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Sunglint-aided Methane Retrieval: Using Sentinel-2 to Detect and Quantify Offshore Oil and Gas Emissions

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ABSTRACT

The extraction, production, and transportation of oil and gas via activities such as intentional venting and fugitive emissions are leading contributors to anthropogenic methane emissions. Offshore operations comprise a significant percentage of all oil and gas operations, yet emission monitoring over the ocean is insufficient. Due to low surface reflectance over the ocean, remote sensing measurements offshore are limited, and therefore offshore contributions to the overall global methane budget are unknown. Regulators such as the Bureau of Ocean and Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE) are unable to validate operator-reported methane emission estimates. The NASA DEVELOP Program partnered with BOEM, BSEE, and SkyTruth to identify potential offshore methane sources in the Gulf of Mexico. Drawing upon existing retrieval methods to detect and quantify onshore methane emissions, we selected sunglint scenes to identify methane plumes over offshore facilities in Sentinel-2 imagery. We detected two methane plumes at the Constitution complex in the Gulf of Mexico and off the coast of Pointe-Noire, Congo. If expanded, these methods could serve a vital role in validating operator reporting and quantifying climate impacts of offshore oil and gas operations.

PARTNERS

BSEE Bureau of Safety and Environmental Enforcement

BOEM Bureau of Ocean Energy Management

BOEM has a statutory requirement in the Outer Continental Shelf Lands Act (OCSLA) and in the National Environmental Policy Act (NEPA) to perform air quality impact assessments leasing program activities. This mandate focuses on criteria pollutants, but may soon begin issuing regulations on greenhouse gas emissions. (BOEM, n.d. (Figure 1)

Figure 1

The Bureau of Safety and Environmental Enforcement (BSEE)—enforces BOEM's rulemaking, and regulates venting and flaring activity (BSEE, n.d). All monitoring occurs through bottom-up assessments from self-reported emission inventories, with occasional inspections using infrared cameras to identify fugitive emissions

BOEM and BSEE have an interest in increasing their monitoring capacity of offshore oil and gas operations through remote sensing.

BACKGROUND

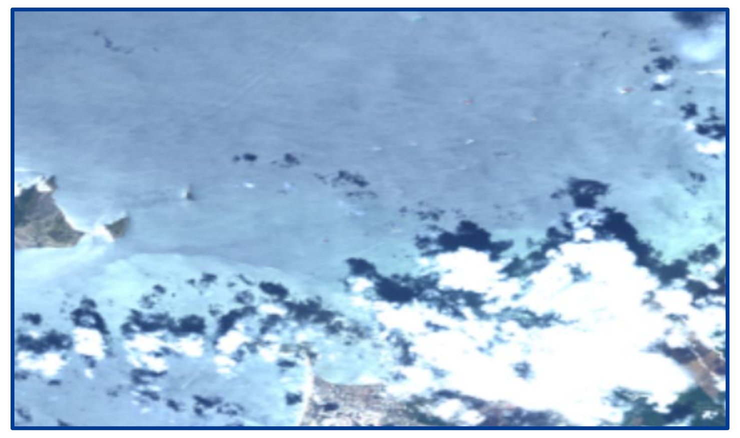

Figure 2. PRISMA sunglint Image collected by Italian Space Agency

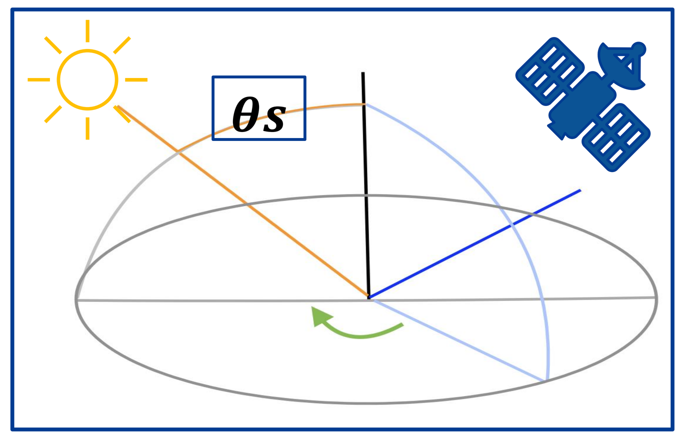

Figure 3. Optimal sunglint observing geometry

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While monitoring offshore methane emissions is critical to meeting global reduction targets, studies conducted both onshore and offshore have consistently found discrepancies between facility reported CH_4 inventories, in situ measurements, and remotely sensed measurements (Gorchov Negron et al., 2020; Xiao et al., 2008; Ayasse et al., 2022). To strengthen the confidence of emission estimate where they exist, and identify fugitive emission sources, a top-down satellite monitoring approach is necessary. Varon et al. (2021) presented three methods for using shortwave infrared (SWIR) measurements from multi-spectral satellites, specifically Sentinel-2, to detect methane plumes and derive source rates. Plumes currently detected by this method are from high-emission events onshore. Offshore methane retrievals are more difficult to execute due to the reflective signature of ocean water, particularly its high absorption of SWIR radiation, and requires solar radiation to be reflected by the water surface in a phenomenon called sun-glint (Figure 2 and Figure 3). Several studies, such as Ayasse et al. (2022), demonstrate the feasibility of using airborne sensors and sunglint to capture methane plumes, while Irakulis-Loitxate et al. (2022) chronicled an ultra-emissions event using the high-resolution WorldView-3 satellite.

This study adapts the existing multi-spectral methodology from Varon et al. to detect and quantify sunglint-illuminated methane plumes using satellite imagery derived from Landsat 8 Operational Land Imager (OLI), Landsat 9 OLI-2, and the European Space Agency's Copernicus Sentinel-2 Multi Spectral Instrument (MSI).

METHODS

Scene Selection

Since a bright background is necessary for detecting and quantifying methane plumes, we needed to ensure high reflectance for candidate offshore scenes. Scenes were selected as follows:

- Select 4km x 4km AOIs around known oil and gas infrastructure from BOEM and BSEE GIS layers and a global product derived from Sentinel-1 CSAR
- Set threshold reflectance for Sentinel-2 SWIR bands based on visual inspection
- Select scenes where > 20% of pixels exceed this threshold
- Remove scenes with higher than 15% cloud contamination across the scene based on Sentinel-2 QA60

Detection

We used a multi-band-single-pass (MBSP) methodology developed by Varon et al., 2021, for the Landsat 8 and 9 OLI/OLI-2 and Sentinel-2 MSI images. This process compares the reflectance of a strong and weak methane absorption band - Band 12 (2190 nm) and Band 11 (1610nm) respectively - in a single satellite pass. A large difference between the bands, if visible artifacts are not present, indicates the presence of methane. This change in reflectance, ΔR, is calculated using Equation 1.

$$\Delta R = \frac{cR_{12} - R_{11}}{R_{11}} \quad (1)$$

where c is the least squares regression coefficient between B12 and B11, accounting for average scene specific differences. The difference is then normalized by R_{11}. Fractional reflectance is calculated for all candidate scenes. Anomalies in fractional reflectance are flagged as potential methane plumes and are compared with visual imagery to rule out false positives stemming from surface features or artifacts.

Quantification

Scenes with potential methane plumes that contain visible enhancements in MBSP images such as clouds, cloud shadows, or facility infrastructure are manually masked to remove these features and then reprocessed prior to quantification. These scenes are then fed into the following fractional absorption model:

$$m(\Delta\Omega) = \frac{T_{11}(\Omega + \Delta\Omega) - T_a(\Omega)}{T_{11}(\Omega)} - \frac{T_{12}(\Omega + \Delta\Omega) - T_b(\Omega)}{T_{12}(\Omega)} \quad (2)$$

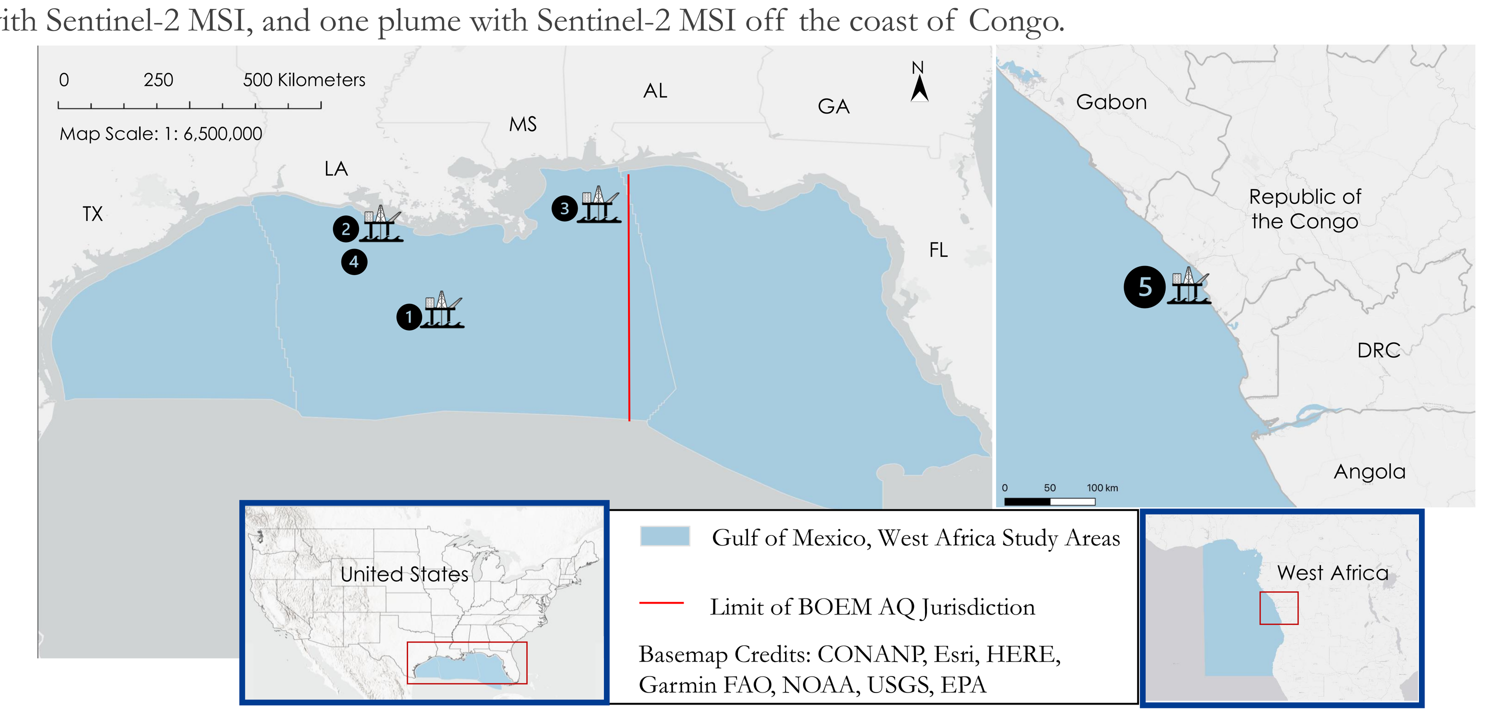
where T_{12} and T_{11} are the top of atmosphere (TOA) radiances for the two bands being compared, where band *12* exhibits a higher sensitivity to methane than band *11*. Ω is the nominal methane column concentration in moles/m^2 and ΔΩ is the methane column enhancement. CH_4 concentrations are determined by minimizing the difference between equation 1 and equation 2. Based on pixel CH_4 concentrations across the scene, plume masks are manually selected. Emissions rates were then quantified using the following equations:

$$Q = \frac{IME \times U_{eff}}{L} \quad (3) \qquad U_{eff} = \alpha U_{10} + \beta \quad (4)$$

where integrated mass enhancement (IME) is the sum of all methane concentrations across all pixels in the plume mask. U_{eff} is calculated using equation 4, where U10 is the nearest 10m RTMA wind speed at the time of the Sentinel-2 acquisition of the plume image. The coefficients - alpha = 0.33 and beta = 0.45 m/s. - are used to simulate dispersion and are the results of LES with Sentinel-2 specifications from Varon et al., 2021. L is the length of the plume in meters., calculated by finding the square root of the plume mask area. This results in an emission rate Q, reported in t h^{-1}.

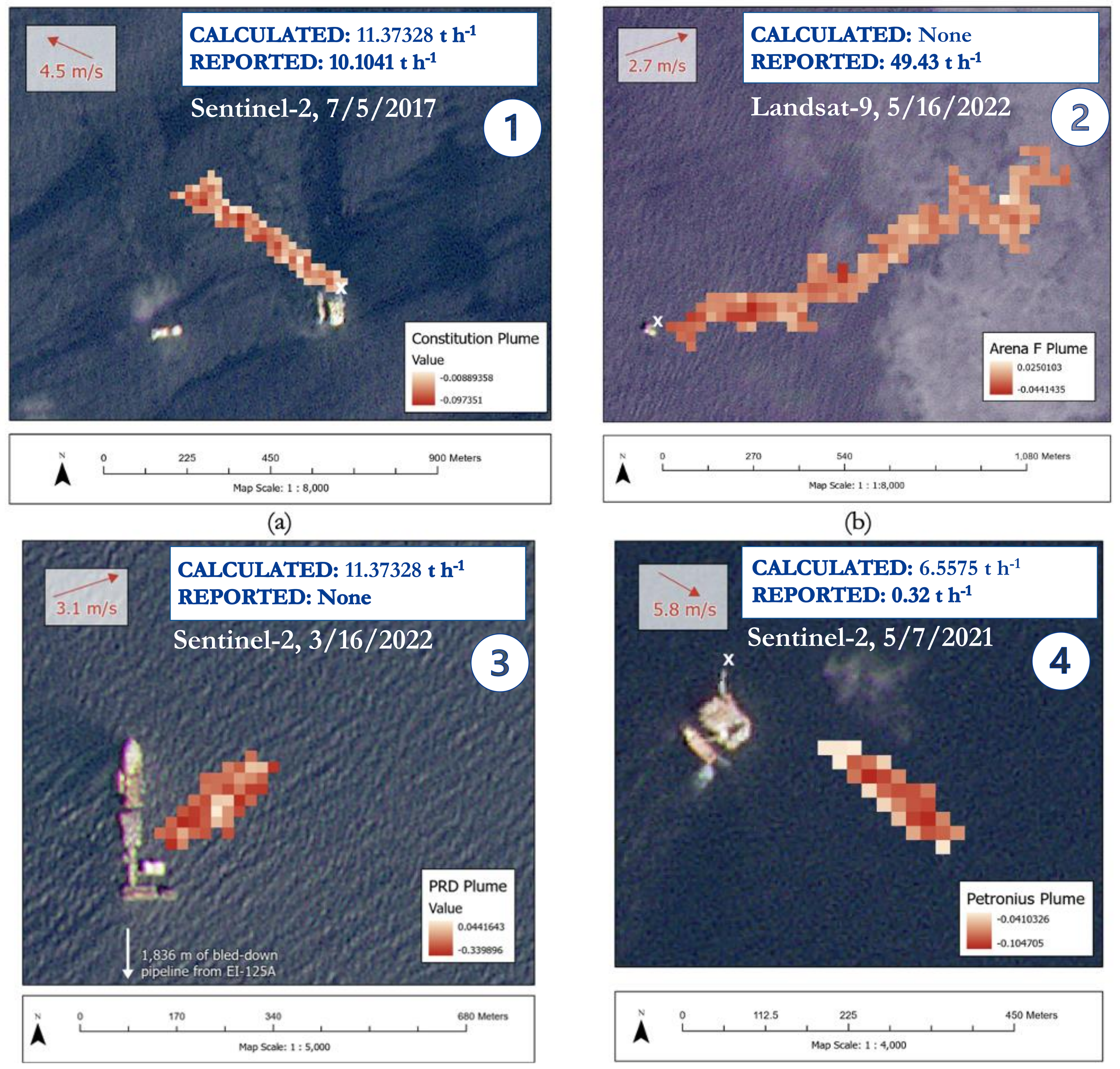
RESULTS

We identified four plumes in the Gulf of Mexico across 2017-2022, one with Landsat 9 OLI-2 and the three with Sentinel-2 MSI, and one plume with Sentinel-2 MSI off the coast of Congo.



Plumes were corroborated with operator reported vented release volumes, comments, and platform schematics along with reanalysis wind directions

Masks for potential plumes are overlaid on asynchronous true color Planet imagery - not reflecting sunglint conditions of detections.



1 Green Canyon Area, Block 680, "Constitution" platform – Wind direction matches trajectory of the plume. On this day, operators reporting venting due to a pipe blow down.

2 Eugene Island Area, Block 276, "F" platform – Confident plume detection consistent with wind direction - yet sunglint conditions are marginal so plume could not be confidently quantified. Likely large emission rate given size. Reported emissions here is a daily total.

3 Eugene Island Area, Block 120, "PRD" platform – No venting or flaring activity had occurred at the time this image was captured, our partners informed us that a pipeline connecting to a nearby platform was "bled-down" to zero pressure the day prior. This detection is likely due to methane released when this pipeline was emptied of its contents.

4 Viosca Knoll Area, Block 786, "Petronius" platform – The plume begins some distance away from the edge of the platform—around 75 meters. Schematics indicate the venting boom extends from the northern point of the platform, even further from the source of the potential plume.

5 Platform off Pointe Noire, Congo – Not pictured. Plume orientation is slightly inconsistent with wind direction, large enhancement with marginal sunglint conditions and therefore not quantified.

These detections illustrate a methodology for more comprehensive offshore monitoring. These two satellite – in tandem – have high global revisit. Even with TROPOspheric (TROPOMI) - previously a land only CH_4 product - recently evolving to include methane concentrations of sun-glint pixels over the ocean, this methodology offers a new ability to detect offshore emission events at much smaller magnitudes.

Conclusions

- Detections illustrate a novel use for Sentinel-2 SWIR imagery
- Ability to detect much lower offshore release rates than that of TROPOMI
- Seasonal and periodic nature of sunglint limits candidate scenes - detections from these satellites alone cannot sufficiently characterize persistence or variability of offshore sources
- Instruments with even lower detection limits are needed for monitoring, and for determining offshore contribution to methane budgets
- Could aid in identifying offshore super emitters that could be targeted with airborne campaigns and future satellite missions – specifically in previously understudied regions around the globe

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