A Review of U.S. Oil and Gas Methane and Air Pollutant Emissions

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A review of oil and gas air pollutant emissions, highlighting current gaps in monitoring.

In 2022, oil and natural gas comprised approximately 70% of U.S. energy consumption.[1] Domestic production is near an all-time high due to advances of horizontal drilling and hydraulic fracturing. Most production occurs onshore, although offshore platforms in the Gulf of Mexico account for 18% of U.S. oil and 3% of gas production.[2] Production is associated with emissions of methane, a potent greenhouse gas, and air pollutants, including nitrogen oxides (NOx) and non-methane volatile organic compounds (NMVOCs). In this article, we summarize studies quantifying emissions in production basins, and outline elements and identify gaps of an emerging tiered observing system (ground, airborne, satellite), designed to strategically reduce emissions and evaluate mitigation/emission reduction programs.

Methane Emissions and Trends

Figure 1 shows a map of onshore[3] and offshore[4] production methane emission estimates, and methane intensities derived from literature values **(see Table 1; https://csl.noaa.gov/pubs/em202309/table1.pdf)**. Here, we define intensity as the amount of methane emitted per amount of natural gas produced. Typical onshore intensities are 3.3% ± 2.5% (1σ). Offshore intensities range from 2.2–3.8%,[2] with shallow water facilities being high emitters.[5] Atmospherically-inferred, or top-down studies, suggest methane emissions that differ by approximately 2 times with official inventories.[2,3,5-9] Comparisons between top-down and bottom-up inventories can be challenging, given differences in sectoral detail and spatial-temporal resolution. To help bridge this gap, government and private sector programs are requiring robust, transparent verification of methane intensity of individual operators.[10-13]

Recent emphasis has focused on detecting methane emissions from super-emitting facilities, which contribute disproportionately to regional totals.[14-16] Advanced measurement technologies have improved leak detection and repair.[17] Rapidly reporting high-emission point sources is central to new federal and state programs such as the U.S. Environmental Protection Agency's (EPA) proposed Super Emitter Response Program and the California Air Resources Board's proposed Oil & Gas Methane Regulation amendments.[18,19]

Trends in methane intensity and oil and gas production are shown in Figure 2. The Greenhouse gases Observing

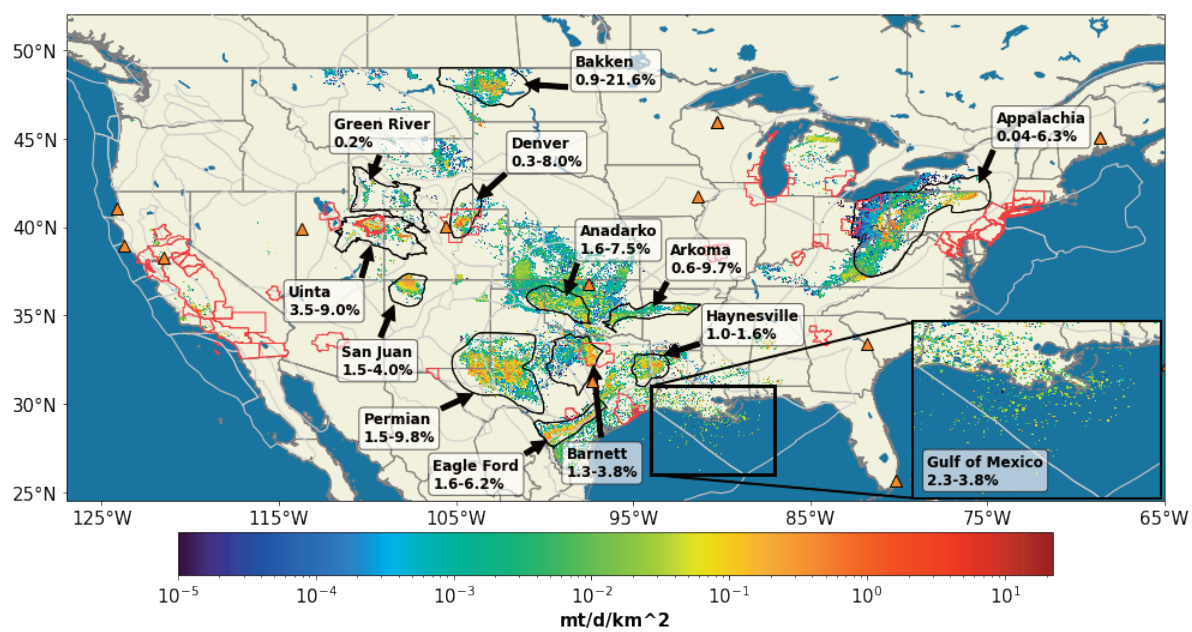

Figure 1. Map of U.S. oil and gas production basin emission estimates of methane (in metric tons / d / km²) from the Fuel-based Oil and Gas (FOG) inventory in 2015 derived from airborne observations,[3] and offshore emissions in the Gulf of Mexico (inset) from U.S. Bureau of Ocean Energy Management (BOEM) in 2021, which excludes facilities in state waters.[4] The range of methane intensities derived from fluxes reported in the literature are shown under each basin name and Gulf of Mexico. Areas in ozone nonattainment under the 2015 NAAQS (70 ppb) are outlined in red. The orange markers show the location of active NOAA Global Monitoring Laboratory surface towers with measurements of methane utilized in CarbonTracker-CH4.
Source: (https://gml.noaa.gov/ccgg/carbontracker-ch4/network_map3.html).

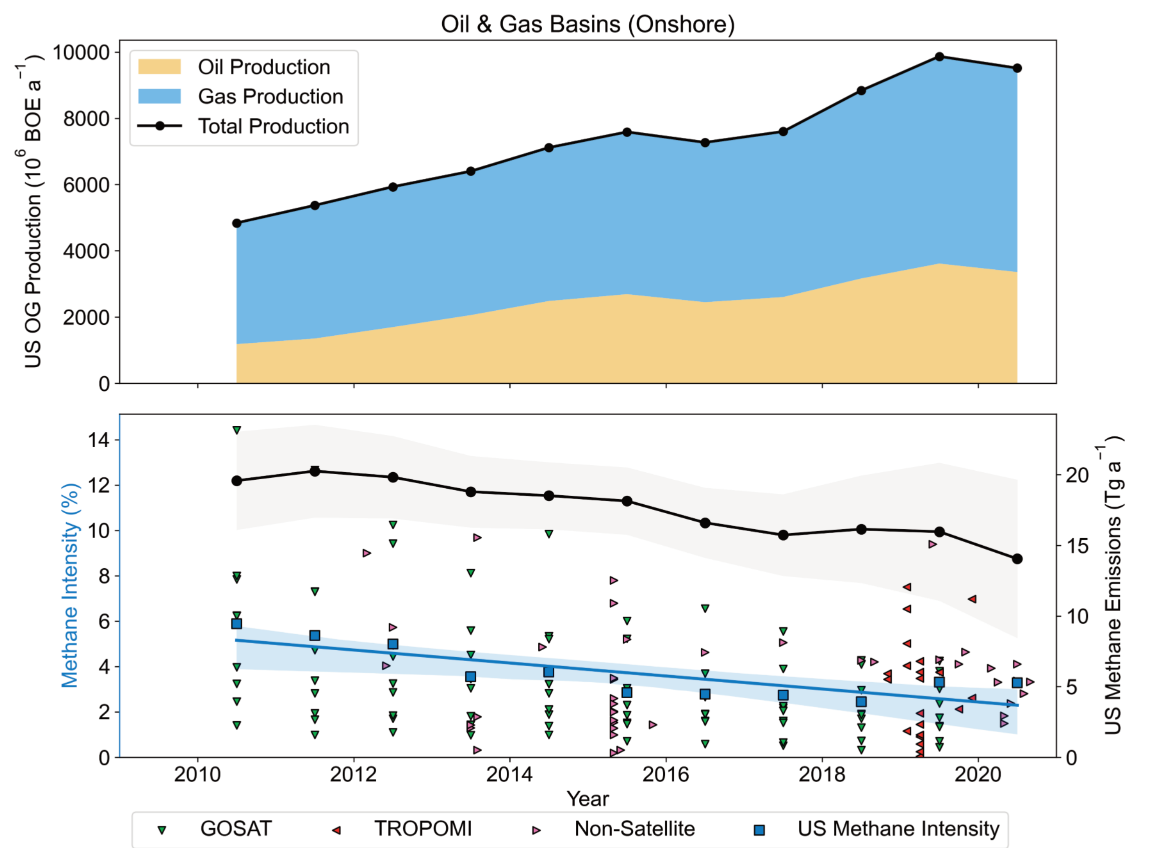

Figure 2. (top) Trend of U.S. oil and natural gas production from onshore basins only. (bottom) Trend of methane emissions intensity across U.S. onshore oil and gas basins. Individual basin-wide flux estimates listed in Table 1 (https://csl.noaa.gov/pubs/em202309/table1.pdf) are plotted for emissions estimated from OSAT (green), TROPOMI (red) and non-satellite (pink) datasets. Blue markers show the U.S. annual average methane intensity weighted by basin-level natural gas production in a given year. Basins with top-down fluxes in Table 1 account for 45–65% of onshore natural gas production in any given year. The blue trend line is an ordinary least squares regression of the blue markers with bands indicating the 95% confidence interval. The black trace shows the U.S. onshore oil and gas methane emissions calculated from U.S. natural gas production multiplied by the trend in methane intensity (blue line).

SATellite (GOSAT) data suggest an overall declining trend in methane intensity from 2010–2019.[7] The overall trend remains downward if we include fluxes derived from the Sentinel-5P/TROPOspheric Monitoring Instrument (TROPOMI) satellite, airborne, and other ground-based observations (studies listed in Table 1; https://csl.noaa.gov/pubs/em202309/table1.pdf). Early work using the SCanning Imaging Absorption spectroMeter for Atmospheric CartographY (SCIAMACHY) satellite is not included in the trend analysis.[20] Repeated long-term ground/airborne monitoring in production regions is sparse, except three ground-based monitors in Uinta[21] and a few towers from the National Oceanic and Atmospheric Administration (NOAA) Global Monitoring Laboratory (Figure 1). Even if methane emissions intensity may be declining, trends in overall emissions are partially offset by growth in U.S. production leading to overall downward, but not statistically significant changes in emissions across a decade.

Air Quality Challenges

NMVOCs are co-emitted with methane with varying composition.[22-26] The speciation depends on the amount of oil ("wet") versus natural gas ("dry") produced.[27] The wetter the gas, the higher the ratio of NMVOC/methane. Similar to methane, top-down NMVOC emission estimates differ by ~2 times with official inventories.[3]

NOx is emitted by engines associated with drilling rigs, artificial lifts, compressor stations, and other machinery. Increasing NOx trends over oil and gas regions have been associated with increased drilling and production.[28-30] Both NOx and NMVOCs are precursors to ground-level ozone formation and can significantly contribute to ozone in some areas, including during winter.[31-36] The 8-hr ozone standard is the most commonly violated U.S. National Ambient Air Quality Standard (NAAQS) across the United States. Several oil and gas basins are located in or near ozone nonattainment areas under the 2015 NAAQS (70 parts per billion, ppb), including the Permian, Barnett, Eagle Ford, Uinta, Denver-Julesburg, and Marcellus (Figure 1). Recently, the U.S. Clean Air Scientific Advisory Committee (CASAC) recommended lowering the 8-hr ozone standard to 60 ppb, which would encompass more oil and gas producing regions.

Around 10% of the U.S. population lives in areas with estimated emissions from oil and gas operations (as shown in Figure 1), and this fraction may be growing.[37] Communities nearby can be exposed to elevated levels of benzene and other hazardous air pollutants (HAPs).[38-40] While measurements of HAPs in oil and gas production areas are generally below health benchmarks, epidemiological studies show increased cancer and noncancer health impacts for populations located near oil and gas operations.[41-44]

Tiered Observing System

Figure 3 shows a schematic of observing platforms relevant to deriving emission fluxes from oil and gas activities. Surface measurements consist of instrumented ground sites and monitoring networks, mobile laboratories, and ship-based measurements. Fixed ground sites have characterized ozone photochemistry,[32] composition of NMVOCs,[22] air toxics,[39]

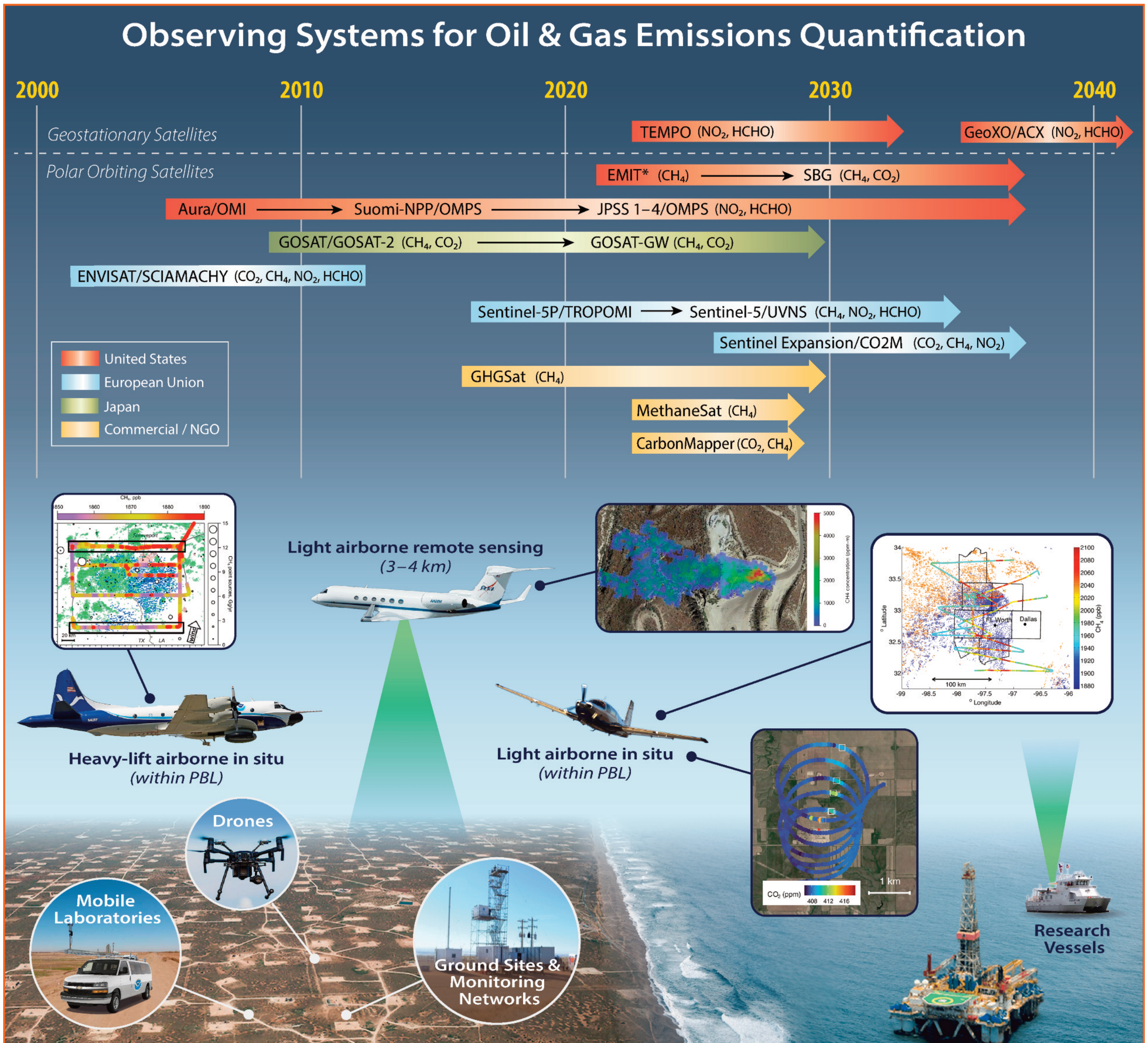

Figure 3. Schematic of tiered observing system from surface, airborne, satellite assets monitoring U.S. oil and gas emissions of methane and ozone precursors. Ground-based assets shown at the bottom for offshore and onshore measurements. Typical airborne flight patterns for quantifying oil and gas emissions are shown in the middle. Timeline of past, current, and planned satellite missions are shown at top. The asterisk on EMIT denotes an example of a satellite designed for other purposes, but capable of detecting oil and gas methane in an experimental capacity. Jacob, et al.[45] has a complete list of other similar experimental satellites that can detect oil and gas methane plumes.

and methane trends.[21] Tracer release experiments,[46] high volume samplers,[47] drones,[48] and optical gas imaging49 can capture fugitive leaks by individual processes. Mobile laboratories can identify super-emitting facilities and sources of air toxics.[50-55] Ships have characterized offshore super-emitting facilities[56] and sources of ozone precursors.[57] A challenge for most surface-based assets is in quantifying total area emission fluxes relative to airborne or satellite observations, when measuring in particular regions for periods of days to weeks or shorter. Long-term surface air composition monitoring from towers can be effective at tracking emissions, but currently is sparse in oil and gas producing regions.

Research aircraft have sampled snapshots of most large U.S. oil and gas regions within the last decade, onshore[58] and offshore.[5] Airborne measurements comprise in-situ instrumentation or remote sensing. Light aircraft are equipped with a few high-time-resolution in-situ instruments and flown to perform mass balances with upwind and downwind legs under steady winds and well-mixed boundary layer/midday to derive fluxes areawide,[59] or flux divergent legs vertically over major point sources. Due to their lower cost, light aircraft can deploy semi-continuously and for emergency response.[60] Heavy-lift aircraft are able to fly mass balance legs and hold many instruments that sample atmospheric composition from greenhouse gases to gaseous/aerosol pollutants.[61] An advantage of heavy-lift aircraft is their wide geographic coverage and ability to measure many basins. A disadvantage is their cost, which limits campaigns to once every few years. Airborne remote sensing instruments on high-flying aircraft have wide geographic coverage, including AVIRIS-NG (Airborne Visible / Infrared Imaging Spectrometer – Next Generation),[62] HyTES (Hyperspectral Thermal Emission Spectrometer),[63] or GCAS (GeoCAPE Airborne Simulator)[64] for methane and co-emitted air pollutants. These instruments generate high-resolution spatial maps quantifying emissions from superemitters,[65] and are less costly to deploy than heavy-lift aircraft.[14]

Relevant methane satellite instruments are shown in Figure 3, focusing on those launched by international space agencies with potential for operational use, and commercial and nonprofit entities delivering Level 2 products (i.e., column averaged methane concentrations). Non-government satellites are expected to continue into the 2030s and beyond pending funding and commitments. Methane near the surface is retrieved in the shortwave infrared (SWIR) and not directly measured from satellites, but derived from radiances. A complete description of current and planned SWIR capabilities is described by Jacob, et al.[45] Satellites are distinguished between those that view areawide emissions (0.1–10 km resolution) or target point sources at very high resolution (<60 m). Coverage (global, regional, hyperlocal) and repeat time (daily, biweekly) are closely connected with spatial resolution. When coupled with atmospheric chemical transport models to perform emission inversions, SWIR satellites have demonstrated capability to investigate methane trends[71], quantify fluxes,[66,67] and identify super-emitters.[16] While it is possible to retrieve methane over oceans in the sun-glint mode, relatively few satellite studies assess offshore emissions at this time.[68]

For air quality, satellite observations of nitrogen dioxide (NO_2) and formaldehyde are retrieved in the ultraviolet-visible (UV-VIS) spectrum. Most satellite studies analyze onshore emissions, as detection is limited over oceans.[57] Satellite NO_2 can track trends in engine activity associated with drilling and production,[28-30] and capture spatial enhancements of NO_2 co-located with methane useful for source apportionment.[69] Though the emissions of NMVOCs can be inferred from formaldehyde, few studies report NMVOC trends or fluxes from oil and gas producing regions.[70]

Current Monitoring Gaps

This review underscores the need for and promise of deploying a tiered top-down observing system that can deliver actionable information for environmental managers. Scoping efforts such as the new U.S. federal strategy for a Greenhouse Gas Monitoring and Information System[71] could benefit from more explicit attention on how to scale up and sustain operational monitoring long term. Here we make the following design recommendations:

1. **Ground.** More high-frequency observations of HAPs from mobile laboratories, drones, fenceline and tethered balloons in combination with passive samplers in targeted locations would help fill gaps elucidating community-level exposure to oil and gas development and petrochemical operations.[72] Expansion of regional atmospheric observatories (e.g., NOAA Greenhouse Gas Reference Network; https://gml.noaa.gov/ccgg/about.html) near more production basins could help with monitoring long-term methane trends from oil and gas extraction.

2. **Airborne.** One of the most comprehensive airborne surveys, the Shale Oil and Natural Gas Nexus (SONGNex) (https://csl.noaa.gov/projects/songnex/) study, is nearly a decade old. Renewed attention to comprehensive airborne sampling by light and heavy-lift aircraft in a strategic manner could help provide corroborating evidence for satellite inferred emission trends (methane, NOx, NMVOCs), and improve trace gas retrievals offshore.

3. **Satellite.** The expanding ad-hoc network of methane monitoring systems, including surface, airborne and space-based observations and analytical frameworks would benefit from increased coordination across government and non-government actors. Currently, there is no planned geostationary greenhouse gas satellite mission over North America. Diurnal methane observations could enhance

basin-level emission estimates of oil and gas infrastructure, which are large, intermittent and vary across the day.[73-75] Future efforts to deploy constellations of small satellites in polar orbit could help mitigate this gap.

Durable mechanisms to finance research-to-operations (R2O) for greenhouse gas emissions data and mitigation, akin to the weather enterprise, is lacking. Sustained R2O funding can help decrease data latency, increase data access and transparency, and enable successfully piloted research projects to becoming operationalized programs. Lastly, a series of workshops aimed at designing an integrated tiered top-down observing system could help with optimal configuration, and in identifying resource needs. **em**

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Please note that Table 1 and the complete list of references for this article are available online at https://csl.noaa.gov/pubs/em202309/table1.pdf.