden.

62 Even new mobile technologies, such as Proton-Transfer-Reaction Time-of-Flight Mass Spectrometry (PTR-ToF-MS),
63 face analytical challenges, including interferences and humidity dependency. PTR-ToF-MS interferences arise from
64 ion fragmentation, isobaric ions, and reagent-ion cluster formation (Coggon et al., 2024) that vary spatially and
65 temporally. An important example is the interference of isoprene with the signal of the well-known carcinogen
66 benzene, which falsely increases the benzene signal (Holzinger et al., 2019). Therefore, accurate quantification,
67 whether correcting PTR-ToF-MS or non-selective analyser data, requires an accurate *a priori* VOC composition
68 profile. This study establishes the VOC composition sector inventories for sources in the Ports' area, providing a
69 baseline to assess pollution burdens and inform effective mitigation strategies.



70 1.2. Study motivation

71 Globally, ports and their associated industries are major air pollution sources that disproportionately impact
 72 downwind, often disadvantaged communities—clearly an environmental justice issue—and also impact terrestrial and
 73 marine ecosystems. Ports typically are located in major urban settings, which generate their own significant emissions.
 74 Consequently, downwind neighbourhoods experience a complex mixture of pollution from both port-related and
 75 general urban sources. Thus, developing effective regulations requires a holistic characterization of all significant
 76 sources. Detailed VOC profiles are essential to disentangle the ports’ signature from the broader urban signature to
 77 accurately assess source-specific impacts on community health, and ultimately inform equitable air quality regulation
 78 and management.

79 The study focused on the trace gas composition profiles of the VOC emissions from significant sources in the Port
 80 area and in neighbouring downwind communities (and reference upwind). Specifically, *in situ* surface trace gases and
 81 meteorology were repeatedly surveyed by a mobile air quality laboratory from 2019 to 2023. Data were collected
 82 during multiple, infrequent, *in situ* surface surveys and airborne remote sensing flights. *In situ* data continuously
 83 measured a wide range of criterion and other pollutants, while also collecting targeted air samples for lab analysis of
 84 a broad range of VOCs.

85 This manuscript is part of a series reporting on an *ad hoc* study that was conceived during the Covid19 shutdown to
 86 leverage the shutdown as a proxy for future emissions reduction from port electrification. Part 1 studied the oxidant
 87 air pollutants NO_x and O₃ (Leifer et al., 2023). Part 2 focused on CH₄ (Leifer et al., 2026). Part 3 (this manuscript)
 88 focuses on VOC emissions, including those impacting health, and includes data collection in port-adjacent
 89 neighbourhoods and background Pacific air. Part 4 will focus on aerosols.

90 1.3. Port air pollution

91 The Ports of Long Beach and Los Angeles are the nation’s busiest, with 2021 traffic of 10.7 and 9.3 million TEU (20-
 92 ft. container equivalent unit), respectively, and cover 26 km² ([https://gcaptain.com/port-of-los-angeles-reports-record-10-7-million-](https://gcaptain.com/port-of-los-angeles-reports-record-10-7-million-teu-throughput-in-2021/)
 93 [teu-throughput-in-2021/](https://gcaptain.com/port-of-los-angeles-reports-record-10-7-million-teu-throughput-in-2021/)). 84% of containers are transported by heavy-duty diesel trucks (HDDTs) (Houston et al., 2014).
 94 Over 40% of all US imported goods transit the Ports (Hricko, 2008). Heavy industry in the port area leverages the
 95 transport network and includes refineries, coke production, wastewater treatment, and oil production (Fig. 1).

96 Pollution also comes from non-port HDDT transportation and natural and anthropogenically modified seepage – the
 97 Ports overlie the extensive Wilmington Oil Field, which currently is under production. The emissions from the port
 98 and surrounding industries impact the nearby, economically and historically disadvantaged, diverse, and downwind
 99 communities of Carson, Long Beach, and Wilmington (Houston et al., 2014).

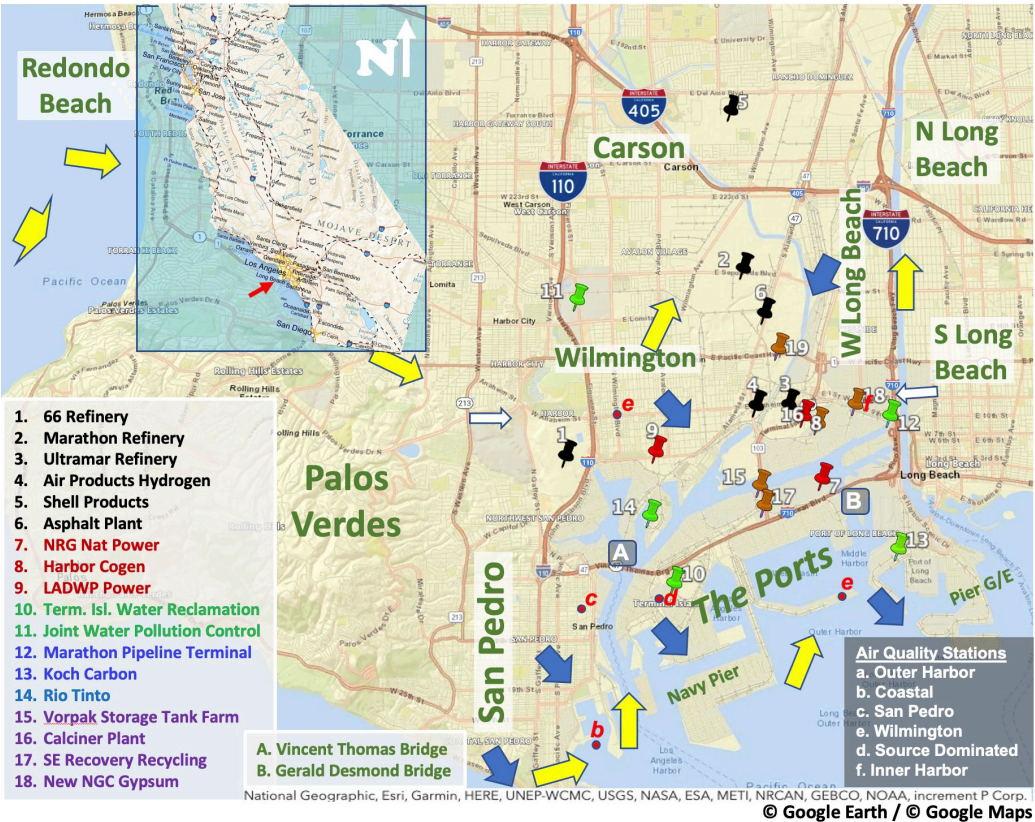


Figure 1. Ports of Los Angeles/Long Beach major industrial sites and infrastructure, neighbourhoods, and typical day (yellow) and night (blue) winds (based on air quality station data 1/2019-9/2020), see Leifer et al. (2023). See Leifer et al. (2022) for details on surrounding industries. White arrows highlight Anaheim St., which was repeatedly surveyed—map from the US Geological Survey national map viewer (Dollison, 2010). Displayed in the Google Earth Environment.

Port area pollutant transport is complex due to the sea breeze wind cycle, which imposes a diurnal cycle, for the ports' irregular coastline with further modification from topographic forcing (Fig. 1). The Port terrain is flat and protected to the west by the Palos Verdes highlands (rising to 373 m), which split the prevailing northwesterly winds. These split winds reconnect in the western port around the Phillips 66 Refinery. Thus, winds near this refinery are often variable. The mountains that define the Los Angeles Basin generally constrain winds to from the west to northwest. Morning winds strengthen, reaching a mid-afternoon maximum. Winds are stronger for the more exposed Coastal and Harbor Sites, which are further from Palos Verdes. Prevailing wind transport patterns suggest that emissions from the Ports may impact the nearby Long Beach communities. In contrast, the city of Carson may be affected by Ports' emissions for onshore winds. Additional time-resolved wind details are provided in Supp. Fig. S1.



115 2.0 Methodology

116 2.1. Overview

117 Mobile surveys characterize emissions and sources at high spatial resolution, albeit only during the survey. In contrast,
 118 air quality stations provide complementary temporal information over long-time scales (Steffens et al., 2017). Fixed
 119 AQ station observations are spatially (specifically, angularly) averaged, which challenges source attribution,
 120 particularly when wind irregularities such as veering and convergence complicate source attribution. Satellite data
 121 provide both spatial context and temporal information, albeit at low spatial resolution. Although satellite spatial
 122 resolution can be improved through oversampling, this process reduces temporal information.

123 Mobile vehicular air quality laboratory surveys were conducted to characterize air quality and meteorology for the
 124 Ports and neighboring communities. These data were collected by a series of evolving science packages, SISTER
 125 (Standard Instrumentation Suite: Truck Enabled for Response). SISTER is a science package developed for
 126 installation in a pickup truck, TMOG (Truck MOBILE trace Gas) Surveyor. Thus, earlier surveys lacked capabilities
 127 that were added afterward. Custom software in MATLAB (MathWorks, MA) provided real-time visualizations in
 128 Google Earth, enabling targeted air sample canister collection and improving survey routing.

129 Ten *in situ* surveys were conducted from 2019 to 2023, including during the Covid19 shutdown. Most surveys included
 130 the east-west-running Anaheim St. (Fig. 1), which was driven one to several times in almost all surveys. Anaheim St.
 131 passes through downtown Wilmington, extending into Long Beach, fronting the Ports' northern edge, passes onshore
 132 of the Valero refinery, and crosses a major HDDT route, I-710. The cleanest air and lowest CH₄ concentrations were
 133 found on the Navy Pier and the southeast coal-loading pier, the furthest offshore sites. The background sites were
 134 surveyed regularly to acquire clean-air reference samples. Additional context was provided by airborne remote sensing
 135 acquisitions by the Mako TIR imaging spectrometer, some of which were acquired concurrently with SISTER data.

136 2.2. SISTER

137 Surveys were conducted by AMOG Surveyor and SISTER in TMOG (Fig. 2). These platforms and instrumentation
 138 packages are described in Supp. Sect. S2, briefly below and elsewhere (Leifer et al., 2016; Leifer et al., 2019a; Leifer
 139 and Melton, 2021; Leifer et al., 2014). These platforms evolved over the course of the study, with more recent surveys
 140 measuring more gases, although some surveys missed an analyzer due to repairs, etc.

141 SISTER2 currently measures meteorology (3D winds, temperature, pressure, humidity); aerosol profiles and aerosol
 142 size spectra (0.1-32 μm , 32 channels, 0.16 Hz, 90-1094 nm, 512 channels, 15 Hz); trace gases (CH₄, C₂H₆, C₃H₈, CO,
 143 H₂O, NH₃, O₃, SO₂, NO, NO₂, NO_x, NO_y, N₂O, and H₂S at sub-ppb levels, CO₂ and H₂O at sub-ppm levels; isotope
 144 ratios of $\delta^{13}\text{CH}_4$ and $\delta^{13}\text{CO}_2$ at sub-milli-percent levels), and ionizing radiation. Analyzers are calibrated before each
 145 field survey, including sample line transport time to correct for the spatial displacement. Relative layback times
 146 (sample-line travel time) between Cavity Enhanced Absorption Spectrometer (CEAS) analyzers are determined by
 147 cross-correlating the H₂O time series measured by all CEAS analyzers and by measuring for one, the FGGA, before
 148 each survey. SISTER also supports up to 96 1-L evacuated stainless steel canisters for lab analysis for a wide range
 149 of trace gases.



One aspect that has evolved over the years is the wind treatment. Currently, two anemometers provide SISTER2 with redundancy for this key measurement. Each anemometer has a 3-axis inclinometer that measures orientation at 5 Hz with 0.05° accuracy (HWT905, Wit Motion, Shenzhen, China). The inclinometers correct the winds for slight offsets between the anemometers' "north" or forward direction and the vehicle's true orientation. Before the recent addition of the inclinometers, an optimization algorithm was used to determine the angular offset. The algorithm minimized the speed dependence of the vehicle motion-corrected velocity. The velocity dependency arises because any anemometer-vehicle angular offset inserts the vehicle's velocity into the wind velocity. This minimization algorithm works for 2-D winds; however, the 3-D inclinometer data are needed to correct 3-D winds for anemometer orientation.

2.3. Air sample canisters

SISTER canister collection uses real-time data to collect samples in the plume's frame-of-reference, e.g., background, plume peak, plume flank, etc., with the atmospheric spatial context provided by continuous SISTER data. An air pump continuously flows air through a snake line with tees to valves to each can and a bypass exit valve. The bypass valve is closed in preparation to collecting an air sample. Air sample collection begins by cracking open the evacuated canister valve to an amount that keeps the pressure below 10 psi. After about a minute, the can will have pressurized to 20 psi, the can's valve is closed, and the bypass valve is opened. The air sample inlet is located at 3.2-m (TMOG) or 5-m (AMOG) height to minimize the potential for sampling traffic exhaust. Real-time data visualization enables the implementation of an adaptive survey strategy (Thompson et al., 2015) and targeted air sample collection. Specifically, visualization of real-time CH₄, CO₂, or other continuous analyser gases to guide air sample collection. Air samples are analyzed by a three-gas chromatograph analytical system with a range of detectors, including ECD (Electronic Capture Detector), FID (Flame Ion Detector), and MSD (Mass Spectrometry Detector). The system utilizes a state-of-the-art vacuum-line injection system and 6 column/detector combinations. See Colman et al. (2001) and Simpson et al. (2010) for a complete description. To verify sampling, the *in situ* CH₄, averaged over the collection time of each air sample, was compared with the CH₄ in the sample for the Ports of Los Angeles and Long Beach. The agreement was within a few percent, even though canister filling is not flow-regulated, requires ~1 minute, and thus may emphasize air collected during a portion of the recorded filling time (Leifer et al., 2022).

2.4. Emission derivation

Derivation of *in situ* emissions is described elsewhere (Leifer et al., 2018a; Leifer et al., 2018b) and in Supp. Sect. S3. In brief, the trace gas concentration, C , is projected onto a wind-orthogonal plane. The concentration anomaly, C' , is calculated by subtracting the background concentrations from C outside the plume by a first-order least-squares linear regression analysis. One to several Gaussian functions are determined by a least-squares linear regression analysis of the C' plume transect, the Gaussian Data Model (GDM). Emissions uncertainty is assessed by Monte Carlo simulations using measured variability in observed parameters, e.g., C' , winds, etc., in the plume model.



184 2.5. Airborne remote sensing

185 The airborne Thermal InfraRed (TIR) imaging spectrometer, Mako (Buckland et al., 2017; Hall et al., 2016), acquired
 186 remote sensing data for this study. Mako operates in the 7.6-13.2 μm range and was flown on a DeHavilland DHC-6
 187 Twin Otter airplane at 3.23 km Above-Ground Level (AGL). This altitude yields a 1.8 m ground-sample distance
 188 (GSD). The whiskbroom scanner can provide areal acquisition rates up to $1430 \text{ km}^2 \text{ hr}^{-1}$ for a flight altitude of 12,000
 189 ft (3.6 km) AGL, corresponding to a 2-m GSD. Mako's spectroradiometric performance is described in detail in
 190 Buckland et al. (2017), with key details presented in **Supp. Sect. S3**.

191 Since 2014, Mako has conducted broad-area surveys of the ports on a near-annual basis. The wide variety of industrial,
 192 commercial, transportation, and residential activities within the ports' industrial corridor presents a target-rich
 193 environment for emissions surveys. Each survey typically searched for 80-110 gases, including VOCs, TICs,
 194 hydrocarbons, halocarbons, combustion products, and organic solvents. The search algorithm correlates the Mako
 195 spectral imagery against >800 spectra to extract trace gas content in the scene using the adaptive coherence estimator
 196 (ACE) approach. ACE is used for this purpose because of its robust false-positive rejection properties (Manolakis et
 197 al., 2013; Buckland et al., 2017). The in-scene method is used to atmospherically compensate the imagery as it is
 198 standalone and does not rely on ancillary data or modelled information (Young et al., 2002).

199 2.6. Satellite data

200 Satellite data from the TROPOspheric Monitoring Instrument (TROPOMI) version 2 (GSFC, 2024) were downloaded
 201 (30 Apr. 2018 to 31 Dec. 2025) and analysed by super-sampling to provide spatial and temporal trend information for
 202 the Port area. The approach is described in detail in Leifer et al. (2026). In brief, TROPOMI pixels are too large (38.5
 203 km^2) to resolve the spatial structures of the CH_4 anomaly at the port scale; thus, data were oversampled, termed herein
 204 super-sampling. We adapt drop-in-the-circle oversampling (Sun et al., 2018) for an elliptical averaging area to account
 205 for source emission dispersions. We use an uneven grid scheme and distance weighting to account for different north-
 206 south (along-track) and east-west (cross-track) resolutions of the TROPOMI pixels. CH_4 average maps are calculated
 207 for each grid point, provided there were five or more observations within a cutoff distance of each grid point. In-region
 208 data were filtered for cloud coverage <50%, solar zenith angle >60°, and quality factor >0.3. For this coastal area where
 209 clouds are a common interference, the quality flag criterion was relaxed; however, in this analysis we reference the
 210 satellite product to maintain consistency with *in situ* observations.

211 2.7. Composition profiles

212 Normalized composition profiles were calculated for each sample to account for dilution from dispersion between the
 213 source and the sample collection location. Please refer to Supplemental Materials for non-normalized values.
 214 Aromatics were normalized by the sum of aromatics and selected methylated aromatics in parts per billion (ppb).
 215 Short-chain hydrocarbons were normalized with the sum of short-chain hydrocarbons in ppb. Other trace gases were
 216 measured and used in the TVOC calculation, but were not used in the composition profile analysis.
 217 Normalized composition profiles are the average of all representative samples downwind of the source. Non-
 218 representative samples, i.e., outliers, were identified by yellow highlighting normalized trace gas concentrations that



were more than 1.05 standard deviations, σ , from the normalized trace gas average (a difference of 5% was not considered significant). Outlier sample identification was iterative—the average was recalculated without the outlier(s) to potentially reclassify outliers. Sample classification as non-representative depended on the number of highlighted outlier concentrations. For example, sample 1313 was classified as a non-representative Port sample with 15 outliers out of 35 compounds. This classification decreased the number of outlier concentrations in the other Port samples from 13 to 3. This outlier identification process only was applied to sample classes with more than three samples. The analysis looked at several trace gas ratios. The ratio of n-butane to iso-butane relates to maturity, and the original petroleum source material or kerogen, whether terrestrial or marine. A higher n-butane/iso-butane ratio indicates greater maturity and correlates with $\delta^{13}\text{CH}_4$, another indicator of gas maturity. The n-pentane / iso-pentane ratio also is a maturity indicator, albeit without the kerogen type dependency (Igari et al., 2007). The xylene-to-ethylbenzene ratio indicates sample age due to significantly different reaction rates (Kalabokas et al., 2001). Ethene (or ethylene) is an important polymer feedstock produced by steam cracking at 800-900°C and distillation. It is present in petroleum hydrocarbons and as a plant hormone (Bakshi et al., 2015). The catalytic reformation of crude oil produces higher-octane gasoline, as well as propane, n-butane, and iso-butane as by-products (Speight and El-Gendy, 2018). Catalytic cracking produces chemical raw materials used to generate unsaturated hydrocarbons, e.g., ethylene, propylene, butenes, and light alkanes (Speight and El-Gendy, 2018). Cycloalkanes are cyclic saturated hydrocarbons with alkyl side chains, are present in crude oil, and increase transportation fuel's "octane number" – 10-20% of gasoline and 20-40% of diesel. The cycloalkane concentration varies depending on the source of the fuel's petroleum hydrocarbon. Methylated cycloalkanes are present in crude oil and are precursor aromatics in chemical synthesis. For example, methylcyclopentane is associated with butadiene production (Zhang et al., 2017). Butadiene is a rubber precursor and a by-product of ethylene production from steam cracking (White, 2007). Methylcyclohexane is a solvent used in the manufacturing of pharmaceuticals and agrochemicals, as well as an important component of jet fuel (Metoree, 2024a). Methylcyclohexane is converted to toluene during fuel production to increase the octane number (Boufaden et al., 2015). Cyclohexane is a nylon precursor and an important solvent in paints, etc. (Metoree, 2024b). Cyclopentane is added to fuel to increase its octane number and is used in foaming agents.

Table 1. Survey details

Start Date	Start - End Time	Pl	T	H	U	Sky	Neighborhoods
DD/MM/YYYY	UTM	-	°C	%	m/s	Te, Aq	-
11/07/2019	20:19:53 - 22:24:03	1	27.7±1.3	54.1±3.1	2.2±0.9	–, –	SP, Wi, Ca, WLB, LB
07/05/2020	21:44:24 - 23:07:33	2	25.1±1.9	58.5±11.0	2.7±1.6	C, P	SP, Po, LB
19/06/2020	22:53:03 - 03:48:51	2	20.8±1.1	67.2±4.9	2.5±1.0	M, P	SP, Wi, Po, Ca, WLB, LB
16/07/2020	23:27:57 - 03:42:03	2	23.0±1.7	62.0±8.8	2.4±1.4	C, C	SP, Po, LB
02/11/2020	22:54:32 - 04:02:12	2	19.7±1.8	76.3±7.7	1.3±0.9	–, C	Co, SP, Wi, Po, Ca, WLB, LB
11/11/2021	23:52:51 - 03:46:03	2	23.5±2.5	52.1±12.4	1.0±0.8	C, –	Co, SP, LB
18/11/2021	03:59:15 - 05:35:27	2	14.2±0.7	69.5±12.4	1.7±1.3	–, –	SP, Wi, Po
18/05/2022	19:16:51 - 01:38:03	3	21.5±1.1	59.5±4.5	1.9±1.0	M, C	SP, Wi, Po, Ca, WLB, LB
29/07/2022	19:26:45 - 04:43:57	3	23.6±2.3	64.1±13.6	2.0±1.0	P, –	SP, Wi, Po, Ca, WLB, LB
08/03/2023	22:53:44 - 04:33:25	3	13.4±0.9	58.2±6.5	2.0±1.1	C	SP, Wi, Po, Ca, WLB, LB

UTM – Universal Time

Pl – Platform: 1-AMOG, 2-TMOG, 3-TMOG2, T – Temperature, H – Humidity, U – wind speed.

Te-Terra, Aq-Aqua, C-Clear, P-Partial cloudy, M-Marine layer

Co-Coast, SP-San Pedro, Ca-Carson, Wi-Wilmington, Po-Port, WLB-West Long Beach, LB-Long Beach



3. Results

3.1. Results overview

A total of 10 surveys were conducted from 2019 to 2023 (Table 1), with air samples collected on most of these surveys. A common survey feature (9 of 10 surveys) was the Anaheim St. transect, which crosses the Port area (Fig. 1). Airborne remote sensing mapped the Ports' area emission source locations at meter-to-sub-meter scales. A total of 55 samples were analyzed for this study.

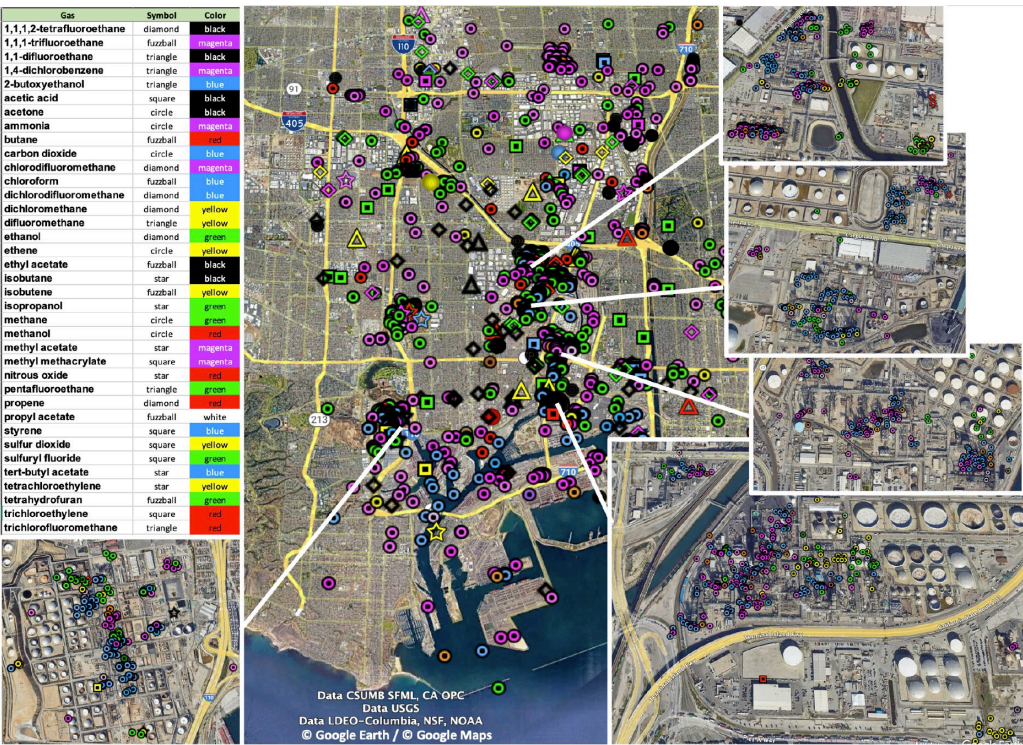


Figure 2 Trace gas detections by the airborne remote sensing sensor, Mako, from 21 surveys, 2015-2023. Inset panels show detailed areas with high spatial density detections, entirely refineries. To explore the dataset, see the Supp. Mater. Google Earth archive for further details.

3.2. Airborne trace gas observation

Airborne remote sensing detected many trace gases, including CH₄ and CO₂, from a range of sources, providing an overview of area sources (Fig. 2). Refinery detections were prominent. Furthermore, multiple gases often were detected in the same plume, usually including CH₄ and/or CO₂, particularly for refinery plumes. CO₂ detection can suggest combustion, although petroleum hydrocarbon reservoir gases often include CO₂. Combustion can be confirmed if the TIR remote sensing shows heat. Additionally, hot plumes have a higher signal-to-noise ratio (SNR), which facilitates CO₂ detection. Offshore and berthed CO₂ detections are from shipping vessels.

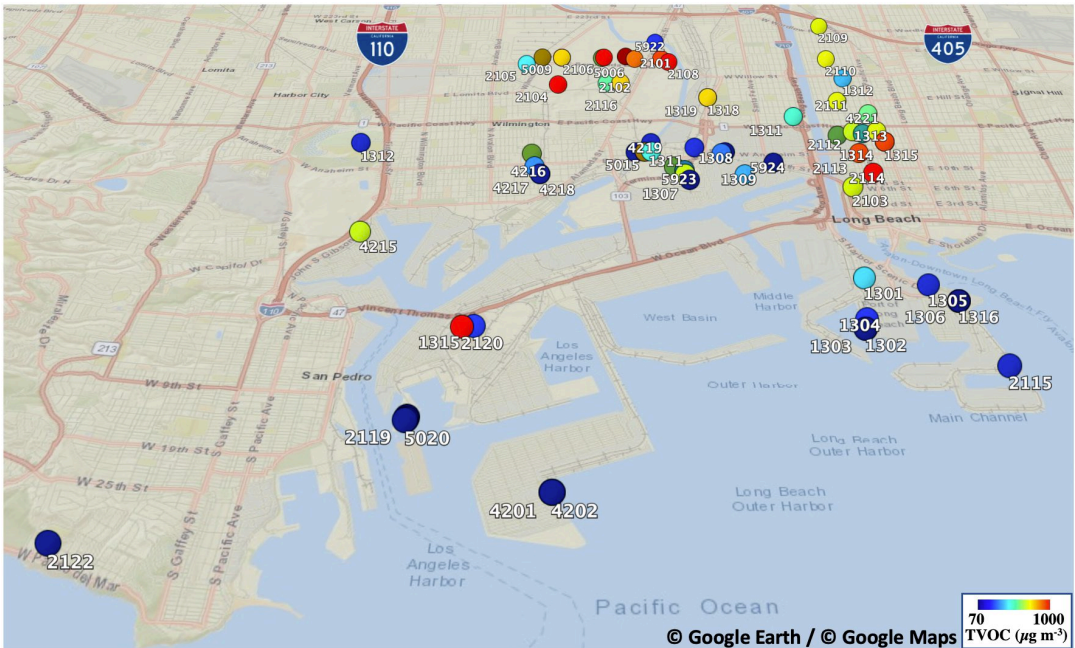


280 Ammonia, NH_3 , also was detected from many sources around the Ports, including industrial compressors and several
281 residences (possibly related to home cleaning products). Many olefins were detected, including ethene, propene, and
282 other complex organic molecules. For example, methyl acetate was detected leaking or venting from a storage tank at
283 a light industrial site in the south of West Long Beach. This site also emitted ethanol. A vehicle recycling yard with
284 piles of semi-demolished vehicles emitted 1,1,1,2-tetrafluoroethane (Freon 134a – a high-global warming potential
285 refrigerant with negligible O_3 -depleting potential).
286

287 **3.3. Trace gas composition of port-area sources**

288 **3.3.1. Background**

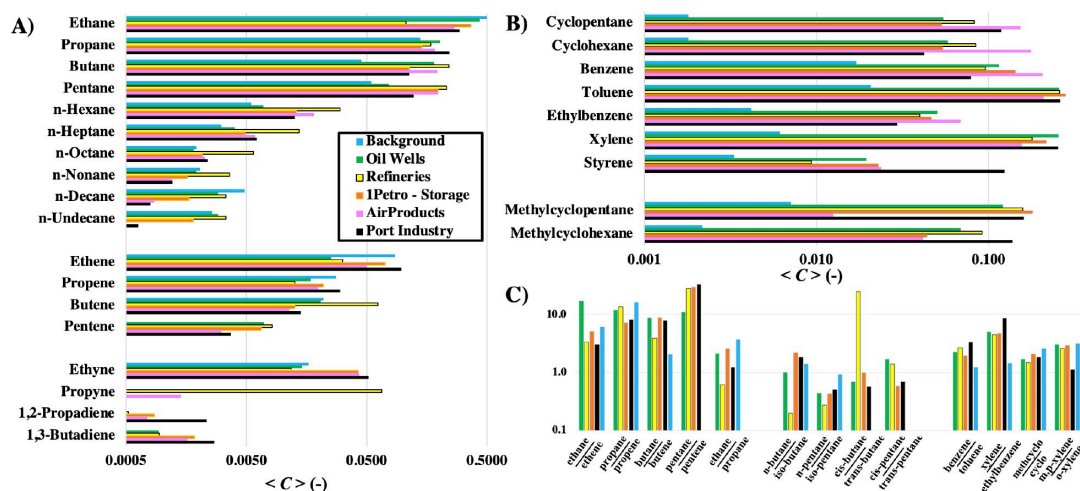
289 Port area emissions follow the flow of petroleum hydrocarbon energy through port area activities, i.e., extraction,
290 refining, and utilization, which organizes this section. A total of 65 air sample canisters were collected and analyzed
291 from 5 Jul. 2020 to 8 Mar. 2023 (Fig. 3). Generally, sample canisters to the south (Pacific air) and to the west
292 (prevailing daytime upwind) exhibit lower TVOC with higher levels near port industrial sources and in Long Beach.
293 TVOC is the sum of short-chain, saturated, and unsaturated non-methane hydrocarbons and volatile aromatic
294 hydrocarbons from the trace gas profile, and thus, are actual TVOC values.
295



296
297 **Figure 3. Summary of air sample canister locations showing sample number and TVOC. Note, some samples are too close**
298 **to show. Map from the US Geological Survey national map viewer (Dollison, 2010). Log scale data key on figure.**



299 The normalized composition profiles of the short-chain hydrocarbons except CH₄ and aromatics are shown in Fig. 4,
 300 the non-normalized profile is shown in Supp. Fig. S4. Sample trace gas concentrations were normalized by dividing
 301 concentrations by the sum of the short-chain hydrocarbon concentrations or the sum of aromatic hydrocarbon
 302 concentrations.
 303 The largest CH₄ and hydrocarbon trace gas emission source for the port area arises from several Refineries; see Fig.
 304 6 for profiles for each refinery. Profiles for each refinery's samples were similar (see Supp. Fig. S6 for the Valero
 305 refinery) but significantly different between refineries. Refinery feedstocks are petroleum hydrocarbons transported
 306 to the port-area refineries by pipelines, vessels, and from local production, the Wilmington Oil Field. Air samples
 307 were collected of active production emissions from the Thums, Warren E&P, and Tidewater leases (Fig. 5). Refinery
 308 output includes vessel fuel stored in tank farms (Fig. 7, Supp. Fig. S8 for the 1-Petro Storage facility). The most
 309 important non-refinery industrial emission source is the Port proper (Fig. 8). Other important industrial inputs are from
 310 a Calciner, an Air Products facility, wastewater treatment plants, and the California Sulfur Company (Fig. 8). Air
 311 Products is a specialist refinery of industrial gases rather than fuels and other petroleum products. The Port Industrial
 312 Profile is the average of samples from three sites, the Calciner, the California Sulfur Co., and the Ports proper (Fig.
 313 6), which were similar, but not Waste Water.



314
 315 **Figure 4. Summary of major port area sources' A) normalized air sample concentrations, <C>, for short-chain, saturated,**
 316 **and unsaturated non-methane hydrocarbons, B) selected volatile aromatic hydrocarbons, and C) ratios of alkanes/alkene,**
 317 **isomers of butane, C₄H₁₀, and pentane, C₅H₁₂, butene, C₄H₈, and pentene, C₅H₁₀, and select aromatics. methylcyclo is**
 318 **methylcyclohexane + methylcyclopentane; cyclo is cyclohexane + cyclopentane. See Supp. Fig. S4 for non-normalized**
 319 **profiles.**

320 3.3.2. Major port-area sources

321 For all Port-area sources (and Background-blue), large alkane (or paraffin) concentrations were significantly lower
 322 than those of small alkanes (Fig. 4), albeit with different patterns of decrease with carbon number, *n*. Background
 323 decreased as a power law (a straight line in these logarithmic scale plots – see Supp. Fig. S5 for illustration) with C₆
 324 and C₈+ undetected.



Refineries and Storage (1Petro) were flat for $n > 7$ paraffins, whereas Oil Wells increased and Port Industry decreased with n for these large molecules. Storage decreased with a power law from ethane to butane, rising to a peak at pentane before dropping precipitously. Refineries smoothly increased from ethane to butane/pentane (butane was equal to pentane), then decreased more slowly to hexane than Storage. Oil Wells decreased from ethane to octane (as does Background, Fig. 4-Blue). These patterns combine to enhance refined product sources (Storage, Fig. 4-orange and Refineries, Fig. 4-yellow), mid-length alkanes compared to production (Oil Wells, Fig. 4-green). Whereas the other sources showed different trends with n for small and large alkanes, a smooth curve describes the Port Industry C_3 - C_{10} trend, except for pentane, which is elevated above trend. Port Industry is the average of the Ports, Calciner, and the California Sulfur Company.

The highest olefin (alkene) concentration for Storage and Port Industry was ethene, decreasing for larger n . In contrast, Refineries peaked at butene, and Background peaked at propene. Olefins for Oil Wells were approximately constant for C_2 - C_4 and significantly decreased for pentene. Ethyne was lower than ethene, but not for Background. One surprising finding was the strongly elevated Refineries propyne concentrations - higher than those of any alkene.

Toluene concentrations were the highest of the aromatic compounds for Oil Wells, Refinery, and Storage, whereas xylene was highest for Port Industry and Background. Xylene for Oil Wells was only slightly lower than toluene. Port Industry styrene was surprisingly high. Note, the aromatic hydrocarbon (AH) and short-chain hydrocarbon (SCH) concentrations are normalized separately. For Port Industry and Background, cyclopentane was higher than cyclohexane. For Production, Refining, and Storage, cyclopentane and cyclohexane were similar. For Background and Port Industry, the two methylated VOC species were comparable, albeit slightly higher, for methylcyclopentane. Refineries, Oil Wells, and Storage strongly favored methylcyclopentane over methylcyclohexane.

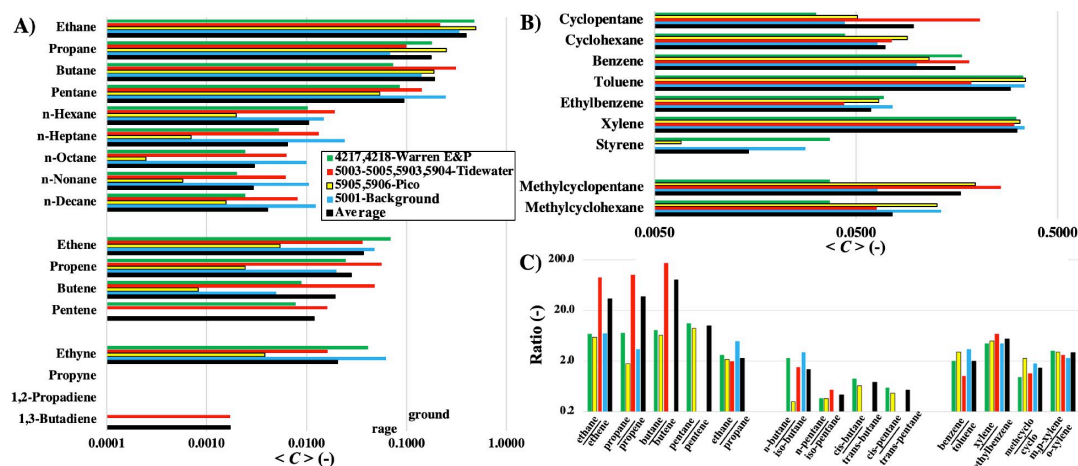
The Refinery and Port Industry alkane-to-alkene ratios showed an increasing zig-zag pattern with n . In contrast, Background decreased with n , Oil Wells were fairly constant with n , and Storage increased with n . Looking at the isomer ratios, cis-butane was strongly favored over trans-butane, and cis-pentane was favored over trans-pentane for Refineries and Oil Wells. Ethane/ethene was highly favored for Background and Production, much less for Refineries, indicating that refining increases ethene and butene.

3.3.3. Oil wells

Oil production from the Wilmington Oil Field occurs from several leases (Fig. 5). Although average Oil Well alkanes gradually and monotonically decreased to pentane, Tidewater showed a butane peak. In contrast, Warren decreased from ethane to butane and then rose to a small pentane peak. All decreased rapidly to hexane, with Pico decreasing the most, then increased from C_8 to C_{11} . Even the local Background showed this increase, suggesting this Background was affected by oil well emissions. As a result, it was not included in the Background average (Fig. 4-blue). The local Background light alkanes (C_2 to C_5) showed a different wave pattern (C_3 minima, C_5 maxima), which was similar to Storage (Fig. 4A-orange). There were more differences in the olefins, with Tidewater peaking for propene. Warren and Pico decreased from C_2 to C_5 —albeit Pico had no detectable pentene. Ethyne was comparable to either ethene or propene for all leases.



360 Tidewater (Fig. 5-red) was highly depleted in alkenes relative to alkanes (>200) compared to the other leases (<10).
 361 Still, the overall trend in ratios was an increasing alkane/alkene ratio with n , except for Pico propane, which had a
 362 lower propane. Pico (Fig. 5, yellow) also had a very distinct, low n-butane/iso-butane ratio; the other leases' n-
 363 butane/iso-butane ratios were similar to each other and to the Storage and Refinery sources. The ethane-to-propane
 364 ratio was ~ 2 across all leases, most similar to Storage (Fig. 4C, orange) and significantly different from Port Industry.
 365 Whereas Tidewater aromatics peaked at xylene, the other leases peaked at toluene, though it is noteworthy that xylene
 366 and toluene concentrations were similar. The Tidewater aromatic xylene peak was similar to the Port Industrial's peak,
 367 but not the other sources. For Warren and Pico, cyclohexane was higher than cyclopentane; for Tidewater, cyclohexane
 368 was lower than cyclopentane, as was the case for Port Industrial. Tidewater was unique because cyclopentane was
 369 higher than benzene, similar to Port Industrial. For the other leases, benzene was lower than toluene. Except for
 370 Warren, where they were similar, methylcyclopentane was higher than methylcyclohexane for the other leases.
 371



372
 373 **Figure 5. Port-area Oil Wells, average, and background normalized air-sample concentrations, $\langle C \rangle$, for A) short-chain non-**
 374 **methane hydrocarbons, B) selected volatile aromatic hydrocarbons, and C) selected gas ratios. See Fig. 4 caption for ratio**
 375 **key. Legend includes sample canister numbers.**

376 3.3.4. Refineries

377 The Refinery's and Oil Wells' trace gas concentration profiles differed significantly. Notably, the Refinery average
 378 poorly represented each refinery's specific pattern, which showed significant differences between refineries (Fig. 6),
 379 although composition profiles were consistent for each refinery's samples. For example, see Supp. Figs. S6 and S7 for
 380 the Valero refinery. Specifically, butane (C_4) and pentane (C_5) were comparable, whereas ethane was lower than C_3 -
 381 C_5 . Additionally, there is a peak at C_4 - C_5 for Valero (Fig. 6-red), at C_5 for Phillips (Fig. 6-green), and at C_4 for Carson
 382 (Fig. 6-yellow). This peak ($C_3 < C_4$ and $C_3 < C_5$) is consistent with propane steam cracking, i.e., depletion, and the
 383 formation of ethyne and propyne. Steam cracking also forms propadiene, which was largely undetected. For Carson,
 384 propyne was only slightly lower than propane.



Concentrations then decrease smoothly for Phillips 66 and Carson for alkanes larger than C₅, while slightly for C₁₀. The highest olefin concentrations were ethene for Phillips and Valero, and an anomalously high cis-butene for Carson Refinery. Carson cis-butene was higher than pentane (a cis-butene / trans-butene ratio of 170), which is highly distinct from all other sources. In contrast, this ratio was 0.76 and 0.82 for Valero and Phillips, respectively. This strong characteristic was not observed in the cis-pentene / trans-pentene ratios, which were 0.47, 0.56, and 6.42 for Phillips66, Carson, and Valero, respectively.

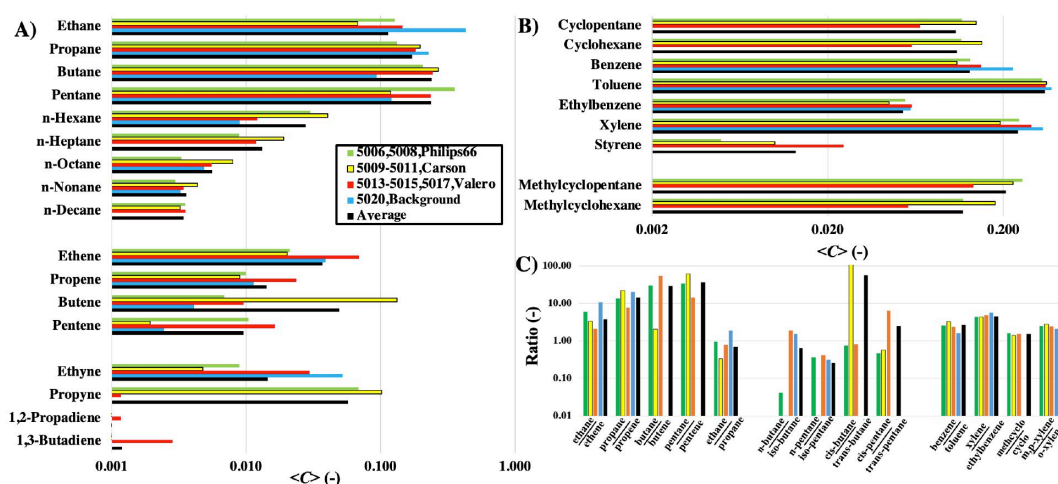


Figure 6. Port area refineries, average, and background normalized air sample concentrations, $\langle C \rangle$, for A) short-chain non-methane hydrocarbons, B) selected aromatic hydrocarbons, and C) selected gas ratios. See Fig. 4 caption for ratio key. Legend includes sample canister numbers.

In contrast, ethyne was comparable across the Refineries and Oil Wells categories, propyne was almost as high for Carson as butene, barely detected for the Valero refinery, and absent for the Oil Wells. The alkane-to-alkene ratio increased smoothly with n for Phillips66 C₂-C₅ and to a C₃ peak for Valero (Fig. 6, red), but in a zig-zag pattern in the ratio with n for Carson (Fig. 6, yellow). A similar zig-zag pattern in the alkane-to-alkene ratio was observed for Port Industry, whereas the ratio for Storage increased monotonically with increasing n . Toluene was the strongest aromatic hydrocarbon, followed by xylene. Cyclopentane and cyclohexane were equal, the same as Oil Wells and Storage, and unlike Port Industrial and Background, for which cyclohexane was lower. For all refineries, methylcyclopentane was higher than methylcyclohexane. The methylcyclohexane / cyclohexane ratio was similar across refineries and slightly lower than for Storage. Higher methylation of aromatics adds anti-knock performance in fuels.

3.3.5. Storage

The profile for 1Petro Storage generally followed that of the refineries for alkanes, alkenes, and VOCs, except for ethane (Supp. Fig. S8). Ethyne was comparable to ethene, but propyne was not detected, unlike Carson, which was prominent, and Port Industrial, where it was detected. The standard deviation of the ratios of storage to refineries (Fig. 7) for alkanes, C₃-C₁₀, was lowest for Valero at 0.32 compared to 1.7 for Carson and 0.69 for Phillips66. Standard



deviations for the BTEX ratios were lower, 0.089, 0.208, and 0.122, for the Valero, Carson, and Phillips Refineries, respectively. This suggests the Valero Refinery is the source of 1Petro Storage. Additionally, the Carson and Phillips Refineries have significantly elevated ethyne and 1,4 butadiene, consistent with the source of Storage (1Petro) being the Valero Refinery.

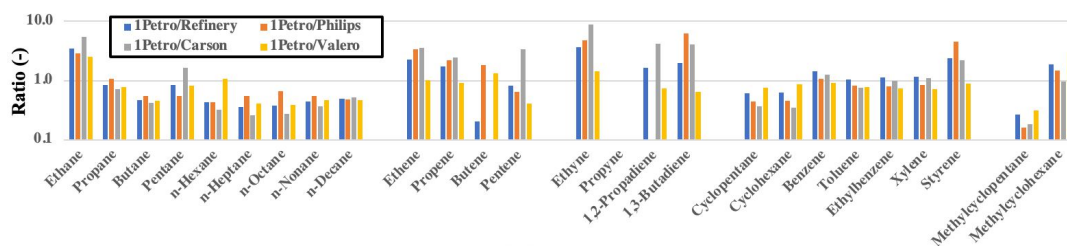


Figure 7. Ratio of average 1Petro (Storage) to average Refineries for normalized air sample concentrations for short-chain non-methane hydrocarbons and selected volatile aromatic hydrocarbons. See Supp. Fig. S8 for individual One Petro Storage samples. Data key on figure

3.3.6. Port Industry and other industrial sources

The largest port-area non-petroleum hydrocarbon-associated industrial sources are the ports of Los Angeles and Long Beach (Fig. 8-black). Other important industrial Port area sources include a Calciner, an Air Products facility, two wastewater treatment plants (Wastewater), and a sulfur processor—the California Sulfur Company (Cal. Sulfur). See Supp. Figs. S8-S13 for detailed individual profiles on these sources.

Port Industry (Calciner, Cal. Sulfur, shown in Fig. 4) and the Ports (Fig. 8-black, Supp. Fig. S9) generally were similar, with some exceptions. The strongest aromatic hydrocarbon for the Ports was xylene, slightly stronger than toluene, whereas toluene was the strongest for the California Sulfur Company (Fig. 8-orange) and Calciner (Fig. 8-white). Toluene is a by-product of coke production and gasoline production, and it also occurs in crude oil. Coke production also yields xylene, which is present in crude oil (Rittman et al., 1916). Storage and Refineries showed that toluene was stronger than xylene. Another difference was in cyclopentane and cyclohexane, with Ports and California Sulfur favoring cyclohexane, whereas the Calciner strongly favored cyclopentane. Note that these two trace gases were roughly equal for Refinery and Oil Wells. Methylcyclopentane was strongly favored over methylcyclohexane for Calciner, Ports, and Cal Sulfur Co.

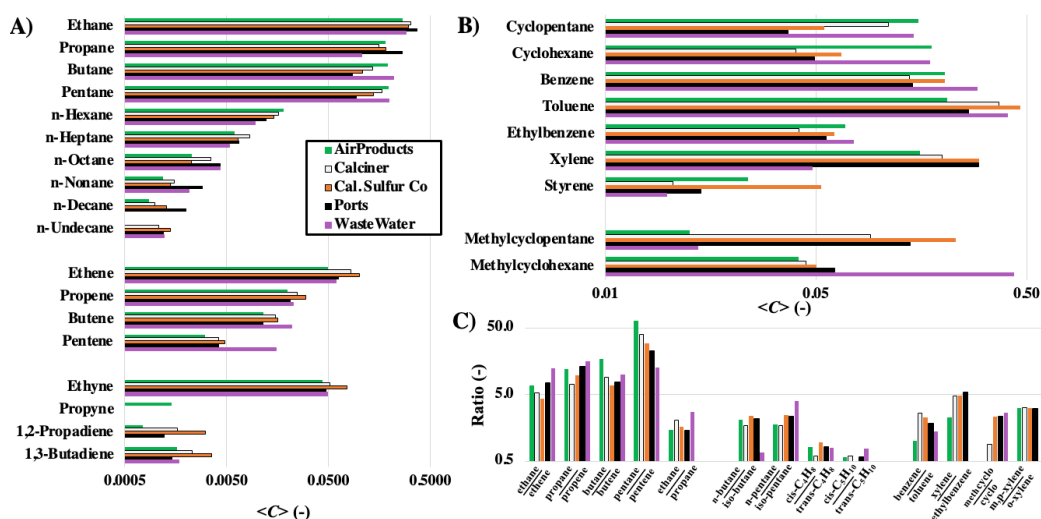


Figure 8. Average, normalized air sample concentrations, $\langle C \rangle$, for significant port-area, industrial (non-petroleum) sources for A) short-chain non-methane hydrocarbons, B) selected aromatic volatile hydrocarbons, and C) selected gas ratios. See Fig. 4 caption for data key. See Supp. Figs. S9-S13 for profiles of samples from each source.

The Ports' alkanes C_2 and C_3 were higher than other Port Industrial sources and lower for C_4 and C_5 , i.e., favored the lightest alkanes. The Ports also decreased smoothly from C_6 to C_{11} , i.e., no flattening. In contrast, the Calcliner (Fig. 8-white, Supp. Fig. S10) and California Sulfur (Fig. 8-orange, Supp. Fig. S12) flattened out for C_{10} - C_{11} , a pattern also observed for Wastewater. A decrease with n also was observed in the alkenes. Larger alkenes for the Ports decreased more slowly than for the Calcliner. Ethyne was the strongest for California Sulfur Company, for which it was slightly lower than ethene; however, for the Ports, ethyne and ethene were comparable. The alkane/alkene ratio increased smoothly with n , whereas this ratio increased with n in a zig-zag pattern for the Ports and California Sulfur, similar to Refineries.

The Air Products facility is a unique refinery that produces specialty gases rather than primarily producing fuels, and thus has a fairly distinct profile from Refinery (Fig. 8-green, Supp. Fig. S11). Light alkanes were flat for C_3 - C_5 , decreasing strongly to C_6 and smoothly for larger alkanes. Refinery either increased for light alkanes to a peak at C_4 (Carson, Valero) or C_5 (Phillips66). Alkenes also decreased smoothly with n , similar to the Ports, whereas Refinery showed no consistent trend. Only two sources featured notable propyne, Air Products and Refineries, primarily Carson and Phillips66, with the Refinery propyne higher than ethylene. In contrast, Air Products propyne was less than ethyne. Propyne is an undesired by-product of steam cracking propane to propene and exists in equilibrium with propadiene (Buekens and Froment, 1968), which also was detected. Steam cracking of propane also produces ethene or ethylene (Buekens and Froment, 1968), consistent with ethyne and ethene having comparable concentrations. Air Products aromatics were much flatter from cyclopentane to toluene (where there was a peak) than Refineries. Atypically, methylcyclopentane was lower than methylcyclohexane, unlike any other source (except Background). The alkane-to-alkene ratio increased smoothly with n , a trend observed for the Phillips 66 refinery.

The Wastewater plant trace gas profile was distinct, with two peaks in the light alkanes – ethane and butane, but propane was similar to butane (Fig. 8-purple, Supp. Fig. S13). Large alkanes (C_8 - C_{11}) decreased smoothly, albeit



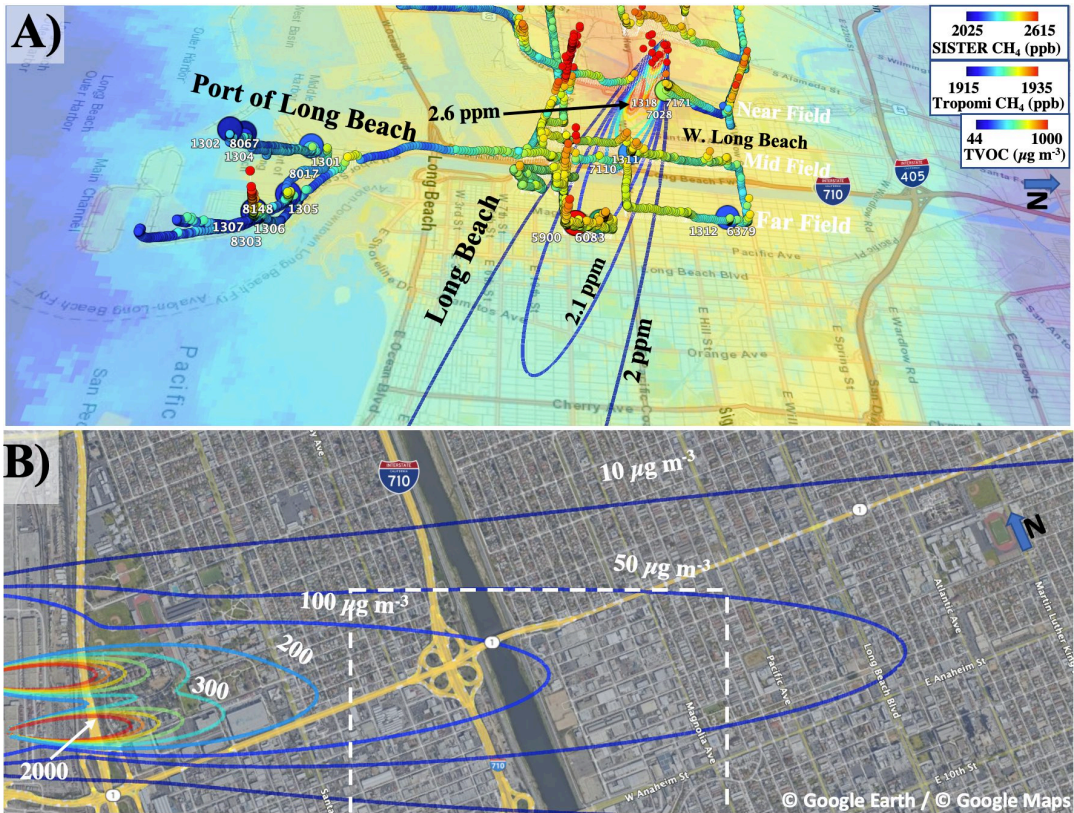
458 decane was not detected; alkenes decreased unevenly with n , with far higher pentene than other industrial Port area
459 sources. As a result, the alkane-to-alkene ratio was roughly constant with n . Also, n-pentane was strongly favored
460 over iso-pentane, whereas iso-butane was strongly favored over n-butane. Toluene was the strongest aromatic for
461 Wastewater, which smoothly decreased for both larger and smaller aromatics. Additionally, styrene was significantly
462 lower than for other sources.

463 **3.4. Long Beach community trace gas composition**

464 Long Beach community surveys were conducted during the afternoon to early evening, when prevailing and steady
465 winds transported air from the Ports and Refinery into these neighbourhoods (Fig. 9, Supp. Fig. S14 for enlarged
466 views of the Port of Long Beach and W. Long Beach). A plume was transected multiple times at different downwind
467 distances on 8 Mar. 2023, each of which provided a different emissions measurement. Air samples also were collected
468 on each transect and clean Pacific air for reference Background. Super-sample analysis of Tropomi CH₄ long-term
469 data shows that the snapshot plume observations are consistent with long-term spatial CH₄ patterns.
470 The plume structure was most detailed in the near-field transect and primarily showed two well-defined plumes riding
471 on a broader plume, which was modelled as a line source. The plume inversion model focused on the area covered by
472 data collection. The forward plume model did not extrapolate beyond the *in situ* data range.



473



474

475 **Figure 9. A) *In situ* methane, CH₄, and wind speed, *u*, and super-sampled TROPOMI satellite, median CH₄, for settings:**
476 **easting and northing grid resolutions, 0.0005°, 0.0002°, respectively, averaging length, 0.016°, cutoff distance, 0.040°, and**
477 **eccentricity, 1.25. Canister samples shown as big colored circles at the collection locations, see Supp. Figure S14 for enlarged**
478 **views and Supp. Figure S15 for the full *in situ* dataset. Circle color indicates total volatile organic compounds (TVOC, all**
479 **organic gases larger than ethane), as in the data key with sample number labeled. Also shown is the Gaussian plume model**
480 **for CH₄. B) Forward-modeled TVOC plume. See text for details.**

481 Plume emissions were 0.82 Gg CH₄ yr⁻¹ and 67 tons ethane yr⁻¹. The ethane analyzer response was slower than the
482 CH₄ analyzer, which "smoothed" the detailed CH₄ plume structure. Thus, the ethane plume inversion model was
483 initialized with the CH₄ plume's structure optimized against the transect data. TVOC emissions were derived from
484 canister composition data (Fig. 10, Supp. Fig. S16) scaled by the *in situ* CH₄. The TVOC-CH₄ scaling to estimate
485 emissions was based on air samples and showed a ratio of 0.96 µg m⁻³ CH₄' to 221 µg TVOC m⁻³. This TVOC scaling
486 (Fig. 9B) yielded 1.2 Gg TVOC yr⁻¹, where TVOC is defined here as all organic compounds larger than ethane, and
487 represents the actual TVOC based on the actual trace gas composition profile.

488 The near-field transect (#7171 and #7028) shows a propane minimum and butane maximum for light alkanes (C₂-C₅)
489 with a peak at C₅ that was essentially equal to C₄ (Fig. 10-dark blue). For larger alkanes, the decrease is smooth and
490 slightly asymptotic in log-space. The large alkane pattern was similar to that of the Carson and Phillips refineries,
491 albeit steeper. In contrast, the small alkane peak at C₅ was similar to that for Refinery except for ethane, which was



higher in the plume than propane, a pattern seen for Air Products; however, larger alkanes for Air Products decreased smoothly. Alkenes decreased smoothly with n , a trend not observed for the Refinery class, but which is observed for the Pico Lease, although not the other leases, Storage, the Ports, Wastewater, Calciner, and the California Sulfur Company. Ethyne was comparable to ethene for many of these sources, but not Storage, Refinery, or Oil Wells.

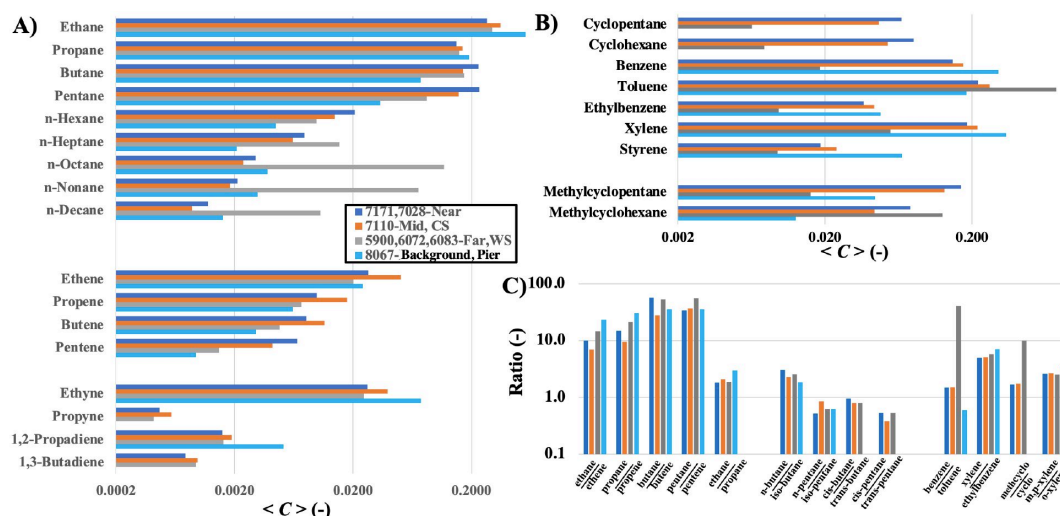


Figure 10. Normalized concentration, $\langle C \rangle$, for selected chain, saturated and unsaturated non-methane hydrocarbons in samples (sample number(s) noted on legend) for A) selected aromatic hydrocarbons for the Long Beach plume and Background, and C) Selected gas ratios. Data key on panel A. CS-Cabrillo High School, WS-Washington Middle School. See Supp. Figure S16 for non-normalized individual sample concentrations and locations.

Toluene was the strongest aromatic hydrocarbon, slightly higher than xylene, which was only marginally higher than benzene. Similar levels of xylene and toluene were observed for the Oil Wells and the Ports; however, benzene levels were lower. However, the Ports featured high styrene and cyclopentane, unlike this plume. Methylcyclopentane was similar to xylene, as observed for the Tidewater lease, but not for Refinery, Storage, and other Port-area sources, or the other oil leases. The alkane-to-alkene ratio increased to a peak at C_4 , only similar to that of the Valero refinery. Methylcyclopentane was slightly higher than methylcyclohexane, a pattern observed for all refineries, the Ports, the Calciner, and the Pico and Tidewater leases.

The mid-distance transect was similar to the near-field transect, albeit with a flatter C_2 - C_5 plateau and a smooth decrease for C_6 - C_{10} , i.e., no peak at C_8 (Fig. 10-orange). In absolute terms, alkane concentrations were lower except for ethane and propane (Supp. Fig. S16). The mid-distance alkenes C_2 - C_4 were elevated compared to the near-field samples, and their decrease with n was smoother. The mid-distance BTEX aromatics were nearly identical to the near-field samples, whereas cyclopentane and cyclohexane and their methylated versions were lower compared to the near field. Additionally, the alkane-to-alkene ratio increased more smoothly to a peak at C_5 than for the near-field transect. The alkane-to-alkene ratio trend was similar to that of the Phillips 66 refinery, Storage, Calciner, and Air Products; however, it differed significantly from the Oil Leases (decrease) and the Ports (zig-zag). The pattern for two of the far-field transect samples collected at the Washington Middle School (#5900, #6083-gray) was quite different,



showing a peak at C₈, spanning from C₆ to C₁₀. This pattern was not characteristic of other Port-area sources and is proposed to be from a closer source, which also is supported by the presence of a narrower plume feature that possibly originated from an upwind cluster of abandoned and idled oil wells (Supp. Fig. S17). The third far-field sample (#6072) was collected east of the middle school and had a pattern consistent with the other transects. Toluene for the Middle School samples was over an order of magnitude higher than that of other aromatics, accompanied by highly-enhanced methylcyclohexane.

Interestingly, background large alkanes also showed a C₈ peak (in the range C₇ to C₁₀), and alkenes decreased with *n* linearly (in log space, i.e., a power law), albeit more steeply than the transects. Background xylene was slightly higher than benzene but well above toluene, with methylcyclohexane, cyclopentane, and cyclohexane not detected. The background sample was collected from the east pier.

The ethane/propane ratios for the Long Beach plume ranged from 1.82 to 1.89, very similar to the Valero refinery at 1.89, but not the other refineries (0.34 and 0.79). The butane isomer ratios were 0.33 to 0.43, similar to those of the Valero refinery, 0.53, and distinct from those of the other refineries (24 and 136). Saturation ratios were significantly lower for the Valero refinery than for the plume, excluding C₄, due to its unusual isomer ratios. For example, the pentane/pentene ratio for the Long Beach plume was 35 to 57; for the refineries, it was 14, 35, and 62 for the Valero, Phillips, and Carson refineries, respectively. Also noteworthy was the presence of 1,2-propadiene and 1,3-butadiene in the Long Beach plume, similar to the Valero refinery.

Alkane-to-alkene ratios differed significantly from those of Oil Production, which were much higher for the Long Beach plume, and varied between transects, but overlapped with Refinery alkane-to-alkene ratios. Specifically, the propane/propene ratio for the Long Beach plume and the refineries ranged from 10 to 22, compared to 8 to 22, respectively, and the pentane/pentene ratio ranged from 35 to 57, compared to 15 to 62, respectively. The ethane/ethene ratio was 8 to 22 for refineries and 7 to 15, respectively.

Cyclopentane and cyclohexane are nearly equal for the Refinery and Long Beach Plume samples, whereas cyclohexane is elevated above cyclopentane in the oil well air samples. The ethylbenzene to benzene ratio for the Long Beach plume was very different, ranging from 0.25 to 0.52, compared to 5.8 to 8.0 for the refineries. Thus, this ratio was more similar to the oil production ratios (0.1 and 0.17). Also notable were the exceptionally high toluene levels in the Washington Middle School samples (#5900, #6083 - gray) and one oil field sample (#6091). This feature could arise from local solvent emissions for both samples and thus may be atypical.

4. Discussion

In the modern globalized world, ports are a critical nexus of economic activity that links industry and transportation. Close access to international and domestic transportation routes attracts heavy industry to the areas around ports. Thus, the larger port ecosystem emits significant greenhouse gases and atmospheric pollutants. Moreover, major urban areas often develop around ports- unsurprising given the significant economic activity they support, also contributing atmospheric emissions. Unfortunately, nearby downwind urban neighbourhoods bear the undue health and social effects of this pollution.



553 The Ports of Los Angeles and Long Beach (the Ports) exemplify typical port characteristics, including environmental
 554 justice issues in the diverse and disadvantaged downwind neighbouring communities. As such, efforts have long
 555 focused on improving air quality at the Ports. For example, the Ports' nitrogen dioxide (NO₂) sulphur dioxide (SO₂)
 556 and particulate matter (PM_{2.5}) aerosols have been reduced by 56%, 97%, and 87% since 2005, respectively (POLB,
 557 2020). The Ports' air quality stations only measure criterion pollutants, thus, there are no VOC trend data.
 558 One potential and novel approach to monitoring and reconstructing past VOC datasets is to leverage gas co-emissions.
 559 Specifically, a satellite-observable (CH₄, CO₂, or NO₂) or air quality-station, co-emitted gas (NO₂) provides the trend.
 560 Then, measuring the source(s) emission ratios for the satellite-observed gas and a second, non-satellite-observable gas
 561 (e.g., VOCs) allows scaling to derive the trend of a second gas. This approach was used to for dairy ammonia (NH₃)
 562 which is satellite observable and hydrogen sulphide (H₂S) which is not (Leifer et al., 2019b). The co-emission
 563 approach, for example, is used to target air sample collection using the real-time monitoring of *in situ* CH₄ data. We
 564 also leverage co-emissions to scale canister data with *in situ* transect CH₄ data to derive emissions for the wide range
 565 of trace gases measured from the canister samples, which cannot be measured by current *in situ* analysers. Forward
 566 plume modelling then provided a TVOC concentration map. We reference satellite CH₄ data to confirm
 567 representativeness – *in situ* surveys are inherently sporadic and infrequent.
 568 There are potential uncertainties and biases in co-emission analysis due to losses from gas reactions and deposition,
 569 which vary between gases and that emission factor ratios may change over time. For the Long Beach plume, 1-2 km
 570 distance corresponds to 0.1-4 hours for the observed wind speeds (1.5-2.5 m s⁻¹). Thus, minimal chemical
 571 transformations are expected for most alkane and aromatic species between the source and measurement locations,
 572 and into neighbouring communities. Chemical reactions become important over longer distances / time scales.
 573 Surface stickiness was implemented in the forward model and inversion as very effective for molecules that are
 574 primarily liquid at ambient pressure and temperatures, set at molecules larger than five carbon atoms. Of course, some
 575 surface-adsorbed gases will desorb; thus, assuming 100% adsorption rate is conservative with respect to concentration
 576 decreasing with distance.

577 **4.1. Source evaluation challenges**

578 Air quality surveys in port environments are highly challenging for several reasons. First, there are numerous sources
 579 in proximity, which can confound inversions. Secondly (and most significantly), many roads and areas are restricted,
 580 preventing access to downwind of some sources for surveying; in other locations, tall buildings block winds (and
 581 plumes). Additionally, the Ports are embedded in a major metropolitan city (the Los Angeles basin), with its attendant
 582 pollution. Key to both these challenges is conducting surveys under acceptable wind conditions, which vary with the
 583 diurnal cycle and across the port (Fig. S2). Here is where persistence in wind flow patterns at different times of day
 584 can guide survey design, including timing, in conjunction with source locations and downwind accessibility. For
 585 example, a survey conducted on 2 November 2022 in the early evening, after other survey priorities were completed,
 586 attempted to map plumes flowing into Long Beach. However, winds shifted from the prevailing afternoon wind pattern
 587 (WNW) to the night breeze (N) during the transect. Thus, a return Long Beach survey was conducted mid-afternoon
 588 under steady, prevailing winds.



Unfortunately, VOC data are not collected by the port area air quality stations, which record criterion pollutants. Such data would be invaluable for understanding the contributions of different sources and their implications. Still, air quality stations are sparse and blend observations from multiple upwind sources, i.e., the station "probes" the direction the wind is blowing from (Leifer et al., 2021). Since winds follow diurnal wind-direction trends (e.g., Fig. S2), air quality stations primarily "probe" certain wind directions at different times of the day. As a result, air quality stations have "blind spots" in different directions at different times of the day. In coastal regions such as the Ports, this is driven by the sea-breeze/night-breeze wind cycle, with further topography-imposed constraints, i.e., diurnal blind spots. Mobile surveys can probe these blind spots by targeting areas near sources and across plumes where concentrations are elevated, providing both spatial context and high signal-to-noise for air samples. Emissions can be derived from continuous *in situ* data and for a wide range of VOCs by data fusion with discrete air samples.

4.2. Port-area volatile organic compounds

A wide range of TVOC arises from industrial activities in the port area, including oil production, refining, vehicular traffic (combustion of refined products), natural gas power generation, and wastewater treatment. The observed VOCs are of concern due to their health impacts (Ramírez et al., 2012), and their roles in the formation of O₃ (Sillman et al., 1990) and Secondary Organic Aerosols (SOA), particularly from toluene and ethyl toluene (Zhang et al., 2017). Port-area air sample showed distinct source composition profiles, albeit with some similarities. For example, toluene is the most abundant aromatic in all sources, even in marine air. Another characteristic was the alkane concentration decrease with carbon number, although there were several decrease patterns. The Long Beach plume sample at Washington Elementary School was an exception, with enhanced C₆-C₁₀ and exceptionally high toluene (>2 ppb). This sample was proposed as possibly from a local solvent emission. Crude oil emissions (Oil Wells) largely were deficient in alkenes and aromatics relative to alkanes. For example, C₂-C₄ are one to a few ppb, whereas aromatics are 20-100 ppt. With increasing carbon number, concentrations decreased to C₆-C₈ and then increased – corresponding to a shift in alkanes from mostly gas phase to mostly liquid phase and the different transport mechanisms to the leak(s). Note, decane is about a hundredth of ethane, and the alkenes are a tenth to a twentieth of the light alkanes, comparable to the heavier alkanes (C₆-C₁₀). This pattern is similar to the atmospheric emissions from the Deepwater Horizon oil spill, where aromatics were significantly depressed relative to alkanes, and alkanes decreased with carbon number and then levelled off around C₈ (Ryerson et al., 2011). For Eagleford oil and gas production (Cardoso-Saldaña et al., 2019) found a C₂/C₃ ratio of around unity; this ratio was ~2 for the port oil fields and from 0.3 to 1.8 for the refineries. Refinery emissions show far higher alkenes relative to light alkanes – a fifth to a tenth, and aromatics, around a tenth to a twentieth compared to crude oil, particularly for the lighter alkanes and alkenes (Fig. 4-yellow versus green). This is perhaps unsurprising as these components (alkenes and aromatics) improve the gasoline octane level (Tang et al., 2015). Tang et al. (2015) identified 180 compounds in gasoline, including predominantly alkanes and/or aromatics and, to a lesser extent, alkenes, with higher alkenes for higher gasoline grades.



The toluene to benzene ratio, T/B, varied from 1.2 for the Air Products facility to 4.0 for the Ports proper, i.e., toluene was the strongest aromatic hydrocarbon (AH). Refineries and Background had a ratio of 2.7, whereas T/B for Oil Wells was 2.2. A ratio of 2 is associated with vehicular combustion (Baltrėnas et al., 2011). This suggests (port area) background is driven by recirculated refinery emissions. Observed average benzene and toluene concentrations were below 1 ppb, lower than the several ppb reported by Baltrėnas et al. (2011) for a Baltic refinery, which has T/B ranging from 0.5 to 0.8, most similar to the Air Products facility. Baltrėnas et al. (2011) showed that basic meteorological conditions explained 30-40% of the concentration variability; however, they did not consider boundary layer height. The air samples were collected primarily in the afternoon when the typical boundary layer is high. Thus, higher downwind nighttime concentrations are expected when winds are calmer and the nighttime boundary layer is lower. Night conditions continue into the early morning. Photochemical reactions are unlikely to have altered the T/B ratio in this study or in Baltrėnas et al. (2011), who sampled ~3 km from a Baltic refinery, due to insufficient time for chemical transformation during transport.

The plume's alkane concentration profile pattern was similar to that of the Valero refinery – the plateau at butane and pentane, but not the heptane-hexane plateau. The Carson refinery also peaked at butane, but had anomalously high butene, unlike the Long Beach plume. Several important ratios were similar, the ethane/propane and butane isomer ratios; however, others were not. Also, the Valero ethene was almost an order of magnitude greater than hexane, but lower for the other two refineries. In contrast, ethene was similar to hexane in the Long Beach plume. Crude oil patterns were quite different in the light alkanes, heavy alkanes, and alkenes. The Port alkane profile shared characteristics with the Long Beach plume – a smooth, nearly linear (in log space) decrease for the large alkanes. Also, alkenes decreased smoothly with n for the Port and the Long Beach Plume, whereas Refinery alkenes trended erratically with n . The Ports' xylene was higher than toluene, unlike in the Long Beach Plume or the Refinery samples. To summarize, the Long Beach plume exhibited characteristics similar to Port area sources, but did not match others. One likely explanation is that the plume included contributions from multiple sources. Additionally, uncertainty also likely was due to inadequate source characterization to address spatial and temporal heterogeneity. This is particularly true for refineries, which encompass numerous chemical processes with complex trace gas profiles as raw feed is converted into a variety of intermediate and final products. The level of uncertainty in the trace gas profile characterization of different sources arise in part from the constrained number of samples collected for this exploratory and internally funded nature of this study.

4.3. Downwind community implications

Emissions from the Ports' and surrounding industries, including oil production, refining, industrial activities, and the Ports proper, affect downwind community air quality. Many diverse sources contribute a wide range of criterion pollutants, e.g., ozone and particulate matter, and non-criterion pollutants, e.g., straight-chain hydrocarbons and aromatic VOCs, this manuscript's focus. Although we included branched hydrocarbons in the TVOC calculation, their compositional patterns were not analysed.

West Long Beach air samples were collected using real-time, co-emitted CH₄ visualization to ensure samples targeted the plume. These samples showed a wide range of VOCs at non-trivial concentrations in the community, raising



659 concerns about health impacts. TVOC emissions of 1.2 Gg yr^{-1} were derived by data fusion of air sample species
660 concentrations with *in situ* continuous data. The best-fit plume from the inversion was forward modelled to derive
661 exposure contours. Satellite CH_4 data (**Fig. 9**) showed that this southeast drifting plume was not atypical at TROPOMI
662 overpass time, i.e., exposure is chronic.

663 The plume contains high concentrations ($> 1 \text{ ppb}$) of light alkanes ($\text{C}_2\text{-C}_5$) and with large alkane concentrations
664 approximately an order of magnitude lower. Alkenes $\text{C}_2\text{-C}_5$ were similar to the large alkanes, with ethyne's
665 concentration similar to ethene and heptane's. Aromatic hydrocarbon concentrations (benzene, toluene, xylene) were
666 similar to alkene concentrations (Supp. Fig. S16). These gases, among others observed, are of significant health
667 concern.

668 Alkanes, cycloalkanes, naphthenes, and aromatic hydrocarbons are membrane-perturbing compounds that may impair
669 neurotransmission, leading to neural damage (Fedan et al., 2024). Sub-chronic exposure to petroleum hydrocarbons
670 alters neurotransmitter levels (Fedan et al., 2024). Hexane also depresses the central nervous system, which affects
671 the peripheral nervous system. Hexane exhibits liver toxicity at high doses but appears not to affect the respiratory
672 organs (Jørgensen and Cöhr, 1981). Pentane can cause chemical pneumonitis or pulmonary edema, whereas octane
673 and nonane can impair liver function (Kim et al., 2012).

674 Gases such as benzene, ethylene, ethylbenzene, toluene, styrene, and hexane can damage various organs, including
675 the eyes, liver, and kidneys, as well as a wide range of systems, including the respiratory, hematopoietic, nervous,
676 reproductive, alimentary, endocrine, and cardiovascular systems (Chan et al., 2006). For example, ethylene, styrene,
677 toluene, and hexane affect the nervous system, whereas 1,3-butadiene affects the reproductive system. Toluene also
678 affects the alimentary system and development (Chan et al., 2006). Gases such as 1,3-butadiene and benzene (observed
679 downwind of the Port refineries) have well-known cancer risks (Marquès et al., 2020).

680 The cellular pathways of toxicological effects from crude oil VOC exposure are beginning to be elucidated (Fedan et
681 al., 2024). For example, inflammatory cytokines are observed in the heart and kidneys after VOC exposure (Fedan et
682 al., 2024). In a review of the health impacts, however, Fedan et al. (2024) note that the molecular/cellular-level
683 information on VOC impacts on mammals is limited.

684 Refineries are associated with emissions of VOCs (this study), criterion pollutants such as O_3 and NO_x (Leifer et al.,
685 2023). Criterion pollutant exposure causes a range of health effects that overlap with those of VOCs. An additional
686 concern is the formation of secondary organic aerosols from VOCs and particulates, including aerosols with heavy
687 metals (Domingo et al., 2020), which penetrate deeply into the lungs where clearance times are long, posing a
688 significant health concern (Mauderly and Chow, 2008).

689 Literature reviews of refinery health risks by Marquès et al. (2020) and Domingo et al. (2020) showed higher asthma
690 and other respiratory problems, and adverse pregnancy and birth outcomes. Cancer incidence and cancer mortality,
691 most prominently leukemia and hematological malignancies, as well as cancer of the brain, bladder, and lungs, are
692 elevated (Domingo et al., 2020; Onyije et al., 2021). In a meta-analysis of petroleum workers, Onyije et al. (2021)
693 found lower rates of cancer of the digestive tract and pancreas, which was attributed to lifestyle factors (smoking,
694 physical exercise) than the general population. Contributing to worker health risk is exposure to hazardous materials
695 other than VOCs in the workplace.



Oil extraction or production (Oil Wells) is associated with cancer, liver damage (depressed liver enzymes), immunodeficiency, and neurological health effects in nearby communities (Johnston et al., 2019). Studies focused on incidence, e.g., McKenzie et al. (2017) reported elevated childhood leukemia risk near oil extraction.

The Ports proper are a strong VOC source – for example, Ports' toluene, xylene, and styrene were the highest among industrial sources – 1.3, 1.57, and 0.83 $\mu\text{g m}^{-3}$, respectively. In contrast, Refinery concentrations were 0.46, 0.32, and 0.016 $\mu\text{g m}^{-3}$, respectively. In fact, Ports' styrene, a neurotoxin, was 30 to 100 times higher than other Port area industrial sources and is reasonably anticipated to be a human carcinogen (National Toxicology Program, 2021). In contrast, butane, pentane, and hexane were higher for Refineries than the Ports, 9.1, 11.0, and 1.7 $\mu\text{g m}^{-3}$, versus 2.3, 2.4, and 0.3 $\mu\text{g m}^{-3}$, respectively. Thus, the VOC exposure health concerns for Refineries and Oil Wells likely also apply to VOC exposure from the Ports.

Typical exposure limits for alkanes like hexane are far higher than observed, for example, 50 ppm for 8 hours (CDC, 2025), orders of magnitude higher than observed in the Long Beach plume. However, sub-chronic exposure is not considered due to a lack of studies; for example, a report prepared for Alberta Environmental reviewed dozens of studies, none of which were sub-chronic (Cantox Environmental, 2004). As these are workplace regulations, exposure to children and infants, who have far lower body mass and different developmental considerations, are not considered. Additionally, synergistic exposures to multiple VOCs (as in the real world) and inhalation of VOC-laden aerosols are not considered.

Differences exist between regulatory agencies. For the probably best-characterized aromatic, benzene, the OSHA exposure limit is 1 ppm (OSHA, 2025), whereas the European Chemical Agency recommends 50 ppb (ECHA, 2025), and the American Conference of Governmental Industrial Hygienists recommends 20 ppb (NIOSH, 2014).

Notably, few port studies have investigated VOCs (Sarmiento et al., 2023); the vast preponderance focused on criterion air pollutants. In a scoping literature review, Mueller et al. (2023) note that globally ~265,000 premature deaths for 2020 were from shipping (primarily at ports where shipping emissions overlap significant populations) from O_3 , NO_x , SO_2 , and aerosol emissions. VOCs were not considered in any of the health impact studies. Thus, as mitigation efforts reduce criterion air pollutants, the largely unstudied VOC health impacts may mitigate against improved health outcomes.

With respect to exposure in neighbouring communities from Port-area sources, the diurnal wind cycle is critical – most of these sources do not exhibit a diurnal cycle. Night concentrations are higher due to lighter winds and a shallower boundary layer; however, nighttime exposure is far lower than daytime, when people are more likely to be outdoors. Port nighttime winds vary from the southeast to south to southwest, depending on the location. The strongest winds are afternoon southwesterlies, which decrease in the early evening. Thus, the highest exposure is likely in the early to mid-morning, when weak winds and a low boundary layer combine with outside exposure.

Considering the wind roses, for the east port, night winds are from the NNW around 40-60% of the time for the San Pedro, Wilmington, and Source-Dominated air quality stations, transporting east port industrial emissions offshore, but most of the rest of the time, winds would push port and refinery emissions into neighbouring communities. For the Inner Harbor, night winds were mostly from the northeast and sometimes southeasterlies, thus generally transporting air from Long Beach into the ports and offshore.



733 4.4. Further research needs

734 The data collected showed a wide variety of VOC trace gases emitted from various industrial sources in the Port area.
 735 For many sources, however, the number of samples was small, either because they were not the primary focus of a
 736 survey (e.g., wastewater treatment plants), due to source complexity (e.g., refineries or ports), and due to limited
 737 internal funds. Also, it is unknown whether the emissions profile varies seasonally, e.g., the winter fuel blend versus
 738 summer fuel blends for the refineries. Ultimately, these data can provide a basis for a health risk assessment, with
 739 exposure based on forward-modelled emissions from the various sources and emission factors, as was demonstrated
 740 for the Long Beach plume. The source emissions can be derived by inversion modelling of satellite GHG observations
 741 and then scaled with emission factors for VOC trace gases.

742 Due to travel logistics to the Ports, surveys were conducted from late morning to late night. Additionally, surveys
 743 began in the closer Ports' western area and extended eastwards, generally arriving at the Long Beach community late
 744 in the afternoon or the evening. This shortfall was addressed in the most recent surveys, including the eastern Ports,
 745 oil production along the I-710, the coal loading docks, and the Carson Refinery. Additional characterization of the
 746 eastern Ports area is needed, particularly with repetition. In addition, little *in situ* data have been collected north of the
 747 I-405, just 450 m north of the Carson refinery. There is a storage tank field north of the I-405. Additionally, there is a
 748 strong need for early to mid-morning surveys, when exposure likely is the highest. To date, morning surveys have not
 749 been conducted.

750 These measurements can form the basis of a health risk analysis. Specifically, we have demonstrated that different
 751 VOC species are not independent – the ratios are consistent for different types of sources. This likely results because
 752 the underlying processes are at temperatures and pressures that dictate the ratios (based on the chemical and physical
 753 properties of the different trace gases). In any case, we argue that the scaling between VOC trace gases extends to
 754 CH₄, which can be remotely sensed by satellites (Fig. 8).

755 Combining measured VOC concentrations (from forward Gaussian Plume modelling) with an inversion of TROPOMI
 756 CH₄ data estimates the seasonal CH₄ trend, which then can be scaled to VOC. Wind data from air quality stations can
 757 provide concentrations at times other than the TROPOMI overpass, although most stationary port emission sources
 758 operate round-the-clock and thus, should have no diurnal cycle. Once zip-code level diurnal and seasonal
 759 concentration trends are estimated, the personal exposure concentration can be calculated based on US EPA (2011)
 760 recommendations and used to calculate the hazard quotient index and lifetime cancer risk, as in Ghobakhloo et al.
 761 (2023).

762

763 5. Conclusion

764 This exploratory study investigated air pollution from the Ports of Los Angeles and Long Beach on downwind
 765 communities through a series of *in situ* mobile air quality laboratory surveys with uncertainty in the chemical profiles
 766 resulting from the limited number of surveys. We demonstrated the derivation of TVOC emissions for a plume flowing
 767 across West Long Beach. The approach can be extended to derive individual trace gas emissions or to estimate



emissions for different classes of trace gases, such as saturated light gas alkanes (C₂-C₅), BTEX, and methylated alkanes, etc. With respect to measurements in downwind neighbourhoods and understanding the health impacts, timing is an important factor given the strong, typical diurnal meteorological cycles. Under prevailing westerlies, air was observed to have a steadily increasing NO_x burden as it crossed the Port area industry into Long Beach. This air also significantly increased its burden of VOCs, which could contribute to worsening O₃ under future low NO₂ scenarios that failed to address VOCs. Given that VOC health risks differ between gases, this information can guide which pollutants are most important to focus on for mitigation.

Data availability: To explore the dataset, see the Supplemental Google Earth archive: “PortEmit_Pt3_VOC(10Jan2026).kmz” and description in Supp. Section S5 for further details. The sample trace gas chemical compositions used in this analysis are found in PortEmit_VOC_AirSampleData_for_ACP.xlsx

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801 **References**

- 802 Bakshi, A., Shemansky, J. M., Chang, C., and Binder, B. M.: History of research on the plant hormone
803 ethylene, *Journal of Plant Growth Regulation*, 34, 809–827, 10.1007/s00344-015-9522-9, 2015.
- 804 Baltrėnas, P., Baltrėnaitė, E., Serevičienė, V., and Pereira, P.: Atmospheric BTEX concentrations in the
805 vicinity of the crude oil refinery of the Baltic region, *Environmental Monitoring and Assessment*, 182,
806 115–127, 10.1007/s10661-010-1862-0, 2011.
- 807 Boufaden, N., Akkari, R., Pawelec, B., Fierro, J. L. G., Said Zina, M., and Ghorbel, A.: Dehydrogenation
808 of methylcyclohexane to toluene over partially reduced Mo–SiO₂ catalysts, *Applied Catalysis A:
809 General*, 502, 329–339, <https://doi.org/10.1016/j.apcata.2015.05.026>, 2015.
- 810 Buckland, K. N., Young, S. J., Keim, E. R., Johnson, B. R., Johnson, P. D., and Tratt, D. M.: Tracking and
811 quantification of gaseous chemical plumes from anthropogenic emission sources within the Los
812 Angeles Basin, *Remote Sensing of Environment*, 201, 275–296, 10.1016/j.rse.2017.09.012, 2017.
- 813 Buekens, A. G. and Froment, G. F.: Thermal cracking of propane. Kinetics and product distributions,
814 *Industrial & Engineering Chemistry Process Design and Development*, 7, 435–447,
815 10.1021/i260027a022, 1968.
- 816 Cantox Environmental: Assessment report on hexane for developing ambient air quality objectives,
817 Alberta Environment, Edmonton, Alberta ISBN: 0-7785-3986-5, 114, 2004.
- 818 Cardoso-Saldaña, F. J., Kimura, Y., Stanley, P., McGaughey, G., Herndon, S. C., Roscioli, J. R.,
819 Yacovitch, T. I., and Allen, D. T.: Use of light alkane fingerprints in attributing emissions from oil and
820 gas production, *Environmental science & technology*, 53, 5483–5492, 10.1021/acs.est.8b05828,
821 2019.
- 822 The National Institute for Occupational Safety and Health (NIOSH):
823 <https://www.cdc.gov/niosh/npg/npgd0322.html>, last access: 30 Nov 2025.
- 824 Chan, C.-C., Shie, R.-H., Chang, T.-Y., and Tsai, D.-H.: Workers' exposures and potential health risks
825 to air toxics in a petrochemical complex assessed by improved methodology, *International Archives
826 of Occupational and Environmental Health*, 79, 135–142, 10.1007/s00420-005-0028-9, 2006.
- 827 Coggon, M. M., Stockwell, C. E., Clafin, M. S., Pfannerstill, E. Y., Xu, L., Gilman, J. B., Marcantonio, J.,
828 Cao, C., Bates, K., Gkatzelis, G. I., Lamplugh, A., Katz, E. F., Arata, C., Apel, E. C., Hornbrook, R. S., Piel,
829 F., Majluf, F., Blake, D. R., Wisthaler, A., Canagaratna, M., Lerner, B. M., Goldstein, A. H., Mak, J. E.,
830 and Warneke, C.: Identifying and correcting interferences to PTR-ToF-MS measurements of isoprene
831 and other urban volatile organic compounds, *Atmos. Meas. Tech.*, 17, 801–825, 10.5194/amt-17-
832 801-2024, 2024.
- 833 Colman, J. J., Swanson, A. L., Meinardi, S., Sive, B. C., Blake, D. R., and Rowland, F. S.: Description of
834 the analysis of a wide range of volatile organic compounds in whole air samples collected during PEM-
835 Tropics A and B, *Analytical Chemistry*, 73, 3723–3731, 10.1021/ac010027g, 2001.
- 836 Derwent, R. G., Jenkin, M. E., and Saunders, S. M.: Photochemical ozone creation potentials for a large
837 number of reactive hydrocarbons under European conditions, *Atmospheric Environment*, 30, 181–
838 199, 10.1016/1352-2310(95)00303-G, 1996.



- 839 Dollison, R. M.: The National Map: New Viewer, Services, and Data Download, Report 2010–3055,
840 10.3133/fs20103055, 2010.
- 841 Domingo, J. L., Marquès, M., Nadal, M., and Schuhmacher, M.: Health risks for the population living
842 near petrochemical industrial complexes. 1. Cancer risks: A review of the scientific literature,
843 Environmental Research, 186, 109495, 10.1016/j.envres.2020.109495, 2020.
- 844 RAC recommends an occupational exposure limit for benzene: https://echa.europa.eu/_/committee-for-risk-assessment-recommends-an-occupational-exposure-limit-for-benzene, last
845 access: 30 November.
- 846 Fedan, J. S., Thompson, J. A., Sager, T. M., Roberts, J. R., Joseph, P., Krajnak, K., Kan, H., Sriram, K.,
847 Weatherly, L. M., and Anderson, S. E.: Toxicological effects of inhaled crude oil vapor, Current
848 Environmental Health Reports, 11, 18–29, 10.1007/s40572-024-00429-8, 2024.
- 849 Ghobakhloo, S., Khoshakhlagh, A. H., Morais, S., and Mazaheri Tehrani, A.: Exposure to volatile
850 organic compounds in paint production plants: Levels and potential human health risks, Toxics, 11,
851 111, 10.3390/toxics11020111, 2023.
- 852 GSFC: Sentinel-5P TROPOMI Methane CH4 1-Orbit L2 5.5km x 7km [dataset], 10.5270/S5P-3lcdqiv,
853 2024.
- 854 Hall, J. L., Boucher, R. H., Buckland, K. N., Gutierrez, D. J., Keim, E. R., Tratt, D. M., and Warren, D.
855 W.: Mako airborne thermal infrared imaging spectrometer – Performance update, Imaging
856 Spectrometry XXI, San Diego, CA, 28 August 2016, 997604, 10.1117/12.2239245,
- 857 Holzinger, R., Acton, W. J. F., Bloss, W. J., Breitenlechner, M., Crilley, L. R., Dusanter, S., Gonin, M.,
858 Gros, V., Keutsch, F. N., and Kiendler-Scharr, A.: Validity and limitations of simple reaction kinetics
859 to calculate concentrations of organic compounds from ion counts in PTR-MS, Atmospheric
860 measurement techniques, 12, 6193–6208, 10.5194/amt-12-6193-2019, 2019.
- 861 Houston, D., Li, W., and Wu, J.: Disparities in exposure to automobile and truck traffic and vehicle
862 emissions near the Los Angeles–Long Beach port complex, American Journal of Public Health, 104,
863 156–164, 10.2105/ajph.2012.301120, 2014.
- 864 Hricko, A.: Global trade comes home: Community impacts of goods movement, Environmental Health
865 Perspectives, 116, A78–A81, 10.1289/ehp.116-a78, 2008.
- 866 Igari, S.-I., Maekawa, T., and Suzuki, Y.: Pentane and hexane isomers in natural gases from oil and
867 gas fields in Akita, Niigata and Hokkaido, Japan: Determination factor in their isomer ratios,
868 Geochemical Journal, 41, 57–63, 10.2343/geochemj.41.57, 2007.
- 869 Johnston, J. E., Lim, E., and Roh, H.: Impact of upstream oil extraction and environmental public
870 health: A review of the evidence, Science of the Total Environment, 657, 187–199,
871 10.1016/j.scitotenv.2018.11.483, 2019.
- 872 Jørgensen, N. K. and Cohr, K.-H.: N-hexane and its toxicologic effects: a review, Scandinavian Journal
873 of Work, Environment & Health, 157–168, 1981.
- 874 Kalabokas, P. D., Hatzianestis, J., Bartzis, J. G., and Papagiannakopoulos, P.: Atmospheric
875 concentrations of saturated and aromatic hydrocarbons around a Greek oil refinery, Atmospheric
876 Environment, 35, 2545–2555, 10.1016/S1352-2310(00)00423-4, 2001.
- 877



- 878 Khatib, M. and Haick, H.: Sensors for Volatile Organic Compounds, *ACS Nano*, 16, 7080–7115,
879 10.1021/acsnano.1c10827, 2022.
- 880 Kim, J.-K., Cho, H.-W., Han, J.-H., Lee, S.-B., Chung, Y.-H., Rim, K.-T., and Yang, J.-S.: Subchronic
881 inhalation toxicity study of n-pentane in rats, *Safety and Health at Work*, 3, 224–234,
882 10.5491/SHAW.2012.3.3.224, 2012.
- 883 Leifer, I. and Melton, C.: Using mobile surface *in situ* and remote sensing and airborne remote sensing
884 to derive emissions from a producing central California oil field in complex terrain, *Air Pollution*
885 *Research*, 12, 101145, 10.1016/j.apr.2021.101145, 2021.
- 886 Leifer, I., Melton, C., and Blake, D. R.: Long-term atmospheric emissions for the Coal Oil Point natural
887 marine hydrocarbon seep field, offshore California, *Atmospheric Chemistry Physics*, 21, 17607–
888 17629, 10.5194/acp-21-17607-2021, 2021.
- 889 Leifer, I., Melton, C., and Tratt, D. M.: Air pollution from the Los Angeles and Long Beach Ports: Part
890 2. Methane emissions, *Atmospheric Environment*, 374, 121636, 10.1016/j.atmosenv.2025.121636,
891 2026.
- 892 Leifer, I., Melton, C., Manish, G., and Leen, B.: Mobile monitoring of methane leakage, *Gases and*
893 *Instrumentation*, July/August 2014, 20–24, 2014.
- 894 Leifer, I., Melton, C., Blake, D. R., Meinardi, S., and Kleinman, M. T.: Air quality trends for the Ports of
895 Los Angeles and Long Beach spanning the covid 19 crisis: Part 1. Oxidant pollutants, *Atmospheric*
896 *Environment*, 312, 119949, 10.1016/j.atmosenv.2023.119949, 2023.
- 897 Leifer, I., Melton, C., Chang, C., S., Blake, D. R., Meinardi, S., Kleinman, M. T., and Tratt, D. M.:
898 Validation of in situ and remote sensing-derived methane emissions from a refinery in a complex
899 wind environment and chemical profile implications, *Atmospheric Environment*, 273, 118900,
900 10.1016/j.atmosenv.2021.118900, 2022.
- 901 Leifer, I., Melton, C., Frash, J., Fischer, M. L., Cui, X., Murray, J. J., and Green, D. S.: Fusion of mobile
902 in situ and satellite remote sensing observations of chemical release emissions to improve disaster
903 response, *Frontiers in Science*, 4, 1–14, 10.3389/fenvs.2016.00059, 2016.
- 904 Leifer, I., Melton, C., Fischer, M. L., Fladeland, M., Frash, J., Gore, W., Iraci, L. T., Marrero, J. E., Ryoo,
905 J.-M., Tanaka, T., and Yates, E. L.: Atmospheric characterization through fused mobile airborne and
906 surface in situ surveys: Methane emissions quantification from a producing oil field, *Atmospheric*
907 *Measurement Techniques*, 11, 1689–1705, 10.5194/amt-11-1689-2018, 2018a.
- 908 Leifer, I., Melton, C., Fischer, M. L., Chatfield, R., Fladeland, M., Gore, W., Hvlaka, D., Iraci, L., Marrero,
909 J., Ryoo, J.-M., Tanaka, T., Yates, E., and Yorks, J. E.: Air pollution inputs to the Mojave Desert by
910 fusing surface mobile and airborne in situ and airborne and satellite remote sensing: A case study of
911 interbasin transport with numerical model validation, *Atmospheric Environment*, 224, 117184,
912 10.1016/j.atmosenv.2019.117184, 2019a.
- 913 Leifer, I., Melton, C., Tratt, D. M., Buckland, K. N., Chang, C., Lieven, C., Franklin, M., Hall, J. L., Leen,
914 B., Lundquist, T., Van Damme, M., Vigil, S., and Whitburn, S.: Estimating exposure to hydrogen sulfide
915 from animal husbandry operations using satellite ammonia as a proxy: Methodology demonstration,
916 *Total Science of the Environment*, 704, 134508, 10.1016/j.scitotenv.2019.134508, 2019b.



- 917 Leifer, I., Melton, C., Tratt, D. M., Buckland, K. N., Chang, C., Frash, J., Hall, J. L., Kuze, A., Leen, B.,
918 Lieven, C., Lundquist, T., Van Damme, M., Vigil, S., Whitburn, S., and Yurganov, L.: Validation of
919 mobile in situ measurements of dairy husbandry emissions by fusion of airborne/surface remote
920 sensing with seasonal context from the Chino Dairy Complex, *Environmental Pollution*, 242, 2111–
921 2134, 10.1016/j.envpol.2018.03.078, 2018b.
- 922 Manolakis, D., Pieper, M., Truslow, E., Cooley, T., Brueggeman, M., and Lipson, S.: The remarkable
923 success of adaptive cosine estimator in hyperspectral target detection, *SPIE Defense, Security, and*
924 *Sensing*, SPIE, 10.1117/12.2015392, 2013.
- 925 Marquès, M., Domingo, J. L., Nadal, M., and Schuhmacher, M.: Health risks for the population living
926 near petrochemical industrial complexes. 2. Adverse health outcomes other than cancer, *Science of*
927 *The Total Environment*, 730, 139122, 10.1016/j.scitotenv.2020.139122, 2020.
- 928 Mauderly, J. L. and Chow, J. C.: Health Effects of Organic Aerosols, *Inhalation Toxicology*, 20, 257–
929 288, 10.1080/08958370701866008, 2008.
- 930 McKenzie, L. M., Allshouse, W. B., Byers, T. E., Bedrick, E. J., Serdar, B., and Adgate, J. L.: Childhood
931 hematologic cancer and residential proximity to oil and gas development, *PLOS ONE*, 12, e0170423,
932 10.1371/journal.pone.0170423, 2017.
- 933 Metoree: Methylcyclohexane Manufacturers in 2024, 2024a.
- 934 Metoree: Cyclohexane Manufacturers in 2024, 2024b.
- 935 Mueller, N., Westerby, M., and Nieuwenhuijsen, M.: Health impact assessments of shipping and port–
936 sourced air pollution on a global scale: A scoping literature review, *Environmental Research*, 216,
937 114460, 10.1016/j.envres.2022.114460, 2023.
- 938 National Toxicology Program: Styrene: CAS No. 100–42–5, National Toxicology Program, Research
939 Triangle Park, NC, 10.22427/NTP-OTHER-1003, 2021.
- 940 Preliminary Field Studies on Worker Exposures to Volatile Chemicals during Oil and Gas Extraction
941 Flowback and Production Testing Operations: [https://blogs.cdc.gov/niosh-science-](https://blogs.cdc.gov/niosh-science-blog/2014/08/21/flowback-2/)
942 [blog/2014/08/21/flowback-2/](https://blogs.cdc.gov/niosh-science-blog/2014/08/21/flowback-2/), last access: 30 November.
- 943 Onyije, F. M., Hosseini, B., Togawa, K., Schüz, J., and Olsson, A.: Cancer incidence and mortality among
944 petroleum industry workers and residents living in oil producing communities: A systematic review
945 and meta-analysis, *International Journal of Environmental Research and Public Health*, 18, 4343,
946 10.3390/ijerph18084343, 2021.
- 947 Osenga, M.: Port of Long Beach starts new electrification program, 2018.
- 948 1910.1028 App A Substace Safety Data Sheet, Benzene: [https://www.osha.gov/laws-](https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.1028AppA)
949 [regs/regulations/standardnumber/1910/1910.1028AppA](https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.1028AppA), last access: 30 Nov.
- 950 Air Emissions Program Details: <https://www.polb.com/environment/air#air-program-details>, last
951 Ramírez, N., Cuadras, A., Rovira, E., Borrull, F., and Marcé, R. M.: Chronic risk assessment of exposure
952 to volatile organic compounds in the atmosphere near the largest Mediterranean industrial site,
953 *Environment International*, 39, 200–209, <https://doi.org/10.1016/j.envint.2011.11.002>, 2012.
- 954 Rittman, W. F., Dutton, C. B., and Dean, E. W.: Manufacture of gasoline and benzene–toluene from
955 petroleum and other hydrocarbons, *Petroleum Technology*, US Government Printing Office, 268
956 pp. 1916.



- 957 Ryerson, T. B., Aikin, K., Angevine, W., Atlas, E. L., Blake, D. R., Brock, C. A., Fehsenfeld, F. C., Gao,
958 R.-S., de Gouw, J. A., Fahey, D. W., Holloway, J. S., Lack, D. A., Lueb, R. A., Meinardi, S., Middlebrook,
959 A. M., Murphy, D. M., Neuman, J. A., Nowak, J. B., Parrish, D. D., Peischl, J., Perring, A. E., Pollack, I.
960 B., Ravishankara, A. R., Roberts, J. M., Schwarz, J. P., Spackman, J. R., Stark, H., Trainer, M., Warneke,
961 C., and Watts, L. A.: Marine spill atmospheric emissions constrain air–water partitioning,
962 hydrocarbon fate, and leak rate, *Geophysical Research Letters*, 38, L07803, 10.1029/2011GL0467,
963 2011.
- 964 Sarmiento, H., Potgieter-Vermaak, S., Borillo, G. C., Godoi, A. F. L., Reis, R. A., Yamamoto, C. I.,
965 Pauliquevis, T., Polezer, G., and Godoi, R. H. M.: BTEX profile and health risk at the largest bulk port
966 in Latin America, Paranaguá Port, *Environmental Science and Pollution Research*, 30, 63084–63095,
967 10.1007/s11356-023-26508-1, 2023.
- 968 Sillman, S., Logan, J. A., and Wofsy, S. C.: The sensitivity of ozone to nitrogen oxides and
969 hydrocarbons in regional ozone episodes, *Journal of Geophysical Research: Atmospheres*, 95, 1837–
970 1851, 10.1029/JD095iD02p01837, 1990.
- 971 Simpson, I. J., Blake, N. J., Barletta, B., Diskin, G. S., Fuelberg, H. E., Gorham, K., Huey, L. G., Meinardi,
972 S., Rowland, F. S., Vay, S. A., Weinheimer, A. J., Yang, M., and Blake, D. R.: Characterization of trace
973 gases measured over Alberta oil sands mining operations: 76 speciated C_{2-10} volatile organic compounds (VOCs), CO_2 , CH_4 , CO , NO ,
974 NO_2 , NO_y , O_3 and SO_2 , *Atmosphere Chemistry and*
975 *Physics*, 10, 11931–11954, 10.5194/acp-10-11931-2010, 2010.
- 977 Speight, J. G. and El-Gendy, N. S.: Chapter 2 – Refinery Products and By-Products, in: *Introduction to*
978 *Petroleum Biotechnology*, edited by: Speight, J. G., and El-Gendy, N. S., Gulf Professional Publishing,
979 Boston, 41–68, 10.1016/B978-0-12-805151-1.00002-3, 2018.
- 980 Spinelle, L., Gerboles, M., Kok, G., Persijn, S., and Sauerwald, T.: Review of Portable and Low-Cost
981 Sensors for the Ambient Air Monitoring of Benzene and Other Volatile Organic Compounds, *Sensors*,
982 17, 1520, 10.3390/s17071520, 2017.
- 983 Srivastava, S. K.: Green supply-chain management: A state-of-the-art literature review,
984 *International Journal of Management Reviews*, 9, 53–80, 10.1111/j.1468-2370.2007.00202.x,
985 2007.
- 986 Steffens, J., Kimbrough, S., Baldauf, R., Isakov, V., Brown, R., Powell, A., and Deshmukh, P.: Near-port
987 air quality assessment utilizing a mobile measurement approach, *Atmospheric Pollution Research*, 8,
988 1023–1030, 10.1016/j.apr.2017.04.003, 2017.
- 989 Sun, K., Zhu, L., Cady-Pereira, K., Chan Miller, C., Chance, K., Clarisse, L., Coheur, P. F., González Abad,
990 G., Huang, G., Liu, X., Van Damme, M., Yang, K., and Zondlo, M. A.: A physics-based approach to
991 oversample multi-satellite, multispecies observations to a common grid, *Atmospheric Measurement*
992 *Techniques*, 11, 6679–6701, 10.5194/amt-11-6679-2018, 2018.
- 993 Tang, G., Sun, J., Wu, F., Sun, Y., Zhu, X., Geng, Y., and Wang, Y.: Organic composition of gasoline and
994 its potential effects on air pollution in North China, *Science China Chemistry*, 58, 1416–1425,
995 10.1007/s11426-015-5464-0, 2015.



996 Thompson, D., Leifer, I., Bovensman, H., Eastwood, M., Fladeland, M., Frankenberg, C., Gerilowski,
997 K., Green, R., Krautwurst, S., Krings, T., Luna, B., and Thorpe, A. K.: Real-time remote detection and
998 measurement for airborne imaging spectroscopy: A case study with methane, *Atmospheric*
999 *Measurement Techniques*, 8, 1–46, 10.5194/amtd-8-4383-2015, 2015.
1000 US EPA: Exposure Factors Handbook 2011 Edition (Final Report), U.S. Environmental Protection
1001 Agency, Washington, DC, 1436, 2011.
1002 White, W. C.: Butadiene production process overview, *Chemico-Biological Interactions*, 166, 10–14,
1003 <https://doi.org/10.1016/j.cbi.2007.01.009>, 2007.
1004 Young, S. J., Johnson, B. R., and Hackwell, J. A.: An in-scene method for atmospheric compensation
1005 of thermal hyperspectral data, *Journal of Geophysical Research: Atmospheres*, 107, ACH 14–11–ACH
1006 14–20, 10.1029/2001JD001266, 2002.
1007 Zhang, Z., Wang, H., Chen, D., Li, Q., Thai, P., Gong, D., Li, Y., Zhang, C., Gu, Y., Zhou, L., Morawska, L.,
1008 and Wang, B.: Emission characteristics of volatile organic compounds and their secondary organic
1009 aerosol formation potentials from a petroleum refinery in Pearl River Delta, China, *Sci Total Environ*,
1010 584–585, 1162–1174, 10.1016/j.scitotenv.2017.01.179, 2017.
1011