SCOAPE-II: A 2024 Multiplatform Measurement Campaign off the US Gulf Coast to Assess Oil and Gas Emissions on the Outer Continental Shelf

Ryan M. Stauffer,[a] Niko M. Fedkin,[a,b] Anne M. Thompson,[a,c] Nikolay V. Balashov,[d,e] Debra E. Kollonige,[a,f] Martin Cadirola,[g] Joshua A. D. Richards,[c] Jonathan Gallegos,[h] Thomas F. Hanisco,[a] Holli D. Wecht,[i] Lok N. Lamsal,[i] Laura M. Judd,[j] Scott J. Janz,[a*] Andrew K. Thorpe,[k] Michael L. Eastwood,[k] Adam M. Chlus, [k] Robert O. Green,[k] Barbara Barletta,[l] Simone Meinardi,[l] Donald R. Blake[l]

[a] *Atmospheric Chemistry and Dynamics Laboratory, NASA/GSFC, Greenbelt, MD*

[b] *Science and Technology Corporation, Columbia, MD*

[c] *University of Maryland Baltimore County, Baltimore, MD*

[d] *Earth System Science Interdisciplinary Center, University of Maryland College Park, College Park, MD*

[e] *Global Modeling and Assimilation Office, NASA/GSFC, Greenbelt, MD*

[f] *ADNET Systems, Inc., Bethesda, MD*

[g] *Ecotronics Ventures, LLC., New Market, MD*

[h] *SciGlob Instruments and Services, LLC., Columbia, MD*

[i] *BOEM Office of Environmental Programs, Sterling, VA*

[j] *NASA/LaRC, Hampton, VA*

[k] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA*

[l] *Department of Chemistry, University of California Irvine, Irvine, CA*

**No longer at NASA/GSFC*

Corresponding author: Ryan M. Stauffer, ryan.m.stauffer@nasa.gov

ABSTRACT

Nine years ago, the Department of Interior's Bureau of Ocean Energy Management (BOEM), the Agency with Air Quality (AQ) jurisdiction over the Outer Continental Shelf (OCS) of the US Gulf Coast west of 87.5° W longitude, asked NASA to determine the feasibility of using satellite data to measure offshore emissions in a region of concentrated oil and natural gas (ONG) operations. To study this issue NASA and BOEM conducted the May 2019 Satellite Coastal and Oceanic Atmospheric Pollution Experiment (SCOAPE) cruise in the Gulf. SCOAPE addressed both technological and scientific issues related to measuring nitrogen dioxide (NO_2, a common air pollutant), including contrasting near-shore and deepwater regimes. Given the April 2023 launch of the geostationary Tropospheric Emissions: Monitoring of Pollution (TEMPO) AQ satellite, a 2024 SCOAPE-II was conducted in the Gulf with both ship and aircraft measurements. We present an overview of the SCOAPE-II campaign, analysis and validation of satellite-observed NO_2, and evaluate measurements of methane from ship, aircraft, and satellite near ONG platforms. Our SCOAPE-II results are as follows: 1) Satellite NO_2 measurements (~13:30 local time) from the TROPOspheric Monitoring Instrument (TROPOMI) are more accurate than TEMPO's hourly scans (8.6 % vs. 23.6% mean absolute bias); a new version of TEMPO data is currently being processed; 2) ship and aircraft measurements captured dozens of NO_2 and methane plumes from ONG operations, showing that they are persistent emitters; 3) satellite measurements of methane failed to replicate ship and aircraft measurements, presenting ongoing challenges for operational emissions monitoring over the Gulf.

SIGNIFICANCE STATEMENT

The exploration, extraction, and processing of oil and natural gas (ONG) from deposits off the US Gulf Coast generate detectable emissions affecting air quality (AQ). However, the lack of regular monitoring of these emissions makes quantifying their impact challenging. We conducted a ship and aircraft campaign in 2024 in the Gulf to characterize surface AQ, validate satellite AQ and methane measurements, and evaluate ONG emissions inventories. Our measurements indicate that ONG platforms are persistent emitters of nitrogen oxides (NO_x) that affect AQ, and methane, a potent greenhouse gas. Satellite nitrogen dioxide (NO_2) measurements are generally of sufficient accuracy for characterizing Gulf AQ, but

technological constraints preclude similar monitoring of ONG methane emissions from space.

CAPSULE

In 2024, a NASA- and BOEM-coordinated ship and aircraft campaign measured nitrogen dioxide and methane emissions from ONG infrastructure on the OCS in the Gulf with multiple instruments and satellite data.

1. Background

The waters of the Outer Continental Shelf (OCS) off the US Gulf Coast (simplified as "the Gulf" in this paper) are dotted with hundreds of offshore oil and natural gas (ONG) platforms and associated infrastructure. The exploration, extraction, and processing of ONG causes emissions affecting both air quality and greenhouse gases (air quality [AQ] and greenhouse gases [GHGs], e.g., nitrogen oxides [NO_x] and carbon dioxide [CO_2]) from combustion and other activities. These activities also lead to so-called "fugitive" methane (CH_4) from leaks, venting, or unlit/inefficient gas flares (**Plant et al., 2022**). Because the water depth in the OCS quickly increases just a few 10s of nautical miles (nmi) offshore, ONG platforms are far more numerous along the coast compared to deeper waters (see markings on **Figure 1** and **Thompson et al., 2023**). The shallow waters (< 400 meters depth as defined in https://www.boem.gov/regions/gulf-america-ocs-region/us-ocs-gomr-oil-and-gas-production-forecast-2022-2031) generally contain older infrastructure that focuses on gas extraction and are susceptible to CH_4 leaks and occasional venting. Technological improvements in recent decades allowed for the development and installation of much larger, deep-water tension leg platforms that extract and process oil, and are therefore larger NO_x emitters than their shallow-water counterparts due to their high energy demand for operations. Typical sources of NO_x emissions from platforms include natural gas, diesel or gasoline engines and turbines, drilling equipment, and combustion via flaring of excess natural gas. Most of the NO_x is emitted primarily as NO, with NO_2 being produced most readily from reaction with ambient ozone (O_3). In general, NO_x emissions control strategies are limited on Gulf platforms.

Over the past 15 years, researchers have used various instruments to quantify AQ and GHG emissions from numerous platforms in the Gulf, including GoMex in 2013 (**Kowalewski and Janz, 2014**), the 2018 ship cruise in **Yacovitch et al., (2020)**, and the

2020-2021 aircraft flights in **Ayasse et al., (2022)** and the Flaring and Fossil Fuels: Uncovering Emissions & Losses (F^3UEL) campaign (**Gorchov Negron et al., 2020; 2023; Biener et al., 2024**). These campaigns all produced valuable data on emissions and AQ conditions but they were only snapshots with limited geographical sampling.

The Bureau of Ocean Energy Management (BOEM), a US Department of the Interior agency, is mandated to ensure that emissions from ONG activities in the Gulf do not significantly affect the AQ of any US state. BOEM's federal air jurisdiction in the Gulf extends west of 87.5° W longitude off the coasts of Alabama, Mississippi, Louisiana, and Texas, to 200 nmi offshore where the US Exclusive Economic Zone terminates.

To assist with their monitoring and understanding of AQ and GHG emissions from ONG activities in the Gulf, every ~3 years BOEM compiles emissions inventories of criteria pollutants and GHGs (e.g., NO_x, sulfur dioxide [SO_2], CO_2, CH_4, Volatile Organic Compounds [VOCs]) from both platform and non-platform sources, such as drilling rigs and shipping traffic. The inventories rely on operator reporting, activity data, and emissions factors, but the lack of measurements of these trace gases in the Gulf makes validating the inventories and monitoring AQ a challenge. In 2017, BOEM and the National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center initiated a partnership to understand if satellite measurements could detect and monitor AQ and emissions over the most concentrated region of ONG facilities in the Gulf. The first outcome of the BOEM-NASA collaboration was a report (**Duncan, 2020**) that identified satellite products relevant to the detection of carbon monoxide (CO), NO_2, and CH_4, as well as related atmospheric variables, e.g., clouds, aerosols, and smoke. A second report (**Thompson, 2020**) described a capstone NASA-BOEM project: a nine-day oceanographic cruise off the Louisiana coast called Satellite Coastal and Oceanic Atmospheric Pollution Experiment (SCOAPE; **Thompson et al., 2023**) conducted in May 2019.

The goals of SCOAPE were threefold: (1) test a new model of the Pandora instrument (**Martins et al. 2016; Kollonige et al., 2017; Tzortziou et al., 2018; Thompson et al., 2019**) for measuring column NO_2 from the surface. This Pandora model was equipped with a sun-tracking camera suitable for a moving platform such as a ship; (2) survey "nose-level" air pollution (or AQ) near-shore and over deepwater (**Figure 1**); (3) validate satellite measurements of NO_2 throughout the Gulf, particularly near ONG operations.

The 2019 SCOAPE campaign vessel, the R/V *Point Sur*, departed from the Louisiana Universities Marine Consortium (LUMCON) in Cocodrie, LA (29.254° N, 90.662° W), outfitted with a suite of in situ trace gas, aerosol, and meteorological sensors, and a Pandora spectrometer instrument that directly validated polar-orbiting satellite NO_2 measurements from Aura's Ozone Monitoring Instrument (OMI; **Krotkov et al., 2016**) and the TROPOspheric Monitoring Instrument (TROPOMI; **van Geffen et al., 2022**). Among the findings of **Thompson et al. (2023)** was that the satellite NO_2 measurements agreed with the ship-based Pandora within about 5-15%, sufficient for accurate monitoring of NO_2 column amounts across the Gulf. Coincidentally, a frontal passage during SCOAPE led to a surge of higher NO_2 values from coastal and terrestrial sources, largely masking the signal from the isolated ONG NO_x sources in the open waters. However, follow-on work by **Fedkin et al. (2024)** examined a multiyear record from TROPOMI and determined that NO_2 column "hotspot" signals over the largest deep-water platforms approach 25% above background during calm wind conditions, showing promise for future calculations of ONG NO_x emissions over the OCS, at least under certain meteorological conditions.

As with other exploratory sampling over the Gulf, SCOAPE met all of its goals, establishing the accuracy of the ground-based Pandora and the potential for operational satellite instruments to map NO_2 over the Gulf. With the suite of instruments on the R/V *Point Sur,* SCOAPE was able to capture the complexity of AQ in the region. For example, under clean (onshore flow) conditions, ambient NO_2, O_3, and CO levels in the greater New Orleans region greatly exceed those over deepwater. However, CH_4 and a number of toxic VOC shipboard measurements spiked near smaller, near-shore operations that supply natural gas. A second phase of NASA-BOEM partnership offered an opportunity to further investigate these aspects of AQ and new satellite capabilities.

The April 2023 launch of the Tropospheric Emissions: Monitoring of Pollution (TEMPO; **Acker et al., 2025; Ghahremanloo et al., 2025**) geostationary AQ satellite instrument, a growing constellation of satellites designed to measure CH_4 emissions from space (e.g., GHGSat, Earth Surface Mineral Dust Source Investigation [EMIT], Environmental Mapping and Analysis Program [EnMAP], Tanager-1; **Jervis et al., 2021; Thorpe et al., 2023; Roger et al., 2024; Duren et al., 2025**), and the availability of mature aircraft remote sensors for NO_2 and CH_4 motivated NASA and BOEM to conduct a SCOAPE-II campaign in June and October 2024. In addition to the R/V *Point Sur* AQ

measurements, SCOAPE-II collected remotely-sensed aircraft measurements of CH_4 (June, coincident with the cruise) and NO_2 (October, aircraft only), and tasked satellite measurements of CH_4 from GHGSat to coincide with the ship and aircraft. This paper describes the design and goals of SCOAPE-II in Section 2, presents an overview and highlights of the measurements in Section 3, and outlines directions for future research in Section 4.

2. SCOAPE-II Design and Instrumentation

The June 2024 SCOAPE-II campaign was formulated with several goals and scientific questions in mind including:

1) Demonstration for the first time remotely-sensed AVIRIS-3 (see text below for a description) aircraft instrument's CH_4 measurements over the Gulf.
2) How accurate are TEMPO's hourly scans of NO_2 over the Gulf compared to TROPOMI and the ship-based Pandora?
3) How accurate is BOEM's latest 2023 OCS emissions inventory for NO_x and CH_4?
4) How might have AQ conditions in the Gulf changed since the May 2019 SCOAPE campaign five years prior?
5) Are satellite measurements of NO_2 (e.g., TROPOMI and TEMPO) and CH_4 (e.g., GHGSat) sensitive and of sufficient quality to operationally monitor Gulf AQ and GHG emissions?

Several of these goals and science questions will be addressed in manuscripts currently in preparation. Our intent with this paper is to describe the SCOAPE-II campaign and measurement data publicly available for the community's use. The SCOAPE-II cruise plan was designed similarly to the 2019 campaign, with the vessel sailing continuously from point-to-point at priority platforms identified as high CH_4 and NO_x emitters by BOEM's 2023 OCS emissions inventory, as well as experience from past campaigns listed in Section 1. Whereas the 2019 SCOAPE campaign focused primarily on large, deep-water platforms and NO_2, SCOAPE-II spent more time probing individual shallow-water platforms and coordinating with aircraft and satellite overpass measurements to simultaneously measure CH_4.

SCOAPE-II ship measurements were collected on the same vessel, the R/V *Point Sur*, as SCOAPE, also departing from the LUMCON Cocodrie, LA, port at approximately 22 CDT on 1 June (03 UTC 2 June) and returning at 10am CDT/15 UTC on 13 June. A map including dates and locations of the R/V *Point Sur* ship track over the course of the 12-day June 2024

campaign is shown in **Figure 1**. Much like SCOAPE, the R/V *Point Sur* was outfitted with a suite of in situ AQ and GHG trace gas (sampling from approximately 10 m above the water surface) and meteorological sensors, a Pandora spectrometer instrument for total column trace gases, and a ceilometer and MicroTops-II sunphotometer for aerosol profile and column information. Ozonesondes paired with meteorological radiosondes were launched daily beginning on 3 June, as the heavy sea state precluded deck work on 2 June. A full list of instrumentation appears in **Table 1**.

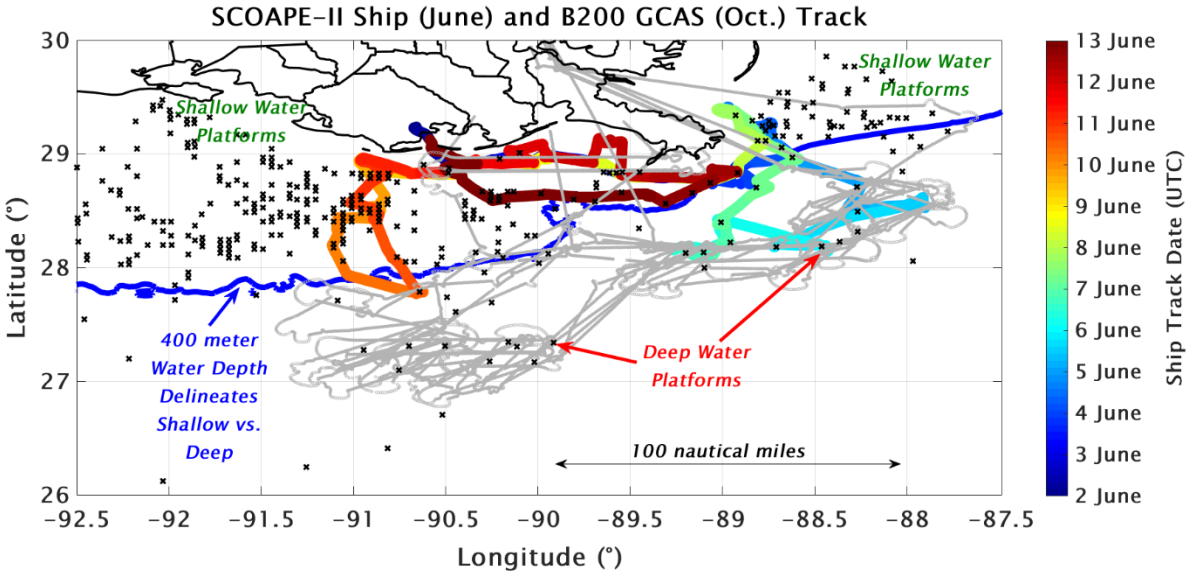


Figure 1. The 2-13 June 2024 SCOAPE-II R/V *Point Sur* ship track colored by date. The grey lines indicate the paths of the NASA/LaRC B200 aircraft with GCAS (aircraft remotely-sensed NO_2; see Section 2 description) measurements during its six flights from 7-13 October 2024. The small black x's indicate the locations of all ONG platforms contained in BOEM's 2017 emissions inventory. A 400-meter water depth isoline has been added to indicate BOEM's delineation between shallow and deep waters.

Measurement	Instrument
Continuous (1-sec) in situ CH_4, CO_2, CO, H_2O	Picarro G-2301
Continuous (1-sec) in situ CH_4, HCHO, H_2O	Picarro G-2307
Continuous (1-min) in situ NO_2	Teledyne API T500U
Continuous (1-min) in situ O_3	Thermo 49i
Total Column NO_2	Pandora Spectrometer

Vertical (UAS) in situ NO_2 profiles	GSFC-developed PCAND NO_2 sonde
Balloon-borne ozonesondes	En-Sci, Intermet-4 RSB radiosondes
Aerosol backscatter profiles, mixed layer height	Lufft CHM-8k Ceilometer
Dozens of in situ VOC species	VOC canister samples
Aerosol Optical Depth	MicroTops-II Sunphotometer
T, RH, p, winds, GPS location	RMYoung, Trimble ABX GPS
CH_4 Column Enhancement	*AVIRIS-3 (B200 Aircraft)*
NO_2 Column Amount	*GCAS (B200 Aircraft Oct 2024 only)*

Table 1. Listing of R/V *Point Sur* and aircraft (in blue text) measurements and instrumentation used during the SCOAPE-II campaign. All instrumentation was deployed in the June 2024 phase, except for the GCAS aircraft measurements during October 2024.

During the June R/V *Point Sur* cruise, measurements were coordinated with the Airborne Visible/Infrared Imaging Spectrometer-3 (AVIRIS-3) instrument flying on a Dynamic Aviation B200 aircraft from New Orleans Lakefront Airport. Briefly, AVIRIS-3 is a hyperspectral instrument operating in the visible to shortwave infrared from 389–2493 nm in 285 bands with 7.4 nm spectral sampling (**Coleman et al., 2026**). The Level 2 processed data include a CH_4 column enhancement product used here with modeled surface winds and other assumptions to compute emissions rates. Because the water surface is very dark in the strong CH_4 absorption bands of ~2200-2400 nm, sun glint from the water surface must be exploited to obtain sufficient signal for the CH_4 retrieval (**e.g., Ayasse et al., 2018**). This is also true for satellite measurements. To achieve this, the B200 aircraft flew in banked "horseshoe" patterns over platform targets to collect measurements during flight. SCOAPE-II represents the first demonstration of AVIRIS-3 over the Gulf.

A more detailed description of the AVIRIS-3 CH_4 emissions rate estimates are contained in the Appendix. AVIRIS-3 flew on seven days during the R/V *Point Sur* cruise, as weather conditions became optimal for remote sensing instruments with limited cloud cover on many of the days from 3-13 June. Finally, the R/V *Point Sur* and AVIRIS-3 measurements were also coordinated with GHGSat overpasses during SCOAPE-II, aiming to understand relative detection limits of the satellite/airborne/in situ instruments. One target platform was imaged by GHGSat each day during the SCOAPE-II cruise, with five images selected for delivery under an existing agreement between GHGSat and the NOAA National Environmental Satellite, Data, and Information Service (NESDIS). We provide a summary of AVIRIS-3

estimated CH_4 emissions rates here; a complete examination of the various measurement platforms and analysis of relative detection limits is a topic of future research.

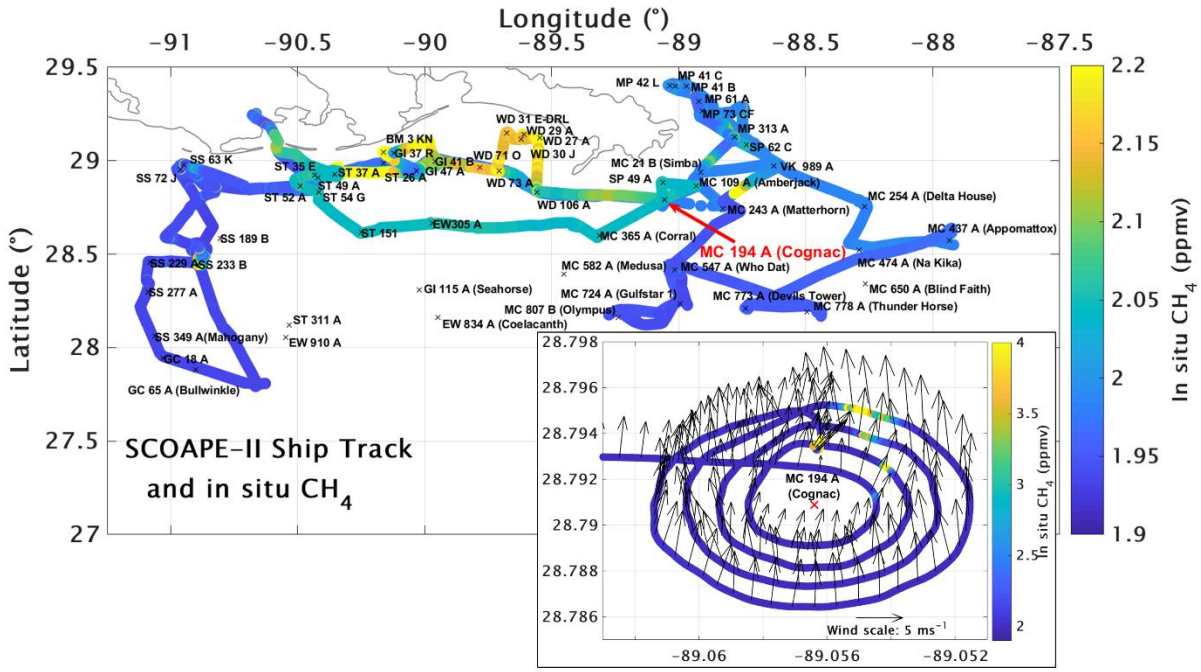
The October 2024 SCOAPE-II deployment consisted of aircraft measurements of NO_2 from the Geo-CAPE Airborne Simulator (GCAS). GCAS is a hyperspectral trace gas and ocean color instrument comprised of two spectrometers in the UV/visible and visible/near-IR. The NO_2 retrieval uses the UV/visible spectrometer operating in the 300–490 nm range with 0.2 nm spectral sampling (**Kowalewski and Janz, 2014**). The Level 2 product from GCAS includes the below-aircraft column NO_2 amount that is analogous to satellite tropospheric column NO_2 products (flight level was 27,000 ft/~8 km). Logistical issues prevented the GCAS instrument from flying on the same aircraft as AVIRIS-3 during the June 2024 phase as originally intended. Therefore, GCAS flew solo on the NASA/LaRC B200 aircraft on six days from 7-13 October 2024 (**Figure 1**), also from Lakefront Airport in New Orleans, LA.

Section 3 below provides a summary of the data collected during June and October 2024 in two subsections: The first describes measurements during June from the R/V *Point Sur*, and the second focuses on satellite, AVIRIS-3 (June), and GCAS (October) aircraft instruments.

3. SCOAPE-II Measurement Highlights

a. Measurements from the R/V Point Sur

We used the suite of continuous in situ analyzers on the R/V *Point Sur* (**Table 1**) to characterize AQ and GHGs for both emissions plumes near platforms and ambient air during transits between waypoints. **Figure 2** shows many of those waypoints and indicates platforms in the SCOAPE-II domain that were imaged by the AVIRIS-3 aircraft instrument. In most cases, platforms are identified alphanumerically, but many of the larger platforms (e.g., MC 194 A [Cognac], MC 437 A [Appomattox], MC 778 A [Thunder Horse]) also receive a name. The background in situ CH_4 values during SCOAPE-II show distinct magnitudes based on location with higher values near the coast, and lower values in the deeper waters.



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246 Figure 2. The 2-13 June 2024 SCOAPE-II R/V *Point Sur* ship track colored by the 1-minute average
247 Picarro G-2301 in situ CH_4 (in ppmv). Locations and IDs of platforms measured by the AVIRIS-3 aircraft
248 instrument are shown on the map. The inset panel focuses on 1-second Picarro ship measurements from 3
249 June at the Cognac platform, with vector arrows indicating in situ wind speed and direction measured from
250 the ship. Note the different CH_4 scales for the two panels.

251 The inset to **Figure 2** shows one of several approaches that were used to probe platforms
252 where CH_4 enhancements were encountered. For this 3 June case near the Cognac platform,
253 the R/V *Point Sur* completed circuits in 100 m intervals from 500-200 m distance to fully
254 capture both upwind and downwind conditions (see wind vectors on plot). Large 1-second
255 CH_4 spikes were observed downwind of Cognac of up to 13 parts per million by volume
256 (ppmv; the scale on the inset of **Figure 2** is capped at 4 ppmv), or more than six times the
257 background value of ~2 ppmv. Other techniques to capture in situ CH_4 plumes included
258 performing a zig-zag pattern while approaching a target, and linear transects across the
259 downwind areas from the platform. Through the analysis of CH_4 background and
260 enhancement values, and in situ ship wind information, emissions estimates will be generated
261 from the R/V *Point Sur* measurements for comparison with coincident AVIRIS-3 imagery in
262 future work.

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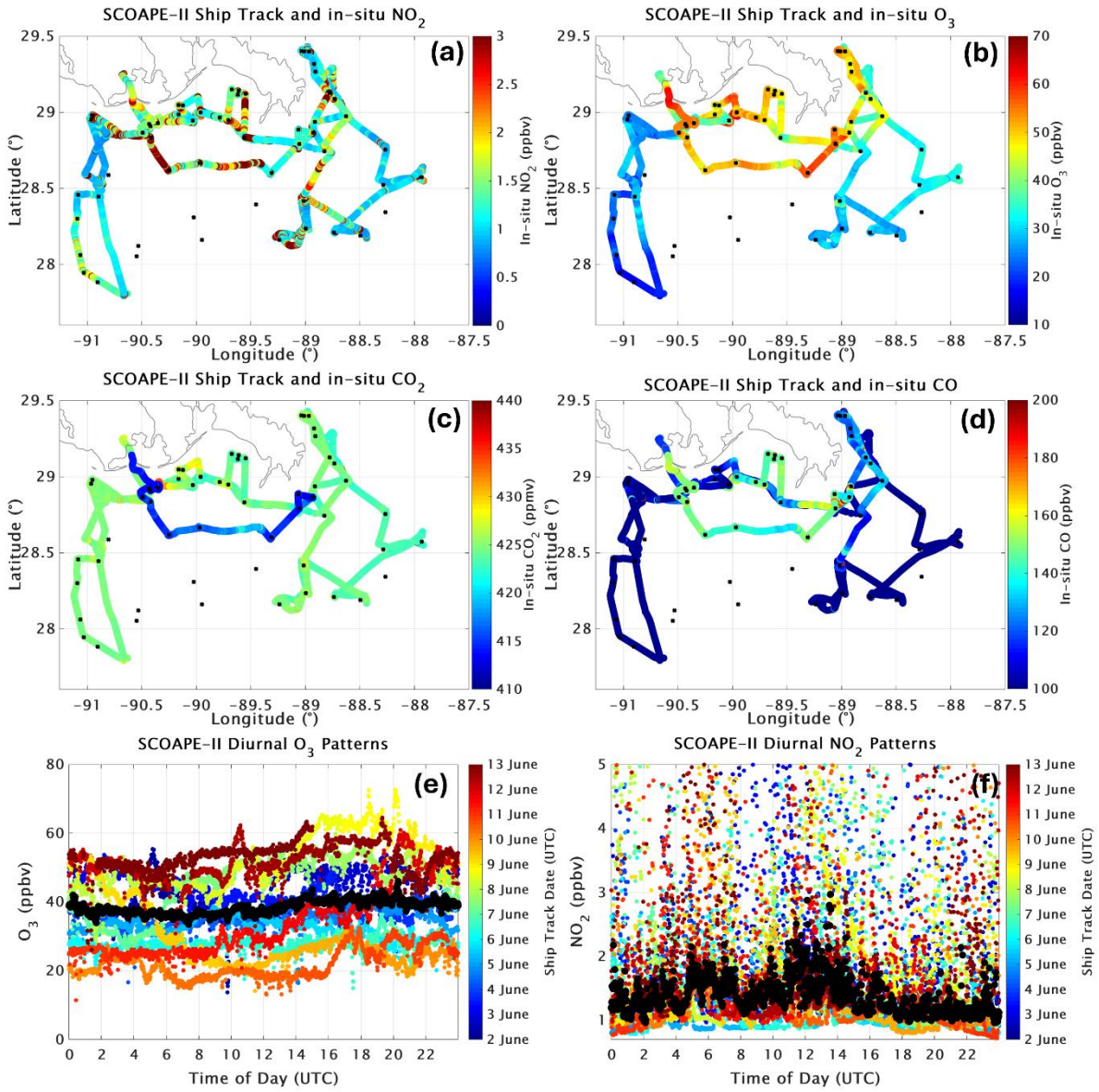


Figure 3. As in Figure 2, the 2-13 June 2024 SCOAPE-II R/V *Point Sur* ship track colored by various 1-minute in situ trace gas measurements (a: NO_2; b: O_3; c: CO_2; d: CO). Locations of platforms measured by the AVIRIS-3 aircraft instrument are shown on the map. Panels e and f show diurnal patterns of O_3 (e) and NO_2 (f) for each day of *Point Sur* measurements, including the overall average (mean for O_3, median for NO_2) values during SCOAPE-II. The NO_2 vertical scale is capped at 5 ppbv for clarity.

Map views of additional in situ species from the R/V *Point Sur* measurements are presented in **Figure 3**. Similar to the CH_4 values in **Figure 2**, we observed distinct patterns in NO_2, O_3, CO_2, and CO that indicate terrestrial influence near the coast with higher NO_2, O_3, and CO, and lower CO_2. The June 2024 SCOAPE-II period was generally characterized by stagnation with light winds and limited cloud cover. This allowed for a slow recirculation and accumulation of pollutants over the Gulf by the middle of the campaign, peaking on 8 June

with surface O_3 values exceeding 70 ppbv, coincident with a 5 ppmv drop in CO_2, indicating depleted CO_2 from terrestrial vegetation uptake. This shift to more polluted AQ with lower CO_2 concentrations is similar to what was encountered after the mid-cruise frontal passage in the 2019 SCOAPE campaign (**Thompson et al., 2023**). Air in the deep waters and the eastern and western sides of the domain was much cleaner and characteristic of background marine air, with surface O_3 at times lower than 20 ppbv, CO below 100 ppbv, and NO_2 of 1 ppbv or less.

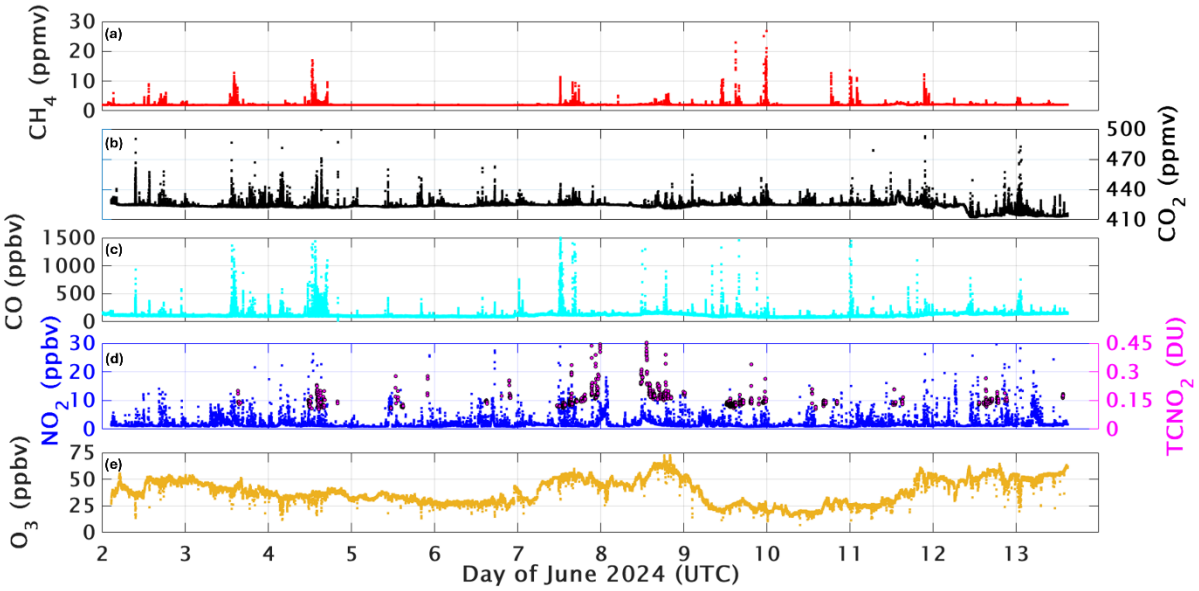


Figure 4. Full 2-13 June 2024 SCOAPE-II time series of in situ (and Pandora remotely sensed; $TCNO_2$ = Total Column NO_2) trace gas data from the R/V *Point Sur*. Each respective y-axis indicates the measured species. These data have been screened for ship exhaust contamination as explained in the text.

Full time series of the constituents shown on **Figures 2 and 3** appear in **Figure 4**, with the addition of the Pandora total column NO_2 values on panel (d). Ship self-sampling has been filtered out when relative wind direction measured on the R/V *Point Sur* was between 160° to 200° (indicating the direction from the exhaust stack on the stern to the bow where measurements were collected) and relative wind speeds were less than 5 meters per second. This resulted in a total of 2.4% of the data being flagged and removed.

The Pandora NO_2 values on **Figure 4d** reflect the more polluted conditions encountered on 7 and 8 June, with the highest values of ~0.5 Dobson Unit (1 Dobson Unit [DU] = 26.9 $x10^{15}$ molec. cm^{-2}) or 13.4$x10^{15}$ molec. cm^{-2} occurring on those dates. The figure also illustrates the dozens of plumes of CH_4 and NO_2 measured by the R/V *Point Sur*. For example, we measured a peak 1-second CH_4 value of 37 ppmv at the SS 233 B platform on

the evening of 9 June, and CO frequently spiked above 1 ppmv (1000 ppbv) and NO_2 above 20 ppbv near ONG infrastructure.

In addition to the continuous in situ measurements, 24 air canister samples were collected and analyzed for dozens of trace gas species, including δ13C, the ratio of carbon-12 and -13, and δ2H, the ratio of hydrogen isotopes in water vapor. Air can sampling strategy included measuring both background air and within plumes when indicated by the continuous measurements. **Figure 5** demonstrates the close agreement of the CH_4 measurements from the continuous (1-second and 1-minute data) in situ Picarro G-2301 and the air can samples, which take approximately 20 seconds to pressurize, both in plumes and in background air. Can samples such as the one collected late on 9 June (CH_4 = 9.1 ppmv) also showed significant enhancements of ethane, propane, benzene, etc., all indicative of a natural gas source/leak.

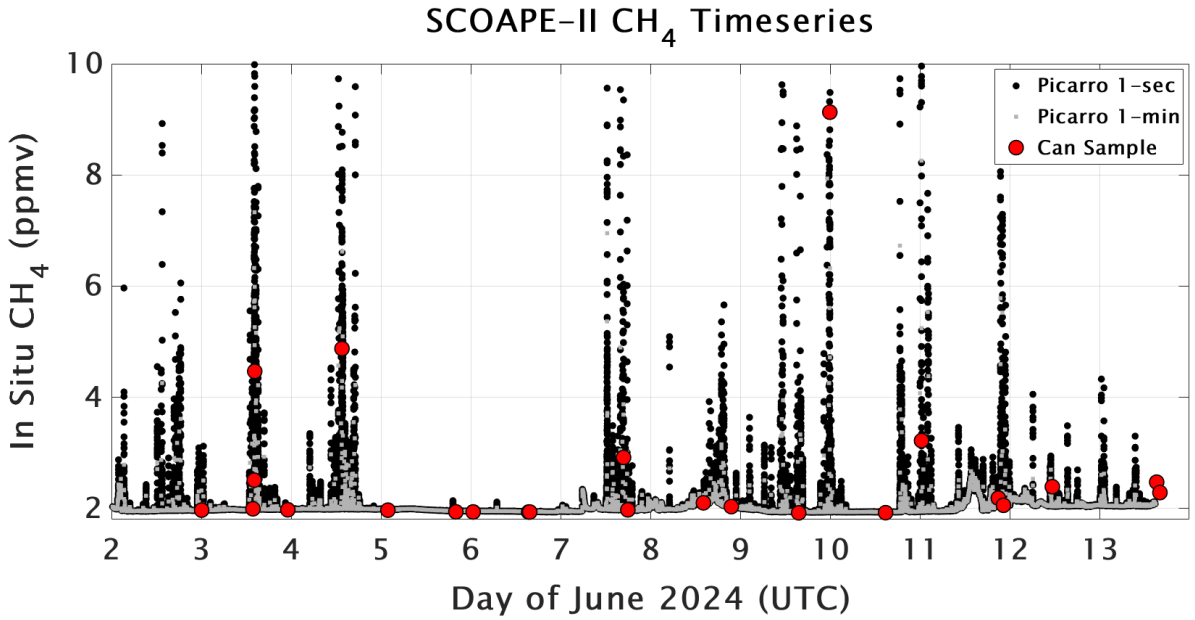


Figure 5. 2-13 June 2024 R/V *Point Sur* in situ CH_4 measurements from the Picarro G-2301 (1-sec: black; 1-min: grey) and VOC can samples (red). The measurements in both background air masses and CH_4 plumes show excellent agreement. For VOC can values below 2.0 ppmv agreement with 20-second (approximate can fill time) average Picarro measurements was within 1%.

Profiles of trace gases and aerosols from the R/V *Point Sur* were collected using free-flying balloon-borne ozone and radiosondes, a ceilometer (not shown here), and a novel NO_2 sonde integrated on an Uncrewed Aircraft System (UAS) platform. **Figure 6** displays the ozonesonde ozone mixing ratio "curtain" (in ppbv) from the 15 profiles collected during SCOAPE-II from the surface to 8 km altitude. The near-surface ozonesonde mixing ratios

match the evolution of the continuous in situ analyzer, with the highest amounts occurring from 7-8 June while sailing through the central portion of the domain and closer to the coast. This coincided with a multiday O_3 pollution event observed along the Gulf Coast from Houston, TX, to much of Louisiana starting on 6 June.

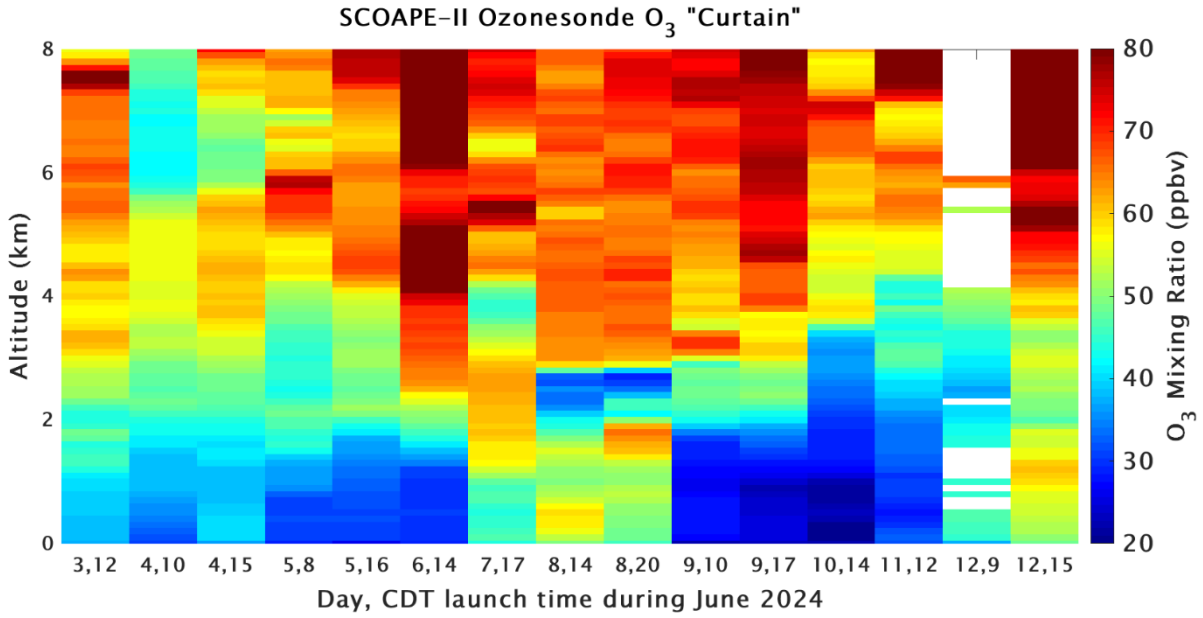


Figure 6. Ozonesonde ozone mixing ratio (in ppbv) "curtain" from the 15 profiles collected from the R/V *Point Sur*. The x-axis indicates the day and CDT time of June 2024 for each profile. White space on the first 12 June profile indicates no signal/data loss.

Also of note on **Figure 6** is the descent of higher ozone mixing ratios from ~6 km altitude on 5 June toward the surface by 8 June. This is the result of a stratospheric intrusion over the Gulf that peaked on 6 June and deposited a large amount of stratospheric ozone into the mid-troposphere, which then descended closer to the surface under an establishing synoptic scale high pressure system in subsequent days. The intrusion feature is illustrated in **Figure 7** which shows MERRA-2 500 hPa geopotential height (H) and Ertel's Potential Vorticity (EPV) from 21 UTC on 6 June (two hours after the ozonesonde profile was collected on 6 June in **Figure 6**).

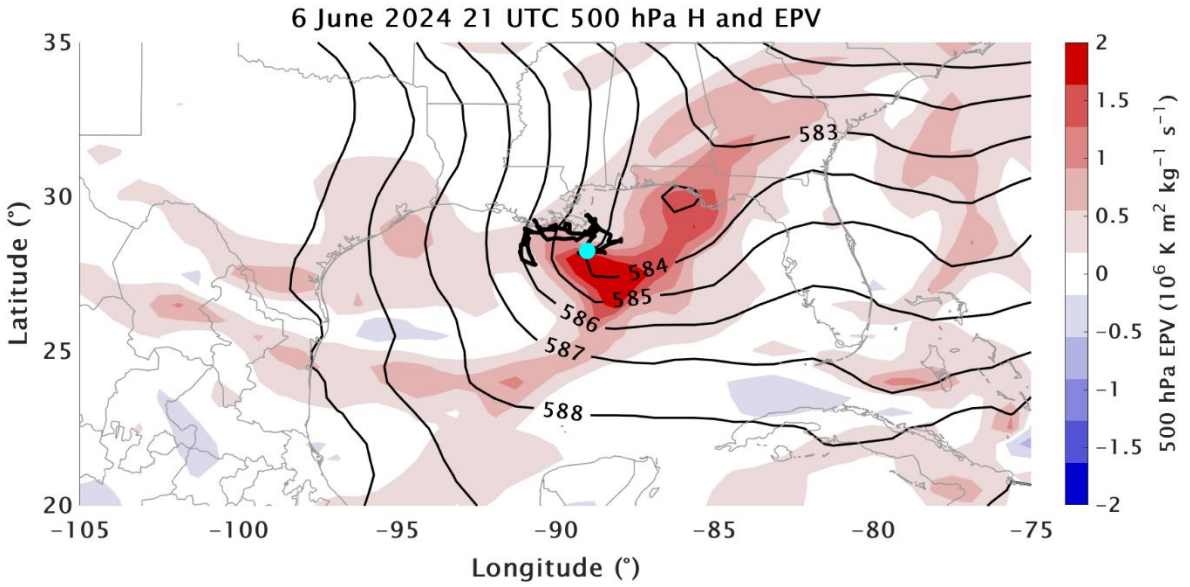


Figure 7. MERRA-2 500 hPa geopotential height (H; dam; black contour lines) and Ertel's Potential Vorticity (EPV; 10^6 K m^2 kg^{-1} s^{-1}; filled colors) from 21 UTC 6 June 2024. The thick black lines show the SCOAPE-II R/V *Point Sur* track with the cyan dot indicating the position of the ship at the time.

In addition to the balloon-borne ozone measurements that were collected, analysis of radiosonde temperature and wind profiles in conjunction with ceilometer aerosol backscatter profiles will also prove useful for future analyses of wind fields and atmospheric stability for computation and verification of CH_4 and NO_2 emissions rates from various platforms.

The Portable Cavity-enhanced Absorption of Nitrogen Dioxide (PCAND; **Bailey et al., 2024**) instrument measured in situ NO_2 profiles while flying on the Atmospheric Validation Experiment (AVE) UAS from the deck of the R/V *Point Sur*. Profiles were collected up to altitudes of ~80-125 m while stopped and positioned downwind of a target platform from as close as 100-200 m distance. Capturing NO_2 emissions plumes from the UAS while flying from the R/V *Point Sur* proved challenging, especially from deep-water tension leg platforms. OCS regulations require that vessels sail no closer than 500 m distance from tension leg platforms, but there are no restrictions on clearance distance for shallow-water platforms.

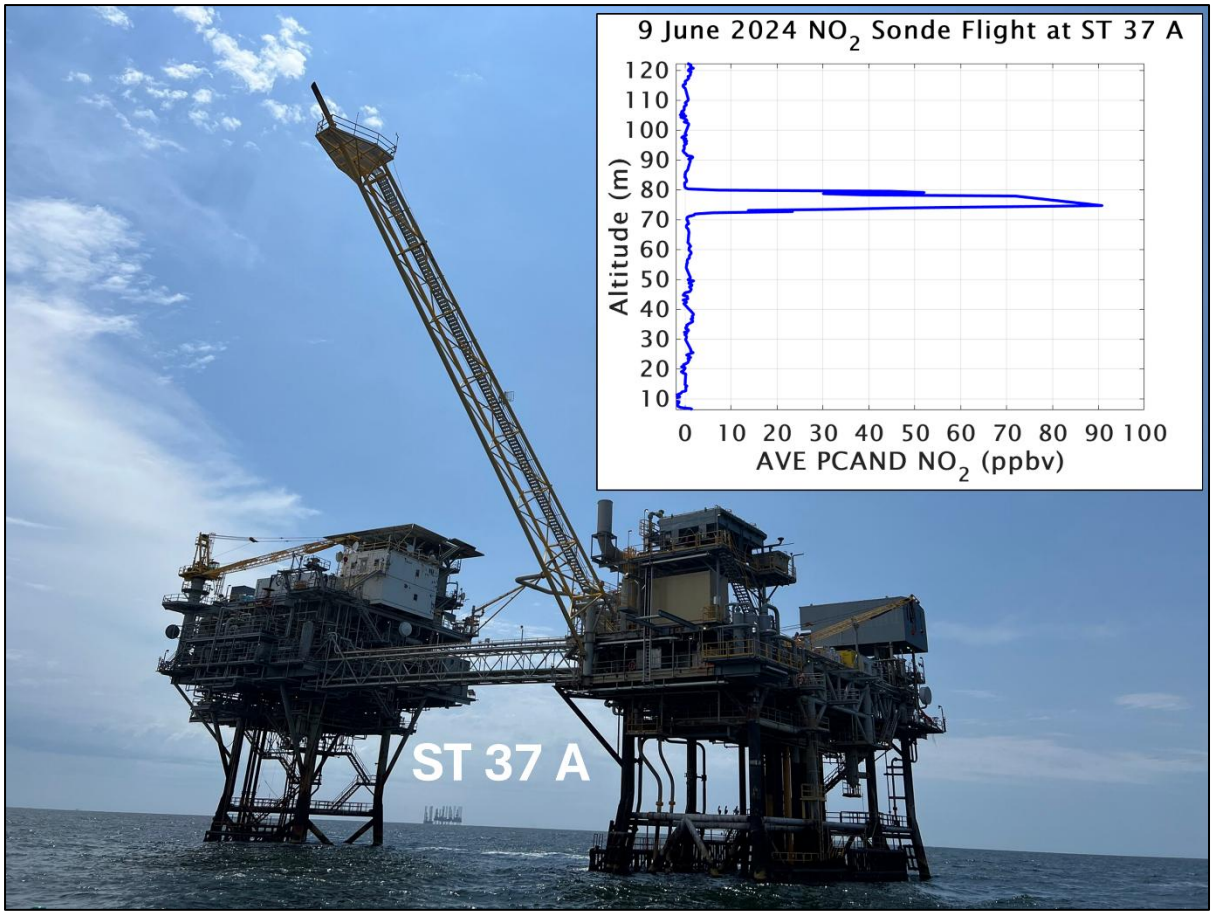


Figure 8. Example in situ NO_2 sonde profile from the PCAND instrument flown on the Atmospheric Validation Experiment (AVE) UAS. A large NO_2 plume reaching up to 92 ppbv was encountered at platform level from 70-80 m above the water surface next to ST 37 A on 9 June 2024 (UTC; late evening local time 8 June). Photo credit: Ryan Stauffer (NASA/GSFC).

The PCAND instrument measurements from evening local time 8 June (early 9 June UTC; **Figure 8**) captured a large spike in NO_2 at the ST 37 A shallow-water platform. NO_2 mixing ratios spiked to >90 ppbv in a layer just 10 m thick from 70-80 m above the water. This approximately corresponds to the height of the platform infrastructure and is clearly high enough in elevation to avoid potential effects from self-sampling of ship emissions. The measurements in **Figure 8** indicate that even shallow-water platforms can be significant emitters of NO_x among cleaner background conditions – the profile displays low NO_2 outside of the plume emanating from ST 37 A. These measurements will also be useful for interpreting GCAS, satellite, and Pandora NO_2 column measurements over the Gulf.

b. Satellite and Aircraft (GCAS and AVIRIS-3) Measurements

Given that validation of TEMPO (and TROPOMI) NO_2 column measurements was a primary goal of SCOAPE-II, we compare coincident measurements of total column NO_2 ($TCNO_2$) from satellite and the R/V *Point Sur* Pandora. Pandora $TCNO_2$ values were averaged within ±30 minutes of the satellite measurements. The hourly scanning of TEMPO compared to ~once per day overpasses of TROPOMI yields far more coincident measurements vs. the Pandora. However, TROPOMI performs much better overall compared to TEMPO in terms of mean absolute bias (**Figure 9**; MAB; 8.6 % vs. 23.6%).

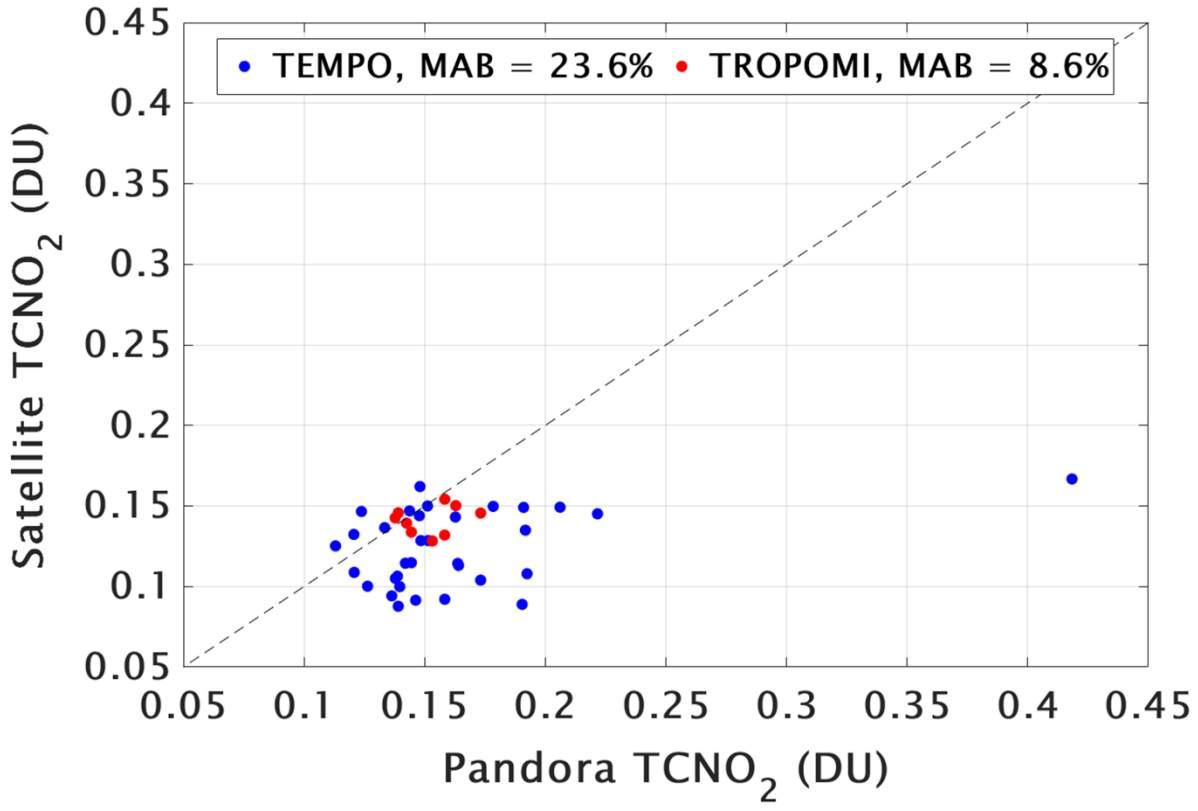
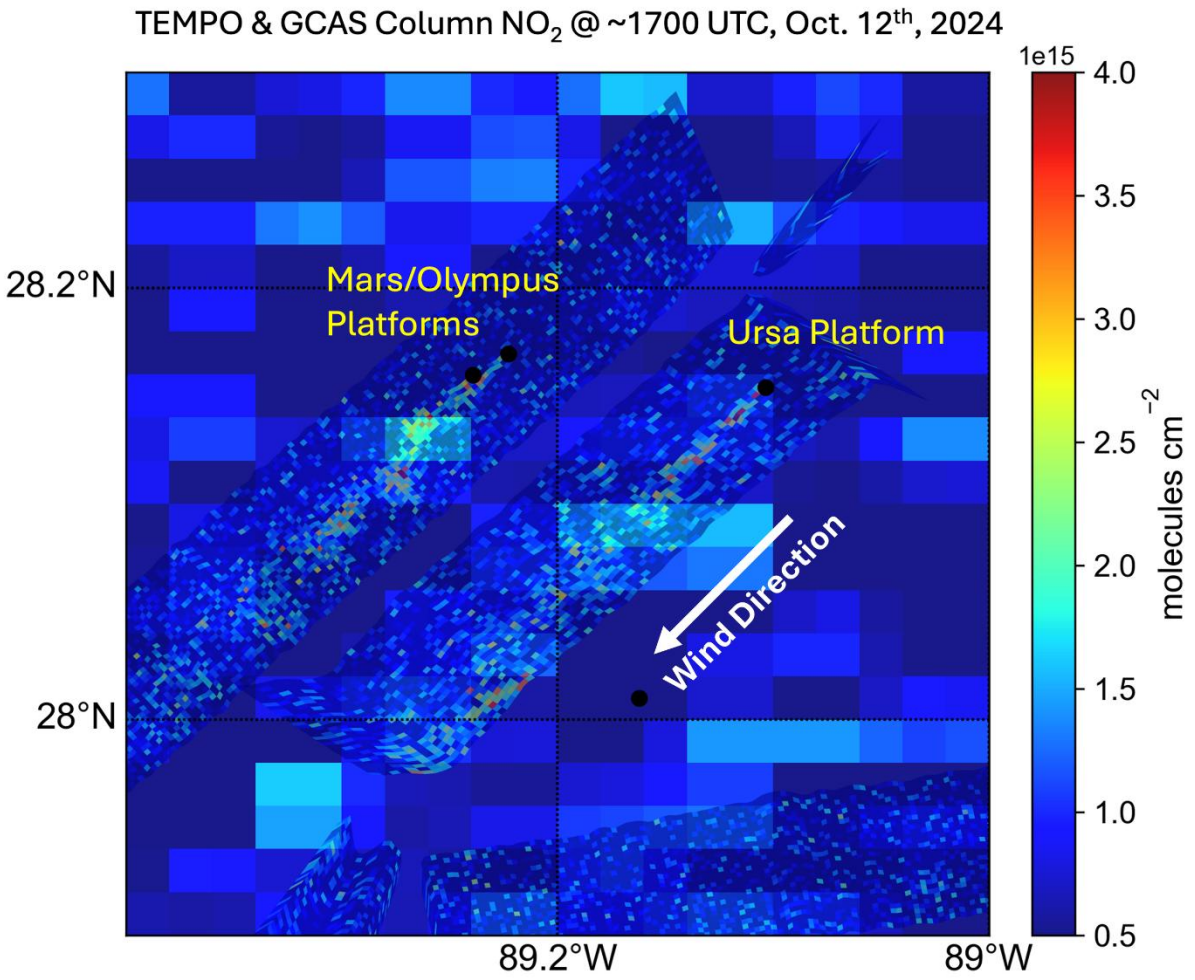


Figure 9. Scatterplot of coincident total column NO_2 ($TCNO_2$) measurements from the R/V *Point Sur* Pandora (1 hour average ±30 minutes of satellite measurement) and TEMPO (blue dots) and TROPOMI (red dots) satellite measurements. The mean absolute biases (MAB) for the measurement comparisons are shown in the Figure legend.

The TROPOMI/Pandora validation results are similar to the 2019 SCOAPE campaign, although both instruments show an overall low bias relative to the Pandora. This is likely a consequence of the R/V *Point Sur* sampling strategy of probing isolated platforms where emissions may occur on sub-pixel scales (e.g., see the outlier Pandora value of 0.42 DU from 8 June at 13 UTC on **Figures 4 and 9**).

More evidence of the small spatial scale of ONG emissions in the Gulf is displayed by the GCAS measurements from 12 October 2024 on **Figure 10**. GCAS below-aircraft NO_2 columns are overlaid with the coincident TEMPO scan tropospheric column NO_2 values at ~17 UTC. The GCAS measurements show distinct NO_2 plumes from the large, deep water platforms MC 807 A (Mars), MC 807 B (Olympus), and MC 809 A (Ursa). Interestingly, NO_2 plumes of similar magnitudes were observed over temporary drill ships during the six GCAS flights, indicating the significance of non-platform NO_x emissions over the OCS. However, TEMPO appears to be relatively insensitive to the GCAS-observed NO_2 plumes. The TEMPO team is currently reprocessing data for v4 (v3 is shown here). Preliminary comparisons of v3 and v4 indicate that v4 greatly reduces "striping" artifacts over the Gulf in v3 that are common with push broom-type scanners like TEMPO. A paper is currently in preparation that will evaluate v4 NO_2 data both during the SCOAPE-II campaign (with Pandora and GCAS) and on longer timescales to understand TEMPO's ability to distinguish ONG NO_x emissions from the clean Gulf background air as in **Fedkin et al., (2024)**. The NO_2 below-aircraft column observations will also allow us to better constrain ONG NO_x emissions to evaluate BOEM's OCS emissions inventories.



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402 Figure 10. Coincident measurements of GCAS (transparent colors) and TEMPO (background opaque
403 colors) tropospheric column NO_2 measurements. The comparison was made for data collected near 17
404 UTC on the 12 October 2024 GCAS flight.

405 Finally, a summary of AVIRIS-3 aircraft-measured CH_4 emissions estimates from June
406 2024 is provided in **Figure 11**. Our preliminary analysis of the AVIRIS-3 imagery identified
407 a total of 39 CH_4 plumes at 13 separate platforms, with emissions estimates ranging from 26
408 ± 5 kg hr^{-1} (1σ confidence interval) at MP 41 C to 1399 ± 177 kg hr^{-1} at ST 37 A and a
409 median value of 229 kg hr^{-1} (mean of 291 kg hr^{-1}). Often, a platform was imaged several
410 times within 30-60 minutes, with multiple detections on subsequent passes by the B200
411 aircraft. Note that on **Figure 11** we show only a single emission estimate per day per
412 platform, although platforms such as ST 37 A were imaged on multiple days over many
413 passes.

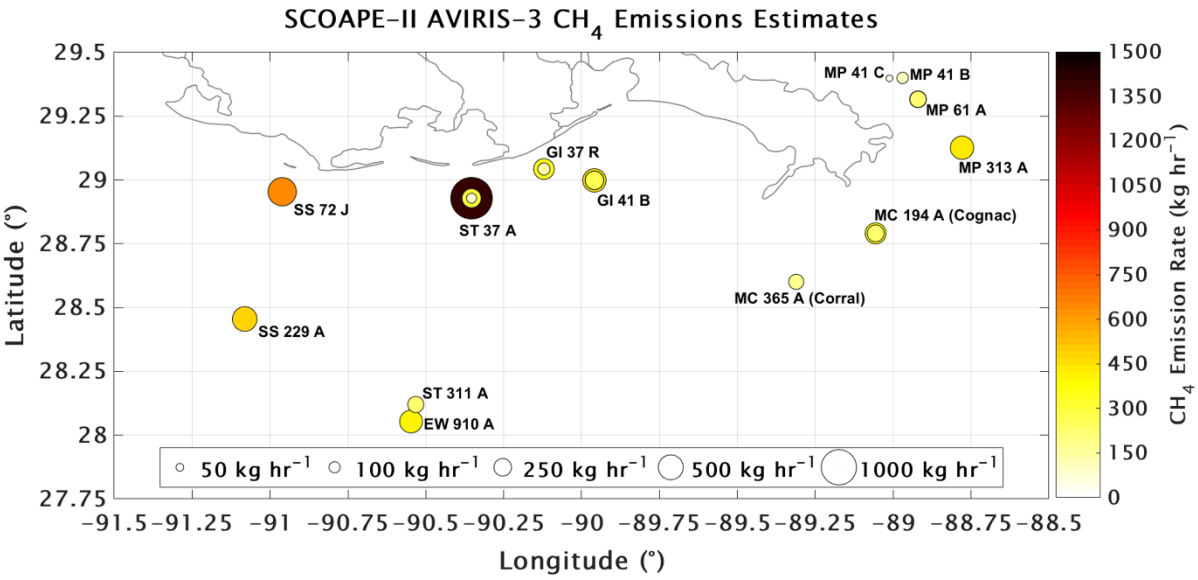

Figure 11. Map summary of CH_4 emissions estimates from plumes measured by AVIRIS-3 during seven flights in the June 2024 SCOAPE-II campaign. The size and color of the dots indicate the emission rate. Platform IDs are shown next to each set of dots. Note that some platforms have emissions estimates collected on multiple days (e.g., ST 37 A).

A detailed description of the AVIRIS-3 CH_4 emissions and uncertainty estimation process, as well as example CH_4 column enhancement imagery, is found in the Appendix. In addition to the CH_4 measurements from AVIRIS-3 and the R/V *Point Sur*, GHGSat satellites were tasked to measure a target platform once each day during the June 2024 deployment. The targets were coordinated so that ship, aircraft, and satellite were all collecting coincident measurements of the same platform on several days. However, our initial analysis of the five delivered GHGSat images, and discussions with the GHGSat team, indicate that the satellites did not observe any CH_4 plumes during SCOAPE-II. The over-water sun glint mode detection limit of the GHGSat constellation of instruments is estimated to be between 160 and 600 kg hr^{-1}, depending on latitude, season, and viewing conditions (**MacLean et al., 2024**). Because multiple SCOAPE-II AVIRIS-3 (and ship) emissions estimates exceed these values, a full analysis of relative detection limits and other considerations are topics of a future manuscript as described further below.

4. Summary and Direction of Future Research

The SCOAPE-II Gulf campaign was held over two deployments in 2024, from 2-13 June (R/V *Point Sur* and B200 AVIRIS-3) and 7-13 October (B200 GCAS only). Primary goals of SCOAPE-II were to: (1) validate column NO_2 measurements from the geostationary TEMPO

AQ satellite sensor with a ship-based Pandora and the GCAS aircraft instrument; (2) demonstrate the capability of AVIRIS-3 aircraft CH_4 sun glint measurements; (3) probe platform CH_4 and NO_2 emission plumes from multiple operations; (4) collect comprehensive data for future assessments of BOEM's OCS emissions inventories. All scientific questions, with much of the related analysis being beyond the scope of this campaign overview paper, will be addressed in future manuscripts in preparation. Ship and aircraft measurements from SCOAPE-II captured dozens of enhancements of both CH_4 (primarily shallow water) and NO_2 (both shallow and deep water) near platforms and non-platform drilling rigs, indicating that Gulf ONG infrastructure is persistently emitting.

Comparisons of total column NO_2 among Pandora and satellites yielded similar results to the May 2019 SCOAPE campaign for TROPOMI (~10% satellite MAB), but a larger deviation for the TEMPO instrument (~25% bias). Future reprocessed TEMPO v4 data will be examined for improvements in a follow-on study. We also collected unique offshore measurements of elevated (in altitude and magnitude) NO_2 from a novel in situ NO_2 sonde, VOC enhancements from two dozen air canister samples, and balloon-borne ozone and radiosondes with other ship-based data listed in **Table 1**. The in situ ship observations are valuable to BOEM for determining "nose-level" AQ and its relationship to satellite measurements as it pursues long-term monitoring of ONG impacts on Gulf Coast AQ. Our results here underscore the importance of large-scale weather conditions for creating poor AQ over the Gulf, and that NO_x emissions from terrestrial sources in total far outweigh those from isolated platforms in the OCS.

The frequent plumes identified by ship- and aircraft-based remote sensing of CH_4 and NO_2, and the lack of sensitivity to them from satellite measurements, underscore the difficulty of capturing small-scale, but often intense, emissions from ONG operations in the Gulf OCS from space. The TEMPO geostationary v3 product appeared to be insensitive to the enhanced NO_2 near large deep-water platforms as measured by the ship Pandora in June 2024 (**Figures 4 and 9**), and the GCAS aircraft instrument in October 2024 (**Figure 10**).

Coordinated CH_4 measurements with ship, AVIRIS-3, and GHGSat satellites yielded no opportunities to compare all three platforms because GHGSat failed to identify any CH_4 enhancements during SCOAPE-II when coincident plumes were encountered by ship and AVIRIS-3. The need to exploit sun glint to retrieve CH_4 measurements over the dark water surface contributes to the challenge for satellites to reproduce AVIRIS-3 SCOAPE-II

emissions rates of ~200-300+ kg hr^{-1}. The multiplatform measurements for both NO_2 and CH_4 will be examined in detail in subsequent analyses to further refine satellite measurements that meet BOEM's long-term operational monitoring needs. Nonetheless, we demonstrated here the value of our unique in situ and remotely sensed AQ and CH_4 measurements near ONG operations in the Gulf.

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Data Availability Statement.

R/V *Point Sur* and GCAS data for SCOAPE-II (as well as the 2019 SCOAPE campaign) are available at https://www-air.larc.nasa.gov/missions/scoape/index.html. AVIRIS-3 data are available at https://www.earthdata.nasa.gov/data/catalog/ornl-cloud-av3-l2b-ghg-2358-1. TROPOMI and TEMPO satellite total column NO_2 data were downloaded from: https://www.earthdata.nasa.gov/data/catalog/ges-disc-s5p-l2-no2-hir-2 and https://asdc.larc.nasa.gov/project/TEMPO/TEMPO_NO2_L3_V03.

APPENDIX

Determining AVIRIS-3 Methane Emissions Rate Estimates

The AVIRIS-3 measures reflected radiance at 7.4-nm intervals across the visible to shortwave infrared spectrum (390-2500 nm), capturing the spectral signatures where CH_4 absorbs light. CH_4 concentrations are estimated using a column-wise adaptive matched filter approach. This technique searches each pixel's radiance spectrum for deviations that match CH_4 characteristic absorption pattern. The final product provides CH_4 enhancements in units of "parts per million meter" (ppm·m), representing the path-integrated concentration of the gas. Each measurement includes per-pixel uncertainty and sensitivity metrics. In the analyzed data each pixel's resolution is approximately 2.8 m^2; therefore, CH_4 data reported for each pixel indicates dry mixing ratio in the 3-dimensional box with the size of 2.8 m x 2.8 m x 1 m. Knowing volume of the box and density of dry air we can calculate total mass of the air in the box allowing us to set up proportion relating ppm of CH_4 to mass of air from which we can calculate mass of CH_4 in the box. One important point is that CH_4 is 45% lighter than air and in the calculation that must be accounted for. Once we know the mass of CH_4 in the box summed across all the pixels that are part of a plume we can compute flux as explained in the next paragraph.

CH_4 emission were quantified using the Integrated Mass Enhancement method applied to AVIRIS-3 imaging spectrometer data. Plume pixels were identified using a dual-criterion statistical filter combining Signal-to-Noise Ratio (SNR ≥ 2.0, corresponding to ~95% confidence) and minimum CH_4 column enhancement (200-600 ppm·m, plume-dependent). The SNR for each pixel was calculated as the ratio of CH_4 enhancement to retrieval uncertainty (SNR = CH_4/UNC), both provided in AVIRIS-3 Level 2B products. This approach ensures that included pixels have statistically significant enhancements above instrument noise levels. Column enhancements meeting quality criteria were converted to atmospheric mass loadings (accounting for molecular weight and air density) and integrated over the filtered plume area. Emissions (Q) were calculated using the following expression:

$$Q = U_{eff} \times M_{total} / L_c,$$

where U_{eff} is the effective wind speed, M_{total} is total plume mass (kg), and L_c is the characteristic plume length scale $\sqrt{n_{pixels} \times area_{pixel}}$. Winds are derived from High-Resolution Rapid Refresh (HRRR) model analysis at plume location and observation time. Various effective wind models based on Large Eddy Simulations (**Varon et al., 2018**) are utilized accounting for turbulence in boundary layer. Uncertainty quantification employed Monte Carlo simulation (n=1,000 iterations) propagating per-pixel retrieval uncertainties

through nine empirical wind dispersion parameterizations, yielding 9,000 total flux realizations. Final emissions are reported as ensemble mean ± 1σ (68% confidence interval) with 90% confidence bounds from the 5^{th} and 95^{th} percentiles of the Monte Carlo distribution.

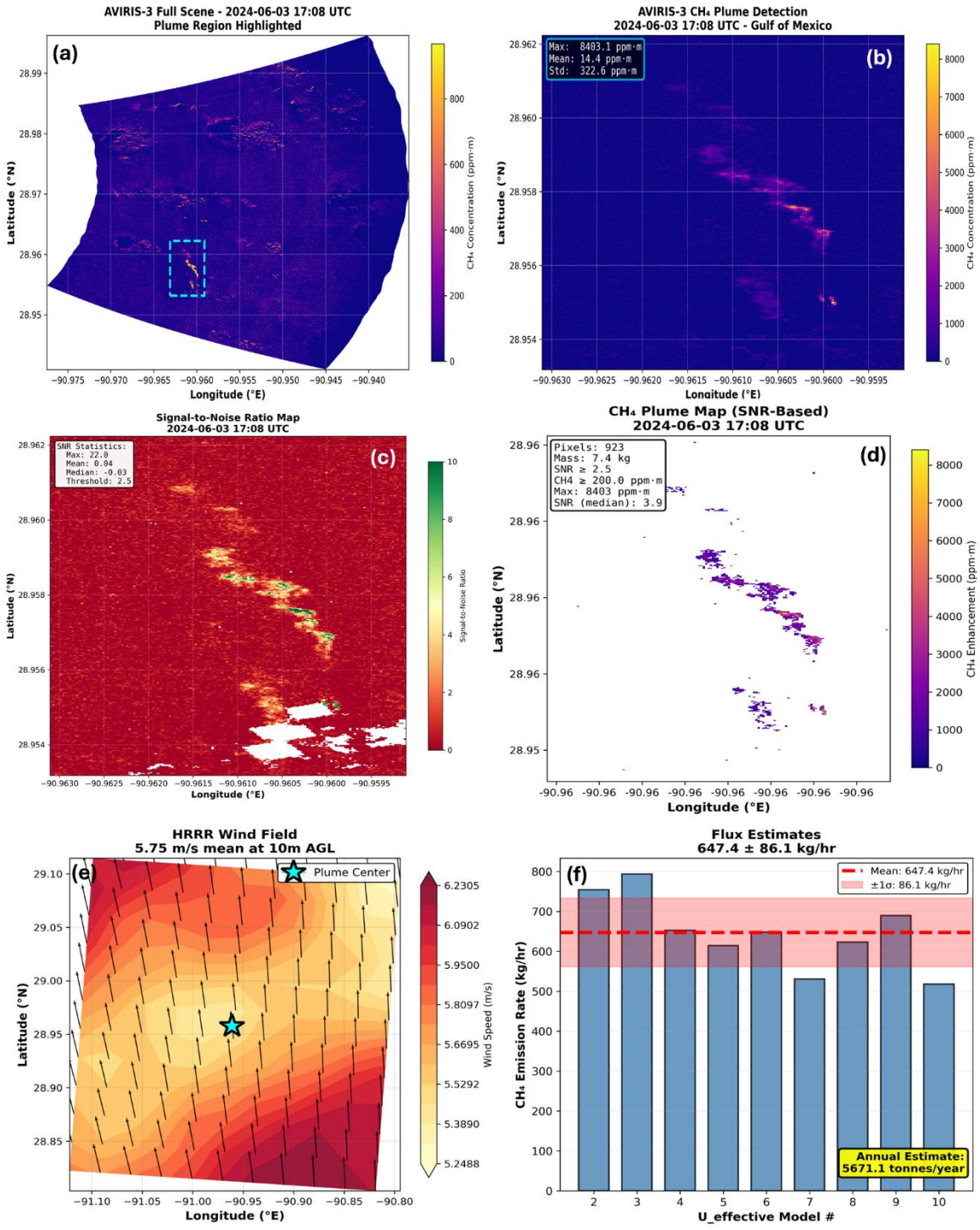

Figure A1. An example from 3 June 2024 of how CH_4 emissions are derived from AVIRIS-3 Level 2B product when a plume is detected where (a) and (b) show CH_4 path-integrated enhancements above the background, (c) highlights a region of SNR above 2.5 if detected, (d) identifies a likely CH_4 plume based on the established SNR criterion, (e) indicates a wind field from HRRR around the platform of interest, and (f) provides estimates of CH_4 emissions from the examined plume from various wind effective models and their average.

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