United States Department of Commerce
National Oceanic & Atmospheric Administration

Rev. Mar 24, 2025

AiRMAPS

Airborne and Remote sensing Multi Air Pollutant Surveys

A NOAA OAR and NESDIS investigation of air pollutant and greenhouse gas emissions and impacts

Objectives

1. Leverage a tiered, integrated satellite, airborne and ground-based observing system for comprehensive, accurate evaluation of air pollutant emissions;
2. Evaluate civilian and commercial spaceborne remote sensing methods for detection and quantification of methane, NO_2, and other pollutants from diverse source sectors; and
3. Quantify air pollutant emissions and air quality impacts from urban areas, the oil and gas sector, and other sources to improve inventories and provide relevant information to decision-makers.

NOAA Office of Atmospheric Research (OAR)

Chemical Sciences Laboratory (CSL): Steven Brown, Brian McDonald, Carsten Warneke, Sunil Baidar

Air Resources Laboratory (ARL): Xinrong Ren, Winston Luke

Global Monitoring Laboratory (GML): Colm Sweeney, Jeff Peischl, Arlyn Andrews

Climate Program Office (CPO): Monika Kopacz, Annarita Mariotti

NOAA National Environmental Satellite, Data and Information Service (NESDIS)

Center for Satellite Applications and Research (STAR): Shobha Kondragunta

National Centers for Environment Information (NCEI): Jeff Privette

csl.noaa.gov/projects/airmaps

The United States requires accurate information to underpin current emissions inventories for air pollutants and greenhouse gases and voluntary carbon markets and credits, and to evaluate the efficacy of mitigation technologies. The United States currently produces more oil and natural gas than at any time in its history, and more than any other country. Crude oil and natural gas exports reached record highs in 2023, with substantial growth in liquified natural gas (LNG). U.S. companies are participants in international methane reporting programs based on measurement frameworks to improve the accuracy and transparency of global emission estimates. Recently enacted requirements for reporting and mitigation of methane intensity in overseas natural gas markets has the potential to affect the size and value of U.S. exports (Talus et al., 2024). Accurate, independently verified inventories support GHG reduction goals, and economic growth and competitiveness. Leaked natural gas that is not captured and sold results in a direct economic loss to operators. Oil and gas methane intensity, defined as the amount emitted per unit of production, has been declining for more than a decade. (Figure 1).

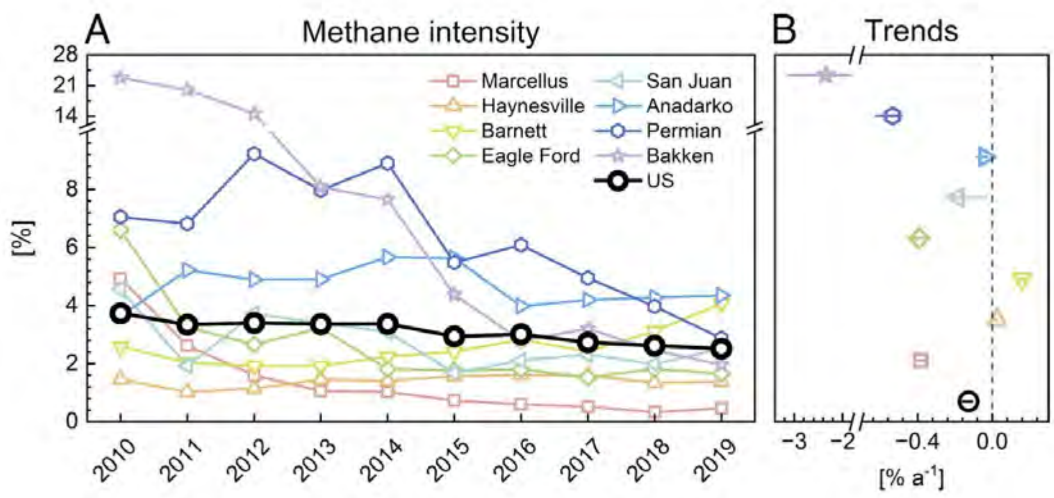

Figure 1. U.S. natural gas methane intensity (emissions per unit produced) derived from satellite observations for 2010 – 2019. Panel B shows trends for each basin (Lu et al., 2023).

Long term decreases in primary pollutants, such as NO_2 from fossil fuel combustion, have led to decreases in urban secondary pollutants such as ozone and particulate matter (Fleming et al., 2018;Skyllakou et al., 2021), but with uneven trends in different locations. Many U.S. regions continue to exceed air quality standards, resulting in more than 100,000 excess deaths and nearly $1 trillion in economic damages annually (Goodkind et al., 2019). The U.S. has recently invested in state-of-the-art geostationary satellite measurements for air quality that will serve as the forerunner for NOAA's GeoXO atmospheric composition program. One of the overarching goals of the GeoXO mission is to serve communities with near real time information so that preventative measures are in place for positive health outcomes.

The NOAA Office of Oceanic and Atmospheric Research (OAR) has committed to organizing its research around societal challenges that include *Confronting Challenges from our Changing Climate* and *Sustaining a Healthy Environment and Economy*. To address these societal challenges, NOAA OAR and NESDIS will lead a series of airborne campaigns in 2024–2026 to provide comprehensive and quantitative top-down emissions data for major air pollutants from a series of urban areas and from the O&G sector at basin scale and selected facility scale. NOAA surveyed a large majority of U.S. O&G production regions in a series of campaigns in 2013, 2014 and 2015 in work that has contributed to a comprehensive evaluation of onshore O&G emissions (Alvarez et al., 2018; Peischl et al., 2018). NOAA has a long history of airborne measurements to address urban air quality and provide timely information to state and local air quality managers. Oil and gas production, methane detection technologies, satellite remote sensing capability, national emissions targets, emissions controls and regional air quality have all evolved markedly over time. Newer and more comprehensive airborne measurements are critically needed.

OAR and NESDIS intend to execute this strategy in collaboration with airborne, remote sensing and ground-based assets from NOAA and partner agencies to **leverage an integrated, tiered observing system** (Figure 2). The NOAA strategy has two main deliverables. (1) **Actionable information to support state and local strategies to improve regional air quality**. Airborne and satellite-based observations will be integrated and evaluated to achieve these objectives. (2) **A quantitative assessment of methane and other emissions from a significant fraction of O&G production regions and selected urban testbeds.** Additional sources such as agriculture, landfills, coal mining and wetlands will be specifically targeted in the course of these surveys. One purpose of this white paper is to foster community and partner engagement.

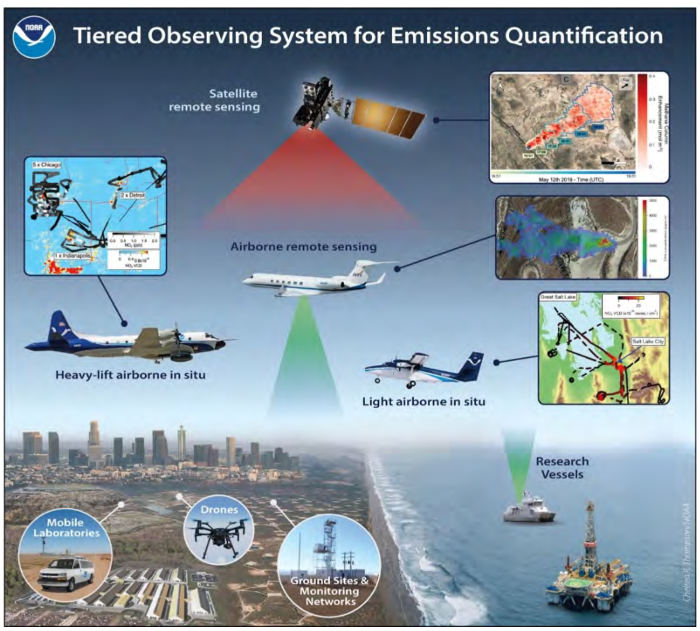

Figure 2. Schematic of a tiered observing system composed of surface, airborne and satellite assets that is used to evaluate and monitor O&G and urban air pollutant emissions. Adapted from (McDonald et al., 2023).

The envisioned activities are based on current programs and conditional on the availability of resources. Participating OAR laboratories and programs include the Chemical Sciences Laboratory (CSL), the Air Resources Laboratory (ARL), the Global Monitoring Laboratory (GML) and the Atmospheric Chemistry Carbon Cycle and Climate Program (AC4) of the Climate Program Office (CPO). Participating NESDIS Programs include the Center for Satellite Applications and Research (STAR) and the National Centers for Environmental Information (NCEI). OAR and NESDIS have established and will seek further collaboration with other NOAA line offices (NWS), federal agencies (NIST, NASA, DOE, EPA, DOI), academic partners, and stakeholders (state and tribal agencies, the O&G industry, NGOs, private sector entities and data providers). NOAA NESDIS and NASA support spaceborne and airborne remote sensing of GHGs, and NOAA OAR, NIST and DOE support ground-based GHG networks. EPA, NOAA and NIST compile activity-based inventories. State agencies in Colorado and Utah have directly supported ongoing AiRMAPS work, and collaborations are developing with states in the mid-Atlantic region for 2025 (Maryland, Pennsylvania) and the south-central U.S. for

2026 (Texas, New Mexico). Discussions are ongoing with other states. NOAA airborne surveys and satellite observations directly meet the needs of these stakeholders and further link together the observing system components from different federal agencies and private sector data providers, evaluate their accuracy and completeness and support the development of more accurate emissions inventories.

The OAR and NESDIS strategy encompasses four principal research objectives:

1. Leverage a tiered, integrated observing system consisting of light and heavy aircraft providing comprehensive airborne surveys; satellite- and aircraft-based remote sensing; and ground-based long- and short-term observations (Figure 2) for comprehensive, accurate understanding of air pollutants;
2. Evaluate civilian and commercial spaceborne remote-sensing methods for the detection and quantification of methane, nitrogen dioxide (NO_2) and other pollutants from diverse source sectors with a wide dynamic range of emissions using a methodology consistent with current standards and definitions;
3. Quantify air pollutant emissions and air quality impacts from urban areas, the O&G sector and other sources in support of evaluating and improving inventories (e.g., EPA GHGI and NOAA-NIST GRA^{2}PES) and providing cities and states relevant information to assist in attaining air quality standards;

Intensive Airborne Surveys

Long-term monitoring of air pollutant emissions requires a comprehensive observing system that is composed of ground monitoring systems as well as airborne and satellite remote sensing systems. The latter are powerful but nascent technologies that need rigorous verification. NOAA airborne surveys and remote sensing approaches represent the currently best-available methodology to validate and augment new remote sensing technology. OAR has developed state-of-the-art research aircraft instrumentation and has a long history in the execution of airborne campaigns. Based on this proven expertise, OAR will derive emissions using airborne surveys involving several detection and analysis methods.

Mass balance. Mass balance derives emissions from the difference between upwind and downwind trace gas concentrations. NOAA CSL's airborne Doppler lidar provides high resolution wind velocities throughout the boundary layer, as well as mixed layer depth, to improve the efficiency and accuracy of this method.

Tracer relationships. Co-measurements of GHGs with other emitted pollutants provide quantitative emission estimates and source attribution (e.g., agriculture, O&G, urban). NOAA OAR has substantial expertise in developing and deploying airborne instrumentation for a wide range of pollutant species.

Eddy covariance. Variation of pollutant concentrations with vertical wind velocity provides surface emissions via an independent and complementary method.

Inverse modeling. Application of chemical transport models to satellite, airborne and ground-based GHG measurements provides complementary emission estimates.

Long-term Satellite Observations

Satellite observations augment ground monitoring capability and have become a viable source of information – they are the “eyes in the sky” that provide routine daily observations for long periods of time and thereby provide continuity and trends from regional to global scales. While well calibrated ground-based sensors often provide the most accurate GHG and pollutant measurements, NOAA and its partner agencies use a fleet of geostationary and polar-orbiting satellites to observe emissions from large sources as well as derive concentrations assuming a well-mixed atmosphere. In the last decade, a host of commercial and non-profit methane observing satellites have come into the fore, including GHGSat, MethaneSAT, Carbon Mapper and many others (Jacob et al., 2022). Civilian and commercial/non-profit satellite instruments serve diverse needs by observing emissions from different source sectors. However, detection and quantification depend on assumptions that require thorough validation:

> *Plume Detection*. Averaged over weekly, monthly, and yearly time scales, methane concentrations from satellite sensors such as the Sentinel 5 Precursor Tropospheric Monitoring Instrument (S5P TROPOMI) can identify source regions, and observations combined with models provide emissions (fluxes). TROPOMI and similar instruments in a polar orbit measuring in the short-wave and near-infrared spectrum can detect plumes from high-emitting facilities, but plume quantification involves assumptions about local meteorology. By contrast, frequent snapshots of high-emitting plumes observed by geostationary satellite imagers, such as the GOES-R series Advanced Baseline Imager (ABI), can be integrated over time to derive emissions without the need for meteorological data or models. *Quantifying plume concentrations and fluxes from remote-sensing data requires an independent source of information*.
>
> *3D Concentration Fields.* Hyperspectral sounders measuring in the infrared such as the JPSS series or Metop Series sounding instruments (e.g., Cross-track Infrared Sounder) observe 3D fields of methane concentrations but retrievals are useful only on monthly to yearly time scales. These data need to be integrated with other in situ observations and models such as NOAA's CarbonTracker to be converted to fluxes. Prior to converting to fluxes, the data need to be well validated to ensure quality control.

The 2024–26 Timeline for Airborne Surveys

The OAR strategy for the airborne campaigns in 2024–2026 is shown in Figure 3. The NOAA Twin Otter and WP-3D aircraft can be instrumented to measure GHGs (methane, carbon dioxide) and other tracers (nitrogen oxides, carbon monoxide). The Twin Otter also measures wind velocities and boundary layer height with a Doppler lidar; a similar system is anticipated on the NOAA WP-3D by 2026. The enhanced NOAA WP-3D measurements also include co-emitted pollutants such as speciated volatile organic compounds (VOCs), oxidized nitrogen, speciated aerosol composition, etc.

> *2024: Colorado & Utah*. OAR conducted a series of flights with a NOAA Twin Otter in Colorado's Denver-Julesburg Basin and Utah's Uinta Basin, and the urban areas of Denver, Colorado and Salt Lake City, Utah (a city with a long record of urban GHG measurements) with the airborne Doppler lidar, GHGs and other tracer measurements. OAR also deployed ground based mobile platforms.
>
> *2025: Baltimore & Marcellus Shale*. Washington, D.C. - Baltimore is a well-established urban GHG emission testbed that remains out of compliance with current standards for ozone pollution. The Marcellus shale is one of the largest U.S. O&G basins. OAR will survey both regions with a NOAA Twin Otter and ground based mobile platforms.
>
> *2026: Texas and South-Central U.S*. OAR will deploy a comprehensive and detailed chemical payload on a NOAA WP-3D aircraft to survey GHGs and co-emitted pollutants from the largest U.S. O&G basins (e.g., the Permian) and major urban areas (e.g.,

Houston, TX). Flights to the Bakken shale basin in North Dakota may be considered. A NOAA Twin Otter will survey a series of O&G basins in Texas, Oklahoma, Arkansas and Louisiana as well as major cites (e.g., Dallas, TX).

This series of flights will survey several urban areas and a significant fraction of O&G production. The emissions estimates from the survey flights and coordinated activities will provide critical evaluation of top-down and bottom-up methods to reduce uncertainty and improve reliability. Coordination of these surveys with complementary methods from remote sensing and surface data will aid in assessing the accuracy of these approaches that provide longer-term monitoring of emission trends.

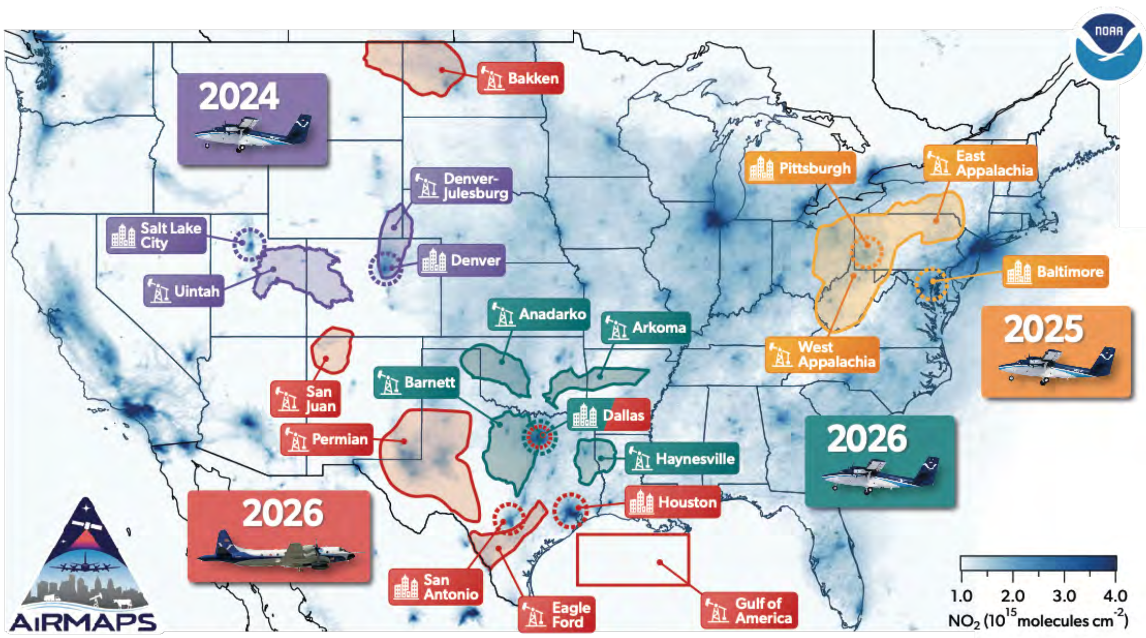

Figure 3. AiRMAPS airborne survey schedule for 2024-2026. The base map shows nitrogen dioxide columns as measured from the TROPOMI satellite instrument for summer 2023. The shaded areas and dashed circles show O&G basins and urban areas for AIRMAPS surveys by year and aircraft (NOAA Twin Otter and WP-3D).

References

Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., Davis, K. J., Herndon, S. C., Jacob, D. J., Karion, A., Kort, E. A., Lamb, B. K., Lauvaux, T., Maasakkers, J. D., Marchese, A. J., Omara, M., Pacala, S. W., Peischl, J., Robinson, A. L., Shepson, P. B., Sweeney, C., Townsend-Small, A., Wofsy, S. C., and Hamburg, S. P.: Assessment of methane emissions from the U.S. oil and gas supply chain, Science, 361, 186-188, 10.1126/science.aar7204, 2018.

Fleming, Z. L., Doherty, R. M., von Schneidemesser, E., Malley, C. S., Cooper, O. R., Pinto, J. P., Colette, A., Xu, X., Simpson, D., Schultz, M. G., Lefohn, A. S., Hamad, S., Moolla, R., Solberg, S., and Feng, Z.: Tropospheric Ozone Assessment Report: Present-day ozone distribution and trends relevant to human health, Elementa: Science of the Anthropocene, 6, 10.1525/elementa.273, 2018.

Goodkind, A. L., Tessum, C. W., Coggins, J. S., Hill, J. D., and Marshall, J. D.: Fine-scale damage estimates of particulate matter air pollution reveal opportunities for location-specific mitigation of emissions, Proceedings of the National Academy of Sciences, 116, 8775, 10.1073/pnas.1816102116, 2019.

Jacob, D. J., Varon, D. J., Cusworth, D. H., Dennison, P. E., Frankenberg, C., Gautam, R., Guanter, L., Kelley, J., McKeever, J., Ott, L. E., Poulter, B., Qu, Z., Thorpe, A. K., Worden, J. R., and Duren, R. M.: Quantifying methane emissions from the global scale down to point sources using satellite observations of atmospheric methane, Atmos. Chem. Phys., 22, 9617-9646, 10.5194/acp-22-9617-2022, 2022.

Lu, X., Jacob, D. J., Zhang, Y., Shen, L., Sulprizio, M. P., Maasakkers, J. D., Varon, D. J., Qu, Z., Chen, Z., Hmiel, B., Parker, R. J., Boesch, H., Wang, H., He, C., and Fan, S.: Observation-derived 2010-2019 trends in methane emissions and intensities from US oil and gas fields tied to activity metrics, Proceedings of the National Academy of Sciences, 120, e2217900120, 10.1073/pnas.2217900120, 2023.

McDonald, B. C., He, J., Harkins, C., de Gouw, J., Elguindi, N., Duren, R., Gilman, J., Kort, E. A., Miller, C. E., Peischl, J., Pétron, G., and Thompson, C.: A Review of U. S. Oil and Gas Methane and Air Pollutant Emissions, EM Magazine, 2023.

Peischl, J., Eilerman, S. J., Neuman, J. A., Aikin, K. C., de Gouw, J., Gilman, J. B., Herndon, S. C., Nadkarni, R., Trainer, M., Warneke, C., and Ryerson, T. B.: Quantifying Methane and Ethane Emissions to the Atmosphere From Central and Western U.S. Oil and Natural Gas Production Regions, Journal of Geophysical Research: Atmospheres, 123, 7725-7740, https://doi.org/10.1029/2018JD028622, 2018.

Skyllakou, K., Rivera, P. G., Dinkelacker, B., Karnezi, E., Kioutsioukis, I., Hernandez, C., Adams, P. J., and Pandis, S. N.: Changes in PM2.5 concentrations and their sources in the US from 1990 to 2010, Atmos. Chem. Phys., 21, 17115-17132, 10.5194/acp-21-17115-2021, 2021.

Talus, K., Steck, G., and Atkin, J.: EU Methane Regulation and its impact on LNG imports, The Journal of World Energy Law & Business, jwae022, 10.1093/jwelb/jwae022, 2024.