GMAC 2026

PROGRAM

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University of Colorado Boulder

Glenn Miller Ballroom in the University Memorial Center

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Session 1:
Keynote Session

Welcome from the Global Monitoring Laboratory

Vanda Grubišić (NOAA - GML)

Opening remarks from Dr. Vanda Grubišić, Director of the Global Monitoring Laboratory since March 2023.

Bio: Vanda Grubišić, Ph.D. has led major international observational field campaigns to study the atmosphere. She is one of the world's leading scientists in the field of mesoscale meteorology, which is the study of atmospheric phenomena with typical spatial scales between 6 and 600 miles, including thunderstorms, downslope windstorms, land-sea breezes and squall lines.

Grubišić previously served as director of the National Center for Atmospheric Research's (NCAR) Earth Observing Laboratory, where she was responsible for its scientific strategy, administrative processes and procedures and budgetary planning for more than 10 years. The laboratory's accomplishments under her leadership include the successful development of novel observational technologies, reconstruction of the NCAR aviation building and safely returning to field campaign operations during the COVID-19 pandemic. She also managed NCAR's Research Aviation Facility, which supports airborne scientific investigations with two aircraft based at the Rocky Mountain Metropolitan Airport near Boulder in Jefferson County.

Grubišić has spent her near 30-year career focused on mesoscale atmospheric dynamics of mountain airflows, which was sparked by curiosity as a child about the legendary bora wind in her native Croatia. In 2015, she was awarded the Spiridon Brusina Medaloffsite link from the Croatian Society of Natural Sciences in recognition for her accomplishments in the field of meteorology for the research of the mesoscale atmospheric dynamics and wind and precipitation processes over complex terrain.

Grubišić obtained her bachelor of science in physics/meteorology from the University of Zagreb, and doctorate in atmospheric science from Yale University. Before serving at NCAR, Grubišić was a full professor at the University of Vienna, Austria and, before that, a researcher and professor at the Desert Research Institute in Reno, Nevada. She has served on numerous scientific commissions and boards, including the National Academies Board of the Atmospheric Sciences and Climate, and has held leadership positions in several professional organizations, including the American Meteorological Society.

The View from NOAA Oceanic and Atmospheric Research

Jennifer Mahoney (NOAA - OAR)

Opening remarks from Ms. Jennifer Mahoney, Acting Deputy Associate Administrator for Science, NOAA Oceanic and Atmospheric Research Director of the Global Monitoring Laboratory since March 2025.

Bio: Jennifer Mahoney comes to OAR's leadership team from directing the NOAA Global Systems Laboratory (GSL) where she led a staff of nearly 200 meteorologists, software engineers, and support staff dedicated to providing solutions that protect society from extreme weather. GSL is proud to host NOAA's new Fire Weather Testbed where users and researchers work together to evaluate new fire weather tools and technology. GSL expertise in data assimilation and verification techniques advances the NOAA Unified Forecast System local-to-global and hourly-to-seasonal timescales that can predict severe weather, and the transport of smoke, and dust. GSL leads the development of Hazard Services, a multi-year, multi-phase, multi-partner effort to streamline the process to create hazardous weather watches, warnings, or advisories for 120 NOAA National Weather Service Offices and six NOAA National Centers. GSL also researches state-of-the-art environmental forecast, warning, decision support, Artificial Intelligence, social science, and visualization capabilities to empower forecasters and decision-makers.

Jennifer is a Fellow of the American Meteorological Society (AMS) serving on the Commission on the Weather, Water and Climate Enterprise Steering Committee. Jennifer serves as the Co-Chair for the Interagency Council on Advancing Meteorological Services on Atmospheric Composition Information and Services working to advance U.S. global leadership in atmospheric composition services, and is a member of the Board of the Climate Resilience Engine advancing collaborative solutions that address the impacts of climate change in Colorado and Wyoming. As a Fellow of the Cooperative Institute for Research in the Atmosphere (CIRA), she is guiding research objectives for the Institute. She is a member of the Management Oversight Board for the Joint Center for Satellite Data Assimilation and serves on the Executive Team for NOAA's Developmental Testbed Center. She also guides NOAA's HPC Allocation Committee enabling the efficient use of computing resources to advance NOAA's forecasting needs.

Prior to her selection as GSL Director, Jennifer served in various roles within NOAA. Additionally, she was recognized twice as the NOAA Research Employee of the Year for her Leadership. She received the NOAA Administrator's award for the establishment of ground-breaking IT security practices, maximizing the effectiveness of partner high performance computing systems for the advancement of NOAA science; a NOAA Bronze Medal for expeditiously and skillfully coordinating research that leveraged the unique scientific opportunity resulting from the COVID-19 global pandemic; and she was recognized by the Colorado State University Department of Atmospheric Science where she received an Outstanding Alumni Award.

Keynote Address:
From Ember to Exabyte: Extreme Fires Across Scales

Jennifer Balch (U. Colorado Boulder)

Fast fires, night fires, and urban fires all reflect how our nation's fire regimes are changing. People have fundamentally altered the three ingredients needed for fire: fuel to burn, hot and dry conditions, and an ignition source. Fire is also a big data frontier with a wealth of information, from satellites to social media, that can be leveraged to understand consequences and develop solutions. We have seen the most expensive wildfire seasons in the U.S. in the past decade, costing over $150B. We need to learn to live with fire, again. But how? Ultimately, we need to burn better and build better.

Bio: Dr. Jennifer Balch is Director of the Environmental Data Science Innovation & Impact Lab (ESIIL) at the University of Colorado-Boulder. She is a Professor in the Department of Geography and a CIRES Fellow. Dr. Balch's research aims to understand the patterns and processes that underlie disturbance and ecosystem recovery, particularly how people are shifting fire regimes and the consequences. Her work leverages big data and spans from temperate regions to the tropics. She has conducted research in the field of fire ecology for over twenty years and has lit a few experimental burns to understand the consequences of altered fire regimes. Dr. Balch leads large teams to generate fire science that matters to key stakeholders and helps us live more sustainably with wildfire.

Session 2:
Decoding Drivers: Assessing Wildfire, Biosphere, and Transport Impacts on the Atmosphere

Understanding the causes of the unprecedented growth of atmospheric CO_2 in 2024

John Miller (NOAA)
Co-authors: Xin Lan (CIRES)

In 2024, global mean atmospheric CO_2 increased by 3.7 ppm as determined from marine boundary layer observations of NOAA's Global Greenhouse Gas Reference Network (GGGRN), the largest annual increase on record. Estimated 2024 global fossil fuel-CO_2 emissions were only 1% higher than 2023, equivalent to only ~0.05 ppm/yr indicating that nearly all of the 2024 anomaly resulted from oceanic and terrestrial biospheric processes. Preliminary estimates of oceanic CO_2 fluxes suggest only small changes between 2023 and 2024 further implying that the 2024 anomaly originated from significant changes to some combination of terrestrial photosynthesis, respiration, and/or fire emissions.

We use the CarbonTracker (CT) inverse model, constrained by GGGRN and other CO_2 observations to quantify net CO_2 fluxes at seasonal and continental scales. Preliminary results confirm our hypothesis that the 2024 flux anomaly was largely driven by tropical terrestrial regions, although the small number of measurement sites sensitive to tropical land limits our ability to attribute the anomaly to South America, Africa, or Asia. Additionally, because of uncertainty in fire emissions, we cannot yet identify the extent to which the 2024 anomalies were driven by fire emissions or net ecosystem exchange (the balance between photosynthesis and respiration) in undisturbed ecosystems.

To better understand the ecosystem mechanisms responsible for 2024 carbon flux anomaly, we evaluate additional global data sets of environmental drivers such as terrestrial water storage, radiation, and air temperature, as well as diagnostics of ecosystem health such as solar induced chlorophyll fluorescence (SIF) and near-infrared reflectance of vegetation (NIRv). 2024 was the warmest year on record, at least partly associated with the end of a strong El Niño. Tropical land temperatures were higher than the two-sigma envelope for every month in 2024, while tropical vapor pressure deficit (VPD) was also highly anomalous, especially for tropical Africa. Both of these factors are consistent with stressed tropical ecosystems releasing significant amounts of carbon via increased fires, reduced photosynthesis, and/or enhanced decomposition. Analysis of SIF, a proxy for photosynthesis, shows large tropical reductions in 2024, in both tropical Africa and Amazonia. Despite CarbonTracker's relatively low resolution within the tropics, our analysis of ancillary data suggests a dominant role for tropical Africa, followed by South America. In addition to these results, we will also discuss the role of El Niño, and the return to a much lower global CO_2 growth rate in 2025.

Smokeless Smoke? Investigating Aerosol Removal in Smoke Plumes

Dan Jaffe (School of STEM/Department of Atmospheric Sciences, University of Washington)
Co-authors: Andrew Langford (NOAA - CSL), Lynne Gratz (Reed College)

The Mt. Bachelor Observatory (MBO) is a mountain top observatory (2.8 km asl) located in Central Oregon. Since 2004 we have measured a suite of gas and aerosol tracers and identified many pollution events from different sources. However, in the recent decade, wildfire and prescribed smoke has emerged as the dominant event type we see. This is confirmed by emission inventories, which show that wildfires are now the dominant source of aerosols in the Western U.S. Since 2004, we have identified more than 100 discrete wildfire and prescribed plume hits. In the vast majority (~97%), we see an excellent correlation between CO and aerosol scattering, but with variable slopes that are indicative of the emissions and processing enroute to MBO. Other pollutants, such as O_3 and NO_y, show much greater variability in the normalized enhancement ratios (NERs), compared to the NER for CO and aerosol scattering. In a very small number of smoke plumes (n=3), we see clear evidence for sub-micron aerosol loss in very humid or cloud processed air. We call these the "smokeless smoke" plumes. While the number of smokeless smoke events we have observed is relatively small, they are an important part of the aerosol life cycle, since cloud processing is probably the dominant removal mechanism for smoke aerosols in the atmosphere. Other experiments, such as FAST-LVOS and observations near the Alexander Mountain Fire near Ft. Collins in 2024, have also, occasionally, identified similar types of events.

Based on this preliminary data, we are now searching for similar cases at other observatories. Given the greater likelihood of cloud processing at altitude, sites like Storm Peak Lab (Colorado) and Whiteface Mountain Observatory (NY) should have the greatest chance to identify smokeless smoke, along with MBO. In this presentation, I will review the evidence for smokeless smoke, suggest ways to mine existing datasets for more data and outline the significance of this phenomena.

Integrating Satellite and Isotopic Observations in CarbonTracker-CH_4 for Improved Methane Emission Estimates during 2019-2024

Youmi Oh (CIRES, CU Boulder; NOAA GML)
Co-authors: Lori Bruhwiler (NOAA - GML)

After ~15 years of decline since the late 2000s, atmospheric stable carbon isotopic ratios of methane (δ^{13}C-CH4) showed a notable increase during 2023–2024. Understanding the drivers of this shift is critical, as δ^{13}C-CH_4 provides key constraints for partitioning source contributions to recent atmospheric CH_4 growth. NOAA's CarbonTracker–CH_4 (CT-CH_4) data assimilation system addresses this challenge by optimizing CH_4 emissions using atmospheric observations within a global transport framework. CT-CH_4 assimilates highly precise but spatially sparse in-situ CH_4 mole fractions and δ^{13}C-CH_4 measurements. In contrast, satellite retrievals provide up to ~0.5 million CH_4 observations daily with extensive spatial coverage, particularly across the tropics. To leverage these complementary datasets, we have extended the CT-CH_4 framework to assimilate satellite CH_4 data from the blended TROPOMI-GOSAT product alongside in-situ CH_4 and δ^{13}C-CH_4 observations.

We perform a suite of inversion configurations for 2019-2024 by including or excluding satellite CH4, in-situ CH4, and δ^{13}C-CH_4 constraints. We evaluate the performance of these configurations by analyzing their ability to reproduce observations. The satellite-only inversion systematically underestimates in-situ CH_4, particularly at high northern latitudes (up to ~20 ppb at sites such as Alert), highlighting the necessity of in-situ constraints for atmospheric inversion systems. Critically, inversions excluding δ^{13}C-CH_4 constraints fail to reproduce observed isotopic trends, indicating that CH4-only assimilations (with or without satellite data) yield less reliable source partitioning.

All configurations reveal that total emissions peaked in 2021 and declined in 2022-2023, with satellite-only inversions producing lower total fluxes. Incorporating δ^{13}C-CH_4 constraints leads to higher mean fossil emissions while attributing interannual variability primarily to microbial sources. Regionally, the inclusion of satellite data enhances emissions over Africa and improves agreement with independent validation sites, demonstrating the value of satellite observations in data-sparse regions. Our fully integrated inversion, constrained by satellite CH_4, in-situ CH_4, and δ^{13}C-CH_4, suggests that a reduction in microbial emissions alongside increases in pyrogenic emissions could explain the observed δ^{13}C-CH_4 increase during 2023–2024. Accounting for OH variability and increased fire emission uncertainties further reduces unrealistic emission adjustments and improves physical consistency in source attribution. These results highlight that robust global and regional methane source attribution requires a balanced inversion framework that integrates satellite CH_4, in-situ CH_4, and δ^{13}C-CH_4 to fully leverage their complementary strengths.

Insights into atmospheric sources, sinks, and transport processes from globally-distributed measurements of long-lived gases

Steve Montzka (GML, NOAA)
Co-authors: Isaac Vimont (NOAA - GML)

Precise trace-gas measurements at globally-distributed sites provide unique insights into the processes affecting changes in atmospheric trace gas sources, sinks, and transport rates. Techniques ensuring a high-degree of site-to-site consistency in calibration, especially globally-distributed flask networks, provide a means to reliably characterize and monitor even small mole fraction gradients and changes in atmospheric distribution that are the tell-tail signs of these processes. Without this observational capability, unambiguously discerning the relative importance of natural and anthropogenic influences on atmospheric changes is not readily possible. For chemicals controlled by the Montreal Protocol and for which emissions have decreased substantially over time, globally-distributed measurements are particularly useful for discerning variability in loss rates modulated by transport processes. Here, we demonstrate how straightforward views of globally-distributed data can provide insights into global emission magnitudes, shifts in emission distributions, and the presence (or absence) and magnitude of tropospheric losses. For longer-lived gases with stratospheric loss, such as CFCs, variations in exchange rates for air between the troposphere and stratosphere are readily apparent in surface measurements. These influences have been particularly anomalous during 2022 – 2024, perhaps related to the Hunga Tonga–Hunga Ha‘apai eruption. When not accurately accounted for, variability in losses can cause substantial errors in budget-based estimates of anthropogenic emission totals.

Acknowledgements:

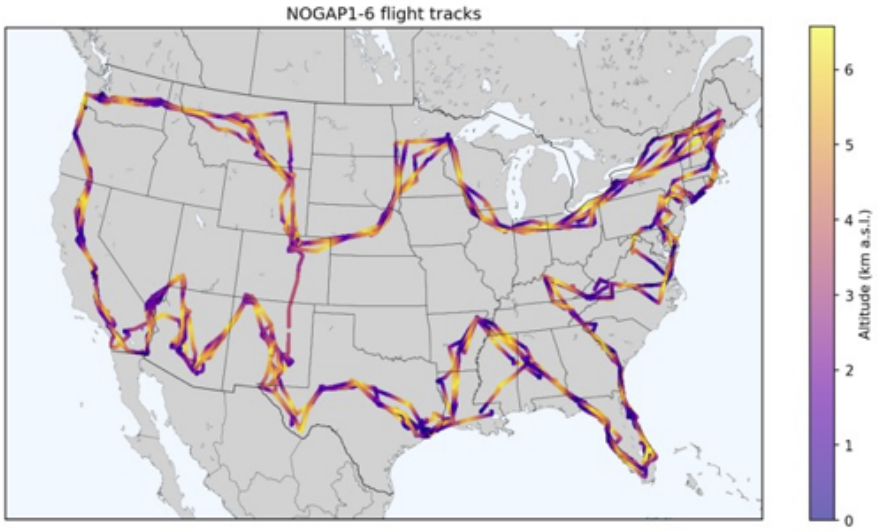
We owe thanks in particular to the personnel handling flask sampling and logistics at remote sites distributed throughout the world, and others in GML and CIRES that support NOAA/GMLs Global Greenhouse Reference Network. Thanks also to Brad Hall and Bob Portman for their assistance in this work.

A comparison of CO_2, CH_4, and CO measurements from the National Observations of GHGs using Aircraft Profiles (NOGAP) Campaign with Three Global Models

Jeff Peischl (NOAA R/GML)
Co-authors: Colm Sweeney (NOAA - GML)

NOAA's Global Monitoring Laboratory operates a network of greenhouse gas (GHG) monitoring sites across the U.S. and the globe. Part of this network is the aircraft vertical profile network, a network of aircraft vertical profiles collecting whole air samples and measuring CO_2, CH_4, CO, and numerous other trace gas species. In North America, there are 13 such vertical profile sites currently operating. The National Observations of Greenhouse gases Aircraft Profiles (NOGAP) campaign is designed to fill spatial gaps in the vertical profile network. The NOGAP campaign involves a series of 96 vertical profiles across the conterminous U.S. aboard a Scientific Aviation Mooney aircraft. On board measurements include fast measurements of CO_2, CH_4, CO, H_2O, O_3, temperature, relative humidity, GPS latitude, longitude, altitude, heading, and wind speed and direction as well as 6 whole air samples per profile pair (up and down). The profiles range from 500 ft. above ground level to 20,000 ft above sea level.

Here, we present a comparison of CO_2 and CH_4 data measured aboard the aircraft with global CO_2 and CH_4 models, CarbonTracker NRT (Near Real Time) for CO_2 and CH_4 and Goddard Earth Observing System (GEOS) NRT for CO_2, CH_4, and CO for the first six NOGAP campaigns from November 2023 through October 2024. We focus on a comparison of vertically-integrated concentrations and where the largest differences in these integrations occur between the measurements and model. These data will eventually be used to constrain carbon cycle models using the fast measurements of concentration and winds, which will help to enhance model accuracy of horizontal transport, vertical mixing, and boundary layer height, which will in turn improve model accuracy of emissions and sinks in the carbon cycle.



Acknowledgements:
This research was supported in part by NOAA cooperative agreement NA22OAR4320151.

Updates on global CO_2, CH_4, N_2O and SF_6 measurements from NOAA's Global Greenhouse Gas Reference Network

Xin Lan (CIRES University of Colorado Boulder/ NOAA Global Monitoring Laboratory)

The NOAA Global Monitoring Laboratory operates a greenhouse gas measurement network with unique global coverage. High quality measurements from this network provides fundamental data for tracking atmospheric greenhouse gas (GHG) abundances, determining carbon budgets and understanding carbon cycle feedback.

In 2024-2025, atmospheric levels of key greenhouse gases, CO_2, CH_4, N_2O and SF_6, continue to rise, reaching new record highs. Global average CO_2 level at the Earth's surface in 2025, derived from remote marine boundary layer measurements, reached 425.6±0.1 ppm (parts per million by moles in dry air). The CO_2 growth rate of 3.7 ppm in 2024 is the highest annual increase since modern measurements began in 1958. This exceptional surge was followed by a more moderate increase of 2.3 ppm in 2025, which is a pattern previously observed in 1998-1999 when the influences from a Super El Niño came to an end. This pattern suggests a carbon-climate interaction that may have intensified as global temperature rises.

Global average CH4 reached 1936.6±0.6 ppb in 2025, approximately 266% its pre-industrial level (729±9 ppb). While CH_4 growth rate slowed slightly in 2023-2025 to about 7.8 ppb/yr, down from a record high average of 15.2 ppb/yr in 2020-2022, observed changes in CH_4 latitudinal gradients and seasonal cycle amplitudes indicate shifting emission patterns. Measurements of a stable carbon isotope of CH_4, $\delta^{13}C\text{-}CH_4$, provides additional sectoral emission information. While a long-term decrease in $\delta^{13}C\text{-}CH_4$ points to a dominant microbial emission increase since 2007, recent $\delta^{13}C\text{-}CH_4$ data also shows a significant signal from enhanced fire emissions particularly in the global south during 2024.

Global average N_2O and SF_6 levels continue to hit record highs. The N_2O increase in 2025 is among the largest in our measurement record, while the SF_6 increase in 2025 set a new record. This presentation will further explore observed spatiotemporal gradients in CO_2 and CH_4 to qualitatively indicate where emissions are changing, alongside quantitative estimates from recent studies using our measurements.

Session 3:
The Carbon Pulse: Ocean Sinks & Terrestrial Feedbacks

Zonal-mean Southern Ocean air-sea CO_2 exchange measured from operational military transport aircraft

Britton Stephens (NSF NCAR)
Co-authors: Yuming Jin (U. California Santa Barbara)

The Southern Ocean Carbon Gas Observatory (SCARGO) is an NSF Office of Polar Programs funded study to measure CO_2 and related gases between Christchurch, New Zealand and the South Pole from the LC-130 aircraft supporting the U.S. Antarctic Program (USAP). SCARGO is led by NSF NCAR in collaboration with NOAA/CIRES and Earth Sciences New Zealand.

The Southern Ocean plays an important role in the global carbon cycle, absorbing a large fraction of our industrial CO_2 emissions. However, existing ocean and atmosphere measurements in the region are limited and estimates of seasonal and annual CO_2 fluxes differ widely. SCARGO is motivated by previous airborne results from the HIPPO and ORCAS (NSF NCAR GV) campaigns and the NASA ATom (DC-8) Mission which demonstrated that airborne profiles provide a better way to quantify large-scale Southern Ocean CO_2 fluxes than previous ship, float, or surface station measurements.
The primary goals of SCARGO are to measure vertical profiles of CO_2 over the Southern Ocean and Antarctica, to quantify seasonal and interannual variability in Southern Ocean CO_2 uptake, and to demonstrate a cost-effective means to monitor Southern Ocean air-sea gas exchange. The SCARGO instrument is contained in a roll-on/roll-off crate and samples from a custom forward escape hatch that also includes a dedicated GPS antenna, both of which are installed and removed before and after every flight of opportunity. The SCARGO instrument, a Picarro G-2401, also measures CH_4, CO, and H_2O concentrations.

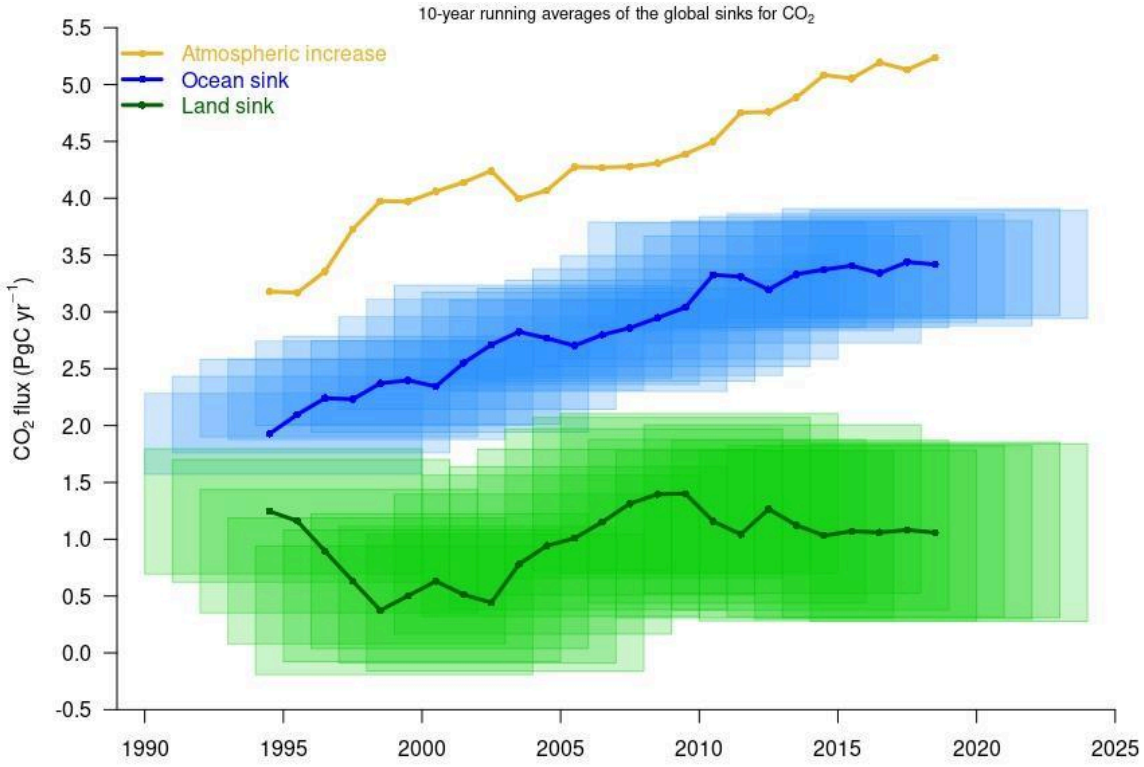
SCARGO conducted a successful test deployment based out of McMurdo Station, Antarctica in Nov – Dec 2022 and completed its first full field season from Nov 2025 – Feb 2026. During this recent season, the team supported measurements from 25 flights over a period of four months. These flights included 12 round trips from McMurdo to the South Pole and 10 flights to or from Christchurch, New Zealand.

The CO_2 measurements from this season define very consistent vertical gradients, with lower concentrations in the lower troposphere reflecting uptake by the Southern Ocean. These observed gradients are enabling robust biweekly zonal-mean air-sea CO_2 flux estimates, which compare well with previous airborne measurements.

Atmospheric O_2 measurements show a strengthening ocean carbon sink and a stagnant terrestrial carbon sink since 1990

Eric Morgan (Scripps Institution of Oceanography)
Co-authors: Ralph Keeling (U. California San Diego - Scripps)

The global ocean and land biosphere take up roughly half of CO_2 emitted from fossil fuels, yet the temporal evolution of these sinks remains difficult to quantify due to data sparsity and limited understanding of underlying mechanisms. Long-term records of atmospheric O_2/N_2 ratios have for some time been combined with CO_2 observations to partition the average magnitude of the land and ocean sinks from a "top down" perspective. Leveraging 30+ years of atmospheric O_2 and CO_2 observations, we extend this approach to show that the long-term trend and decadal variability of both sinks are also readily constrained from atmospheric records. We find that the ocean CO_2 sink increased by 0.63 ± 0.14 PgC yr-1 decade-1, taking up 35% of emissions between 1990 and 2020. In contrast, the net land CO_2 sink has remained roughly constant with no robust trend, despite large decadal variability, accounting for 13% of emissions. We discuss sources of uncertainty with special emphasis on the air-sea flux of O_2.

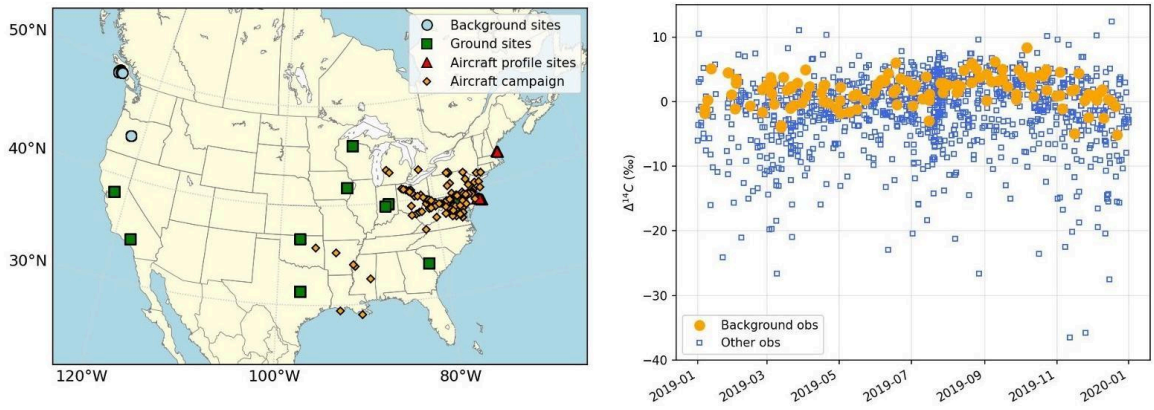


Evaluation of uncertainties in Lagrangian particle dispersion models using atmospheric radiocarbon measurements

Lei Hu (NOAA GML)
Co-authors: John Miller (NOAA - GML)

Emissions of long-lived trace gases are the primary drivers of environmental problems such as global warming and stratospheric ozone depletion, but their emissions cannot be directly measured at scales larger than a few km^2. Inverse modeling is the primary way to constrain trace gas emissions on large spatial scales that are consistent with atmospheric observations. However, errors in atmospheric transport simulations used in inverse methods can significantly limit the accuracy of these estimates for scientific and policy applications. Assessing these errors can be challenging and may require conducting expensive large-scale tracer release experiments. While multi-institutional model intercomparisons are useful, they often do not isolate transport uncertainties from errors in inverse methods.

Atmospheric $\Delta^{14}CO_2$ measurements have the potential to be useful in assessing uncertainties in atmospheric transport models, as the depletion of $\Delta^{14}CO_2$ near-linearly relates to fossil fuel CO_2 emissions, which are considered relatively well known from bottom-up inventories. In this study, we used NOAA/GML's $\Delta^{14}CO_2$ measurements over the U.S. to assess errors in Lagrangian particle dispersion models that are often used to derive emissions from urban- to national- scale. We ran NOAA/ARL's HYSPLIT model with 47 different combinations of model physics and meteorological fields to simulate footprints for NOAA/GML's $\Delta^{14}CO_2$ measurements made in 2019 (Fig. 1). These 47 sets of footprints, along with the two sets constructed from HYSPLIT using different meteorological data in the NOAA/GML's CarbonTracker-Lagrange project, were convolved with three fossil fuel CO_2 emission inventories over the U.S. to simulate fossil fuel CO_2 enhancements. We then compared these simulated enhancements against fossil fuel CO_2 enhancements inferred from $\Delta^{14}CO_2$ measurements. This presentation will discuss the intercomparison and performance of these 49 HYSPLIT simulations, providing insights into optimal selections of model physics and meteorological input data to reduce atmospheric transport errors when using Lagrangian models. Furthermore, it offers observation-based guidance in improving atmospheric transport simulation in future CarbonTracker-Lagrange operations.



Advances in Interpreting Atmospheric CO_2 Variability at Mauna Loa and Maunakea Observatories with Covarying Records

Madat Sardarli (Scripps Institution of Oceanography, University of California, San Diego)
Co-authors: Ralph Keeling (U. California San Diego - Scripps)

The Mauna Loa (MLO) CO_2 record is the longest, continuous, in situ time series of atmospheric CO_2, that spans 1958 to the present. The 2022 Mauna Loa eruption interrupted CO_2 measurements at MLO, prompting the deployment of a substitute system at Maunakea Observatory (MKO). After the MLO record resumed, measurements were continued at MKO, creating a unique opportunity to advance our understanding of CO_2 variability at MLO. After screening both time series for local influences, two baseline records were created. Baselines were nearly identical at MLO and MKO in the phase and amplitude of their seasonal cycles, which suggests that the baseline selection algorithm recovers a regionally representative background. Notable differences exist, however, in the non-baseline data of the two sites. To explore the drivers of this, we compare baseline CO_2 at MLO and MKO with simulated atmospheric time series from an atmospheric Bayesian inversion (Jena CarboScope) (Rödenbeck et al., 2018) at each station to assess how much short-term variability in the observations can be reproduced by the inversion. We explore the drivers of site-to-site differences by fitting a linear model to the residual between observed and simulated baseline, using additional terms for the mean diurnal cycle, site-to-site baseline differences, and local atmospheric transport and we assess model uncertainty with a cross validation approach following Birner et al., 2023. The improved model explains a larger fraction of observed CO_2 variance at both sites.

References:

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A 20-Year Inter-Laboratory Comparison of Atmospheric $\delta^{13}C\text{-}CO_2$ in the Southern Hemisphere: Co-Located Measurements at Baring Head Observatory Demonstrate Improved Compatibility

Haeyoung Lee (Earth Science New Zealand)
Co-authors: Sylvia Michel (U. Colorado Boulder - INSTAAR)

Baring Head Observatory (BHD) is a World Meteorological Organization/Global Atmosphere Watch (WMO/GAW) station representative of the clean Southern Hemisphere background atmosphere. This station has three different co-located sampling and measurement programs for atmospheric $\delta^{13}C\text{-}CO_2$: Earth Science New Zealand (ESNZ) (formerly National Institute of Water and Atmosphere, NIWA), the Institute of Arctic and Alpine Research in collaboration with NOAA (INSTAAR/NOAA), and the Scripps Institution of Oceanography (SIO). Flask samples from all three laboratories were collected under baseline air mass conditions, with ESNZ and INSTAAR/NOAA using an automated sampling system collecting simultaneously, while SIO collected manually on the same day, resulting in 202 simultaneous samples for ESNZ–INSTAAR/NOAA and 114 same-day samples for ESNZ–SIO over the study period (2003–2022). ESNZ uses CF-IRMS with measurement uncertainty of ±0.05‰ (68% C.I.), while INSTAAR/NOAA and SIO use DI-IRMS with reproducibility of less than ±0.02‰.

Through this long-term co-located comparison, we identified that a scale offset in the ESNZ working standards (pressurized cylinders of ambient air collected at BHD) was the primary source of inter-laboratory bias. We re-analyzed ESNZ working standards against JRAC10, a reference cylinder assigned on the JRAS-06 scale (WMO scale), provided by the Max Planck Institute for Biogeochemistry (MPI-BGC, WMO/GAW Central Calibration Laboratory), and applied the corrected values to update the ESNZ $\delta^{13}C\text{-}CO_2$ time series data. After applying the corrected working standard values, the mean difference (ESNZ minus INSTAAR/NOAA) fell within the WMO/GAW compatibility goal ±0.01‰, ranging from −0.001 to −0.004‰. For SIO, which operates on its own scale known to be +0.037‰ more positive than the JRAS-06 scale, the residual difference after correction (ESNZ minus SIO) remained consistent at approximately −0.04 to −0.05‰, as expected from the inter-scale difference. We find a total decrease in annual mean $\delta^{13}C\text{-}CO_2$ absolute values from 2003 to 2022 of −0.483‰ for ESNZ, comparable to −0.458‰ for INSTAAR/NOAA, and −0.431‰ for SIO.

These results demonstrate that long-term inter-comparison experiments at co-located stations are essential for assessing bias in atmospheric monitoring networks, and that adopting a common calibration scale (such as JRAS-06) substantially reduces inter-laboratory biases and brings measurements closer to the WMO/GAW compatibility goal of ±0.01‰.

Kennaook Cape Grim 50 Year Record of Atmospheric Observations and Recent Trends

Issy Borley (CSIRO/Kennaook Cape Grim Working Group)
Co-authors: Ray Langenfelds (CSIRO)

Kennaook/Cape Grim Baseline Air Pollution Station (KCGBAPS) has now been operating for 50 years, jointly operated by Australia's Bureau of Meteorology, CSIRO and partner organisations. It was established in 1976 as Australia's contribution to monitoring atmospheric composition; with the initial focus being carbon dioxide (CO_2). Measurement of other greenhouse gases and ozone depleting gases were phased in over the following years. The long-term records describe impacts of human activities and natural variations in the background, mid-latitude southern hemisphere atmosphere. This talk will briefly detail some of the achievements and observations made by KCGBAPS. It will also comment on large perturbations in carbon monoxide (CO) and hydrogen (H_2) observed in recent years and their linkage to wildfires. Emissions from the Australian Black Summer fires of 2019-20 were assessed using these anomalies and the GEOS-Chem Chemical Transport model. Elevated CO and H_2 during 2024-25 suggest a response to large wildfires in both hemispheres during this period.

Acknowledgements:

The work at Kennaook/Cape Grim is possible through the long-term commitment and funding from Australia's Bureau of Meteorology, and the long-term support from CSIRO, Equally, over the 50 years of measurements and research, Kennaook/Cape Grim has seen many personnel, scientists and technicians. The science and observations achieved over that time would not have been possible without their early commitment and dedication.

Session 4:
Ozone, Particulate Matter, and Air Quality

Free Tropospheric Ozone Trends: New Insights from 25 Years of Ground-Based Observations

Anne Thompson (UMBC & NASA/Goddard)
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Global tropospheric ozone trends are essential for studying climate forcing and surface pollution. However, in contrast to stratospheric ozone for which satellites have reliably tracked changes over 50 years, obtaining tropospheric ozone trends from space is challenging. Numerous "products" disagree with one another and few are consistently calibrated over multiple decades. Thus, researchers working on the Tropospheric Ozone Assessment Report (TOAR-II) activity turned to rigorously "homogenized" data from ground-based (GB) instruments for trends analysis. We summarize the most important findings from five TOAR II GB studies, including reports from the TOAR II Focus Working Group Harmonization and Evaluation of Ground-based Instruments for Free-Tropospheric Ozone Measurements (HEGIFTOM). Tropospheric column trends (surface - 300 hPa) for 2000-2022 from 55 stations fall within -4 to +8%/decade (Van Malderen, et al., 2025a) with greatest increases over SE Asia and southern subtropics, i.e., Kuala Lumpur, La Réunion. For free troposphere (FT, 700-300 hPa) ozone, where SHADOZ, IAGOS and lidar data are used, more modest changes are found, within ± 3%/decade. Grouping the 55-site HEGIFTOM data and adding more IAGOS profiles, produced similar values for regional FT ozone changes (Van Malderen, et al, 2025b). For the tropics and subtropics, 26-yr trends are derived from SHADOZ (D. Kollonige et al., GMAC Paper; https://tropo.gsfc.nasa.gov/shadoz/Archive.html) ozonesondes (Thompson et al., 2025 [T25]; Stauffer et al., 2024 [S24]) or combinations of SHADOZ and IAGOS aircraft data (Gaudel et al., 2024). For FT ozone trends at sites within ±15 degrees for ~2000-2022 these latter 3 studies and the HEGIFTOM analyses display consensus ~(-3-+3)%/decade (Figure). Over SE Asia declining convection causes FT ozone to increase 5-15%/decade during March-May (S24). Van Malderen, et al (2025a) and T25 conducted important sensitivity tests. The most important results are: (1) Multiple Linear Regression (MLR) and Quantile Regression (QR) give the same trends in ~90% of cases. (2) Reducing monthly samples to two or adding thousands of IAGOS profiles to SHADOZ data yields little change, i.e., ozonesonde sampling (2-5/month) is sufficient for FT trends. These studies with GB data provide robust annual and seasonal tropospheric ozone trends, constituting essential references for satellite- and model-derived trends over the past 25 years.

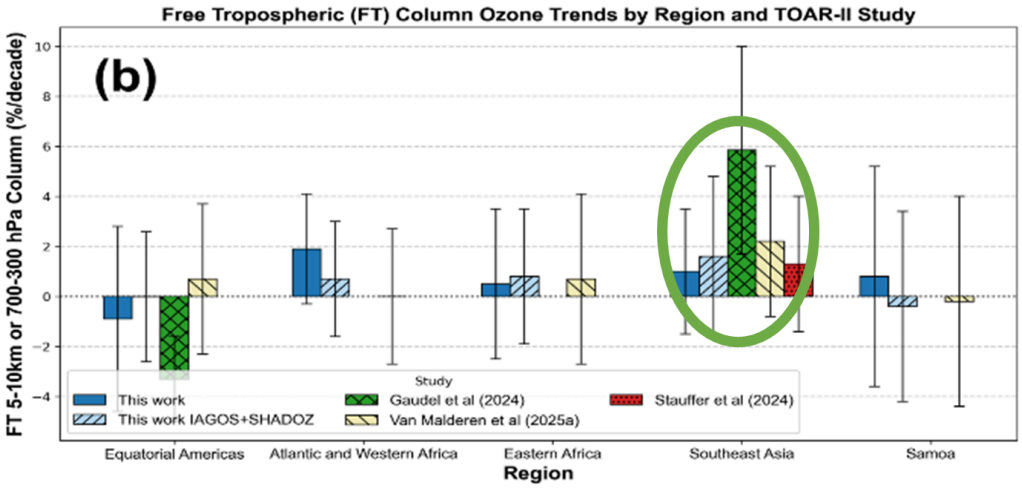

Figure 1. Compares FT ozone column trends ~2000-2022 ("This work" refers to Thompson et al., 2025), based on IAGOS and SHADOZ data from 4 studies (5 over SE Asia). Within uncertainties, the trends all agree. Changes are marginally small except over SE Asia where FT ozone increases, based on Kuala Lumpur and Watukosek SHADOZ data with IAGOS profiles from Kuala Lumpur and Singapore, are +(2-4)%/decade.

Acknowledgements:

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Influence of ENSO Teleconnection on Surface Ozone Exceedances (1980-2024)

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Co-authors: Gary Morris (NOAA - GML)

The number and magnitudes of ozone exceedance events in the Boulder-Denver Region of Colorado have changed little over the last 25 years, despite many EPA policies and air quality regulations in the region. Our research sought to discover other influences that might contribute to the regular occurrence of ozone exceedances. In particular, in this study, we examine the influence of the El Nino Southern Oscillation (ENSO) teleconnection on air quality within the region. Utilizing 45 years of surface ozone observations from continuous ambient monitoring stations run by the Environmental Protection Agency (EPA), we evaluated these large-scale influences and their relationship to exceedances of the 70 ppbv National Ambient Air Quality Standard (NAAQS) for ozone. Linear regression fits to the daily peak 8-hour average concentrations for each county revealed an increasing trend throughout the selected period. Utilizing the Oceanic Nino Index (ONI) index to distinguish El Nino, La Nina, and neutral phases of ENSO, and removing an overall increasing trend in ozone revealed an earlier onset of the summer ozone season (May-Aug) during El Nino. We perform statistical analyses to further explore this finding and examine how meteorological conditions associated with El Nino may increase surface ozone in June in the region. One of the potential factors would be El Nino's influence on the North American Monsoon. A delay in the onset of the North American Monsoon (NAM) during El Nino events could cause decreased cloud cover and precipitation leading to more radiative energy reaching the surface, making it more favorable to have an ozone exceedance event.

An Ensemble Kalman Filter Approach to the Dobson Umkehr Ozone Retrievals

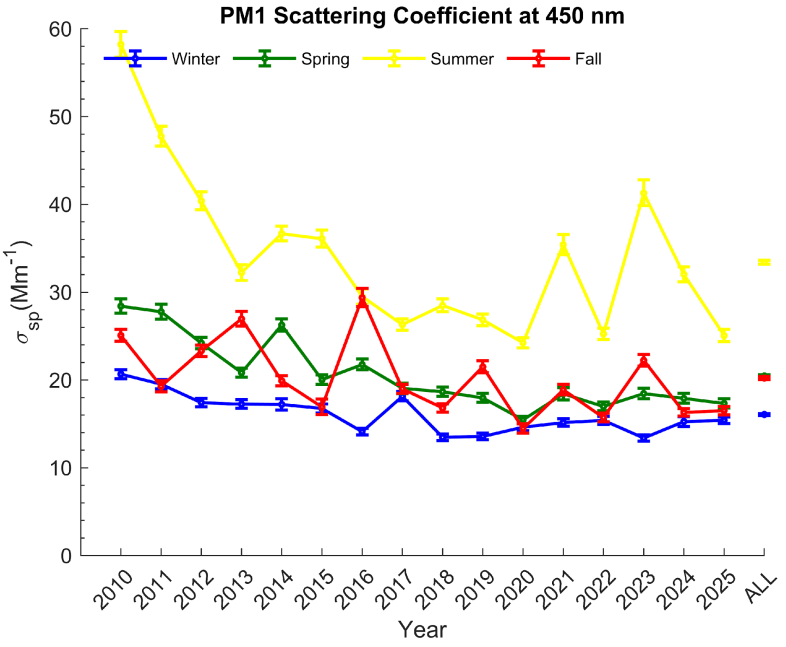
Peter Effertz (NOAA GML, Cooperative Institute for Research in Environmental Science)
Co-authors: Irina Petropavlovskikh (CIRES)

Long-term, accurate measurements of the vertical ozone distribution are critical for monitoring stratospheric ozone recovery and have been integral to studies of the long-term trends in the vertical ozone profile. The ground-based Umkehr technique provides the longest continuous records of vertical ozone profiles using remote sensing methods (the Dobson ozone spectrophotometer). The current retrieval algorithm has been optimized for long-term trend analysis by linearizing the profiles about a static climatological a priori ozone profile (dependent only on the total column ozone and the season) and a fixed prior covariance matrix. While this algorithm has been essential for long-term trend analysis using monthly-mean ozone anomalies, there has been renewed interest in understanding day-to-day variability and in comparing individual Umkehr profiles with other ground-based and satellite profiles. This study presents a novel retrieval framework utilizing an Ensemble Kalman Filter (EnKF) to process Umkehr ozone measurements. The EnKF approach approximates the state distribution (vertical profile of ozone) using an ensemble of states and updates it based on noisy real-world measurements. This approach uses flow-dependent error covariances rather than the fixed prior covariance used by the current algorithm. We will compare and contrast the EnKF Umkehr with the current Umkehr algorithm through a standard synthetic/observing system simulation experiment (OSSE). We will generate synthetic ‘true’ ozone profiles from the ozonesonde measurements and use the SCIATRAN radiative transfer model to create synthetic measurements (with synthetic instrument noise). We will then use both the EnKF and current Umkehr techniques to retrieve a vertical profile of ozone. The retrieved profiles will be compared with our synthetic ‘true’ profile by calculating the mean bias and root-mean-square error. Vertical resolution will be assessed through the averaging kernel width, and degrees of freedom will be calculated to understand the information content of each technique. Ultimately, we will show whether the EnKF approach leads to a better understanding of day-to-day variability, improves the information content, and provides a better estimate of the uncertainty of each profile.

Changing SE U.S. Air Quality and Aerosol Radiative Effects

James Sherman (Appalachian State University, Department of Physics and Astronomy)
Co-authors: Kate Martin (Appalachian State University)

The southeastern U.S. is home to high summertime loading of biogenic organic and sulfate aerosols, which may have played a role in the region's lack of warming over the past century (Goldstein et al., 2009). Established in 2009, the high-elevation (~1080m asl) AppalAIR facilities at Appalachian State University (APP) in Boone, NC are home to the only co-located, active NOAA FAN, NASA AERONET, and NASA MPLNET sites in the continental U.S (Sherman and McComisky, 2018; Sherman et al., 2015). This presentation focuses on long-term changes and variability in aerosol loading and aerosol intensive properties at APP, placed in the context of changing regional aerosol speciation and relationships between aerosol optical, chemical, and microphysical properties measured at APP. The coarse features of long-term aerosol optical depth (AOD) and PM1 aerosol light scattering trends at APP coincide with reductions in sulfate aerosol between 2010-2016 and were accompanied by lower particle hygroscopicity and increased hemispheric backscatter coefficient, indicative of shifts in PM1 particle distribution to smaller sizes. The reductions in scattering and AOD were largest in summer months and smallest during winter. Scattering decrease was not accompanied by a decrease in particle number concentrations but rather decreasing scattering cross section. However, the past 10 years have been more difficult to interpret. Scattering coefficient inter-annual variability during summer (and to some extent, fall) is largely influenced by episodic wildfire smoke (Mickey et al., 2025). Other signs of an increasing influence due to aged biomass aerosols for all seasons include an increase in absorption Angstrom exponent (AAE) and decreasing scattering Angstrom exponent (SAE), with the largest changes during summer. While scattering and AOD vary primarily on seasonal scales, aerosol absorption coefficient and number concentration exhibit larger diurnal and (to lesser extent) weekly cycles, indicative of local sources (traffic). The results have implications for aerosol radiative forcing, water uptake, and their ability to serve as cloud condensation nuclei (CCN), which have been measured and studied synergistically at APP since 2024 (Sherman et al., 2025).



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Change in surface radiation budget due to smoke from the wildfires during 2018 and 2019 fire seasons in the US: Insight from high-resolution WRF-Chem modeling and ground-based radiation observations

Minsu Choi (CIRES/NOAA GSL)
Co-authors: Ravan Ahmadov (CIRES)

Wildfires are increasing in frequency and intensity, exerting substantial impacts on regional air quality and the Earth's radiation budget through emissions of trace gases and aerosols. In this study, we use the Weather Research and Forecasting model coupled with chemistry (WRF-Chem) at 3 km resolution (i.e., HRRR-Chem) to investigate the effects of western U.S. wildfires on surface radiation. A brute-force (zero-out) approach is applied by conducting simulations with and without wildfire emissions to quantify the wildfire contribution. The simulations cover selected periods of two major field campaigns, the NOAA/NASA Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ, August 2019) and the Western Wildfire Experiment for Cloud Chemistry, Aerosol Absorption and Nitrogen (WE-CAN, July-August 2018), which provide comprehensive in situ measurements across diverse wildfire and weather conditions. The model reasonably reproduces fresh smoke aerosol concentrations during large wildfire events and captures daily PM2.5 concentration in downwind regions. However, it underestimates contributions from smaller fires, indicating limitations in satellite-based emission inventories for detecting low-intensity or short-lived fire events. By combining in-situ observations from the field campaigns with downwind surface radiation measurements from the NOAA Global Monitoring Laboratory SURFRAD and SOLRAD networks, we examine wildfire impacts from fresh plumes to long-range transport, enabling a more complete characterization of smoke evolution and associated radiative impacts. Results show that smoke aerosols substantially attenuate surface downwelling radiation through both regional influence and long-range transport. During intense smoke episodes, hourly surface shortwave fluxes are reduced by approximately 100 to 300 W m^{-2} relative to simulations without wildfire emissions. These findings demonstrate the significant regional radiative impact of wildfire smoke and highlight the need for expanded surface radiation flux measurements, including mobile observations, together with integrated modeling and surface networks to better constrain and understand wildfire-driven radiative impacts across the United States.

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The statements, findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the views of NOAA or the U.S. Department of Commerce. This work is supported by Task Ⅱ: This research was supported in part by the NOAA cooperative agreement NA22OAR4320151, for the Cooperative Institute for Earth System Research and Data Science (CIESRDS). We are grateful to the principal investigators, co-investigators, and broader science teams of FIREX-AQ and WE-CAN for their extensive efforts in the design and execution of the field campaigns and in the collection of the observational datasets analyzed in this study. We also acknowledge R. Bradley Pierce for his contributions to the Realtime Air Quality Modeling System (RAQMS) and for providing boundary condition data. Contributions from collaborators associated with these campaigns will be appropriately recognized, and co-authorship will be offered in accordance with journal authorship guidelines as this work advances toward publication.

Evaluating Long-term Seasonal Variability of Aerosol Optical Properties in Colorado

Erin Boedicker (GML GRAD, CIRES / NOAA)
Co-authors: Betsy Andrews (CIRES)

The western U.S. climate has undergone significant changes over the past several decades marked by warming (Higuera & Abatzoglou, 2021), drought (Leeper et al., 2022), and declining snowpack (Mote et al., 2018). These environmental changes have led to enhanced wildfire activity (Pederson et al., 2013), intensity (Iglesias et al., 2022; Mote et al., 2018), and increases in annual burn area, resulting in declining air quality conditions (Wilmot et al., 2021). These shifts are closely linked to earlier springtime warming (Mote et al., 2018; Pederson et al., 2013) which strongly influences spring and summertime land surface aridity and aerosol loading, which can also lead to an increase in dust. These events introduce considerable uncertainty into both climate research and public health assessments (IPCC, 2023).

To gain a deeper understanding of western U.S. aerosol properties, we analyzed 13 years (2011-2024) of surface in-situ aerosol optical data from Storm Peak Laboratory (SPL) in northwestern Colorado, and 6 years (2019-2024) of surface in-situ aerosol optical data from Table Mountain (BOS) in central Colorado. The aerosol optical properties at both sites demonstrate a strong summer wildfire smoke signal (peaking in August) and evidence of springtime dust events. BOS exhibited higher aerosol loading than SPL, particularly during spring and winter, consistent with the proximity of BOS to urban sources and its lower elevation.

While the general patterns observed for SPL are consistent with a previous climatological analysis (covering the period 2011-2016) for the site, the longer SPL dataset used here shows that there has been a significant increase in extreme wildfire smoke events for 2017-2024 relative to 2011-2016. Both summer and fall exhibit statistically significant positive trends in the upper percentiles of scattering coefficient with trends of 10 ± 1% yr-1 at the 98th percentile in the summer and 2.4 ± 0.4 % yr-1 at the 96th percentile in the fall (Fig. 1). Co-variability among some of the aerosol optical properties is used to further identify aerosol types and temporal patterns, demonstrating similarities between the two sites.

Acknowledgements:

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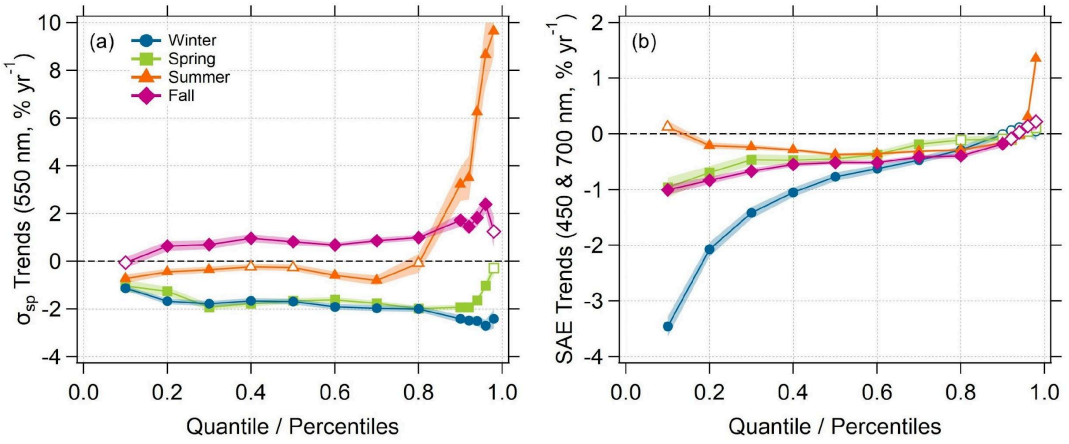

Figure 1. Quantile regression trends for PM_{10} (a) σ_{sp} and (b) SAE at SPL over all seasons from 2011 to 2024. Winter = Dec – Feb, Spring = March - May, Summer = June - Aug, Fall = Sept - Nov. Open markers show trends that were not significant (p-value ≥ 0.05). Shading represents the standard error calculated using a nonlinear interaction decomposition method.

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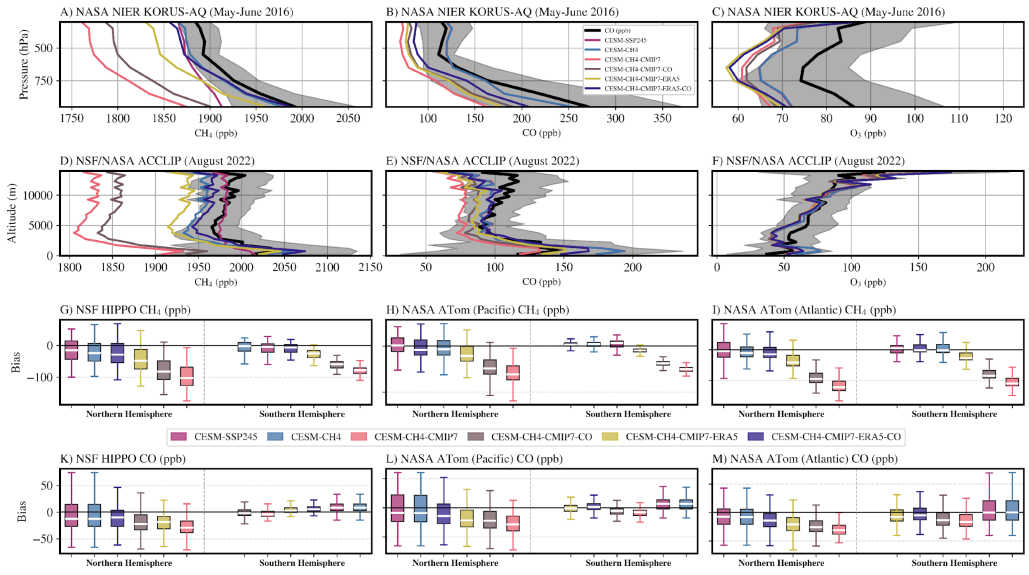
Session 5:
Methane & Trace Species: Sources, Sinks, and Isotopes

Modelling OH Radicals Impacts on the CO and CH_4 Budget During 2003-2022

Benjamin Gaubert (ACOM, NSF NCAR)
Co-authors: Amin Mirrezaei (U. of Arizona)

Although interactive chemistry models provide a mechanistic understanding of hydroxyl radicals (OH) sources and sinks, their use is often limited in the estimation of the methane (CH_4) budget, in particular for emission and atmospheric growth rate quantification. Here, we employ emission- and concentration- driven methane simulations using the Community Atmosphere Model with chemistry (CAM-chem) of the Community Earth System Model Version 2.2 (CESM2.2). Our model setup includes an improved short-lived halogen chemistry representation, NOAA CarbonTracker CH_4 version 2025 for CH_4 emission fluxes as well as an interactive soil uptake parameterization. We conduct 20-year simulations (2003-2022) with different meteorological nudging dataset and chemical emissions, including the anthropogenic and biomass burning CMIP7 dataset. Our evaluation strategy includes observations from the NOAA Greenhouse Gas Marine Boundary Layer Reference, airborne in-situ field studies, and ground-based and satellite remote sensing (i.e., NDACC, MOPITT, GOSAT and TROPOMI). We find that some model configurations have great skills in reproducing trends, interannual variability and seasonal cycle for CH_4 and CO, including an annual growth rate that is outperforming the simulation with zonally average prescribed concentration field. We present a detailed global budget of OH, CO and CH_4 from 2003 to 2021 together with an attribution and a quantification of the Earth System dynamical and chemical processes driving the OH changes impacting the CH_4 growth rate, with a focus on reasons behind the pause (2003-2007) and the renewed growth in 2020 and 2021. Ensemble simulations for the years 2018 to 2020 indicate strong and nonlinear land-atmosphere-chemistry Earth System feedback. As chemical complexity increases the OH recycling probability, we argue that studies using a naive OH representation, with prescribed fields or overly simple chemistry schemes will overestimate the role of OH on the methane growth rate. Further work should include multi-model comparison estimates of OH, CO and CH_4 budgets.



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Measurements of ^{14}CO and $^{14}CH_4$ in the FETCH4 project global network to constrain [OH] variability and the CH_4 fossil source

Vasilii Petrenko (Earth and Environmental Sciences, University of Rochester)

Emissions of methane (CH_4) contribute strongly to anthropogenic warming and air pollution. Hydroxyl radicals (OH) are the main sink of atmospheric CH_4, and considerable uncertainties remain in OH abundance and spatiotemporal variability. Radiocarbon monoxide (^{14}CO) can serve as a proxy for OH concentration ([OH]) because atmospheric 14CO has a well-constrained primary source (production by cosmic rays) and OH serves as the main ^{14}CO sink. We measured ^{14}CO concentration ([^{14}CO]) in samples from a global network of 7 stations during two 12-month intervals: calendar year 2021 and April 2024 – March 2025. The measurements are being interpreted with the aid of the GEOS-Chem chemical transport model. GEOS-Chem is able to simulate [^{14}CO] well at most stations and our results indicate that [^{14}CO] can place strong constraints on the [OH] seasonal cycle and meridional gradient.

CH_4 emission from fossil fuel extraction and use is one of the largest CH_4 sources to the atmosphere, but important uncertainties remain about the magnitude of this source. $^{14}CH_4$ is useful for distinguishing between fossil and microbial CH_4 emissions, but interpretation is complicated by the uncertain magnitude of direct $^{14}CH_4$ emissions from the nuclear industry. We have recently started measurements of $^{14}CH_4$ in a global network. First results clearly identify an interhemispheric $^{14}CH_4$ gradient and will help to constrain the magnitude of the nuclear source.

Atmospheric $\Delta^{14}CH_4$ supports high baseline fossil methane emissions of ~140 Tg/yr in 2010-2020 consistent with dual-tracer (CH_4 + $\delta^{13}CH_4$) inversion

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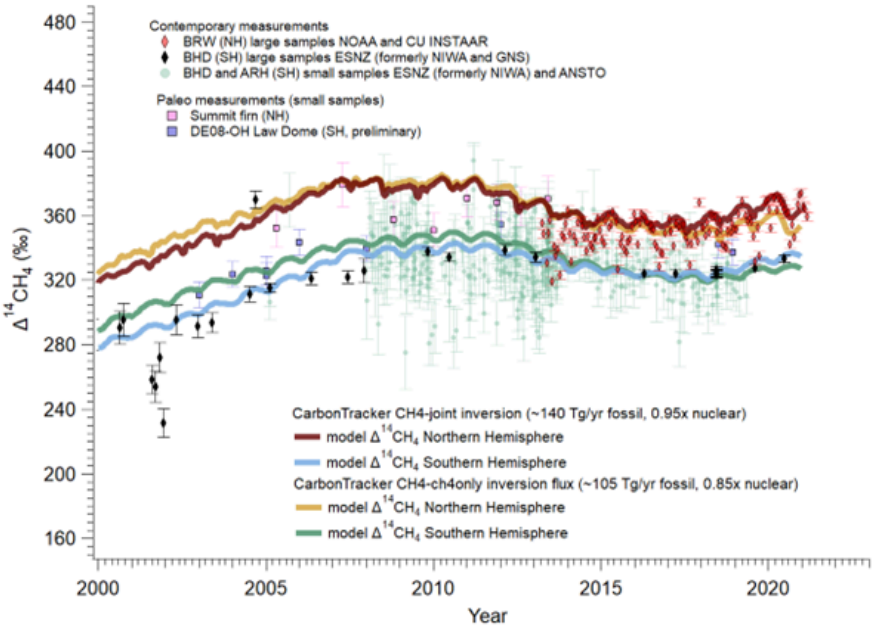
Co-authors: Scott Lehman (U. Colorado Boulder - INSTAAR)

Atmospheric methane mole fraction (xCH_4) today is 160% higher than preindustrial levels [1] and accounts for ~17% of the total anthropogenic radiative forcing [2]. Despite international pledges to reduce emissions [3], xCH_4 continues to rise, and large uncertainties remain in the global CH_4 budget [4]. Measurements of the relative abundance of ^{13}C vs. ^{12}C in atmospheric CH_4 (commonly expressed with the isotopic delta notation "$\delta^{13}CH_4$") can be used to better constrain the CH_4 budget [5]. However, dual-tracer atmospheric inversions using both CH_4 and $\delta^{13}CH_4$ observations infer a higher baseline of fossil emissions and attribute the recent xCH_4 rise almost entirely to microbial sources [6], whereas CH_4-only inversions infer a lower baseline of fossil emissions [7] and split the attribution for the recent xCH_4 rise between fossil and microbial sources [8]. It has been argued that uncertainties in $\delta^{13}CH_4$ source isotope signatures and kinetic isotope effects (KIE) from atmospheric removals may limit the reliability of $\delta^{13}CH_4$ inversions [9].

Radiocarbon (^{14}C) measurements of atmospheric CH4 ($\Delta^{14}CH_4$) provide complementary constraints to the CH_4 budget [10]. The ^{14}C budget of atmospheric CH_4 is arguably simpler than $\delta^{13}C$. ^{14}C is produced in the upper atmosphere through nuclear reactions between cosmic rays and nitrogen. The newly produced ^{14}C atom is then quickly oxidized to $^{14}CO_2$ and assimilated into the carbon cycle. Biogenic CH_4 sources such as wetlands, biomass burning, ruminants, and agriculture all emit CH_4 with $\Delta^{14}C$ signatures that follow the contemporary atmospheric $\Delta^{14}CO_2$ with certain time lags (τlag, also commonly referred to as biospheric turnover time), which are delays between the assimilation of environmental carbon and its release as CH_4. Meanwhile, CH_4 from fossil sources does not contain any ^{14}C ($\Delta^{14}C_{fos}$ = -1000‰). Unlike $\delta^{13}CH_4$, atmospheric $\Delta^{14}CH_4$ is not sensitive to uncertainties in the KIEs of CH_4 sinks.

Here we present a long-term record (~10 years) of very high precision (±3.6‰ reproducibility on authentic sample pairs, 1σ) contemporary atmospheric $\Delta^{14}CH_4$ measurements from an Arctic background site, Utqiaġvik (formerly Barrow), Alaska (BRW; 71.32°N, 156.61°W) between 2012-2022, complemented by $\Delta^{14}CH_4$ records from two Southern Hemisphere background sites: Baring Head, New Zealand (BHD; 41.41°S, 174.87°W) and Arrival Heights, Antarctica (ARH; 71.83°S, 166.20°E) from the same time period. We also present new $\Delta^{14}CH_4$ measurements from firn air and ice cores collected from Law Dome, Antarctica, during the 2018-2019 austral summer (DE08-OH; 66°44'S, 112°50'E). We use all available paleo and historical contemporary $\Delta^{14}CH_4$ data to provide an updated constraint on the turnover time of biogenic CH_4 (τ_{lag} = 2yr). Using an updated bottom-up inventory of direct $^{14}CH_4$ emissions from nuclear power plants [11], our preliminary analysis shows that atmospheric $\Delta^{14}CH_4$ observations seem to be more consistent with a high baseline of fossil CH_4 emissions (~140 Tg CH_4/yr in the mid-2010s) derived from a dual-tracer inversion.



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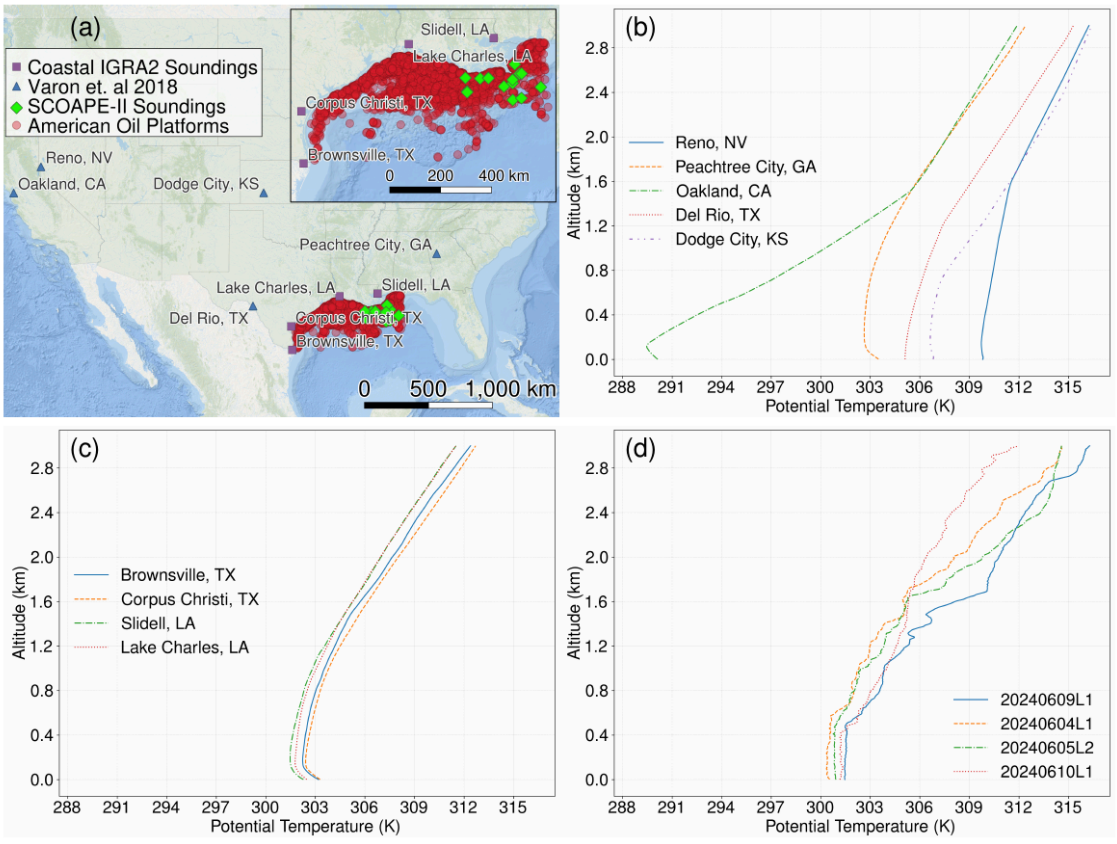
SCOAPE-II: A 2024 Multiplatform Measurement Campaign off the US Gulf Coast to Assess Oil and Gas Emissions on the Outer Continental Shelf

Ryan Stauffer (NASA/GSFC)
Co-authors: Anne Thompson (UMBC - GESTAR II)

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.



Machine Learning-Based Analysis of Oil and Gas Methane Emissions in the Gulf of Mexico Using Publicly Available Satellite Data

Pedro de Melo (Mechanical Engineering; CIRES; GML, University of Colorado Boulder; NOAA GML)
Co-authors: Lori Bruhwiler (NOAA - GML)

Methane emissions from oil and gas (O&G) extraction processes pose a significant economic burden due to losses in product value, equipment damage, maintenance issues, and safety risks, which can result in increased operational costs. Fortunately, mitigating emissions through infrastructure maintenance and fugitive methane capture offer a cost-effective solution and are feasible with current technology, bringing short-term benefits to the environment. To effectively identify high-emission areas, reliable leak detection and estimation methods are essential. Hyperspectral satellites offer a promising approach to monitor methane plumes at regional scales, leveraging high spatial resolution and frequent revisit times without requiring access to observation sites. Recently, significant efforts have been devoted to the development of machine learning plume detection (U-plume) and estimation tools (integrated methane mass enhancement, IME) to process satellite data, using large eddy leak simulations (LES) as a proxy to generate satellite pseudo-observations to be used as training data. However, current methods have been primarily designed for inland regions, and their application in offshore O&G extraction areas is essential for reducing emissions and ensuring the long-term viability of these operations. Notably, under-reporting of emissions is a significant concern, exemplified by the Gulf of Mexico (GOM), the largest offshore O&G extraction basin in the US. Our research addresses the lack of offshore data representation in current tools, by expanding the IME, improving on machine learning detection methods, and incorporating plume data from LES using offshore meteorological data from the NASA Satellite Coastal and Oceanic Atmospheric Pollution Experiment-II field campaign. Specifically, 40 hours of WRF-LES at a 25 m resolution for a 9 x 9 km^2 x 3,000 m domain were added to our plume analysis dataset, with 20 of these hours generated with meteorological data from the NOAA IGRA2 database at four different sites along the Gulf Coast, and 20 combined hours of WRF-LES with input ozonesonde measurements at four O&G platforms in the GOM, with different local ocean depths. Our results allow the evaluation of errors in source rate estimation of offshore leaks when the effective wind speed curve parameters are generated using inland plumes only, by comparing them to the same estimates using our updated “offshore curve”, which we fit from plumes with influence from the marine boundary layer. Our overall goal is to develop the tools needed to assist the monitoring of offshore O&G extraction areas by expanding the accuracy and applicability of current techniques to support more effective methane emission mitigation strategies, especially for instruments with publicly available data, like NASA’s Earth Surface Mineral Dust Source Investigation (EMIT) and Carbon Mapper’s Tanager-1.

Underestimation of Oil and Gas Industry Emissions in Regulatory Inventories

Detlev Helmig (Boulder A.I.R. LLC)
Co-authors: Dani Caputi (U. California Davis)

This study synthesizes peer-reviewed literature to evaluate persistent discrepancies between top-down and bottom-up emission estimates from oil and natural gas (O&NG) operations, with direct implications for emissions reporting, regulatory compliance, and climate policy (Fig.1). A decade ago, the landmark analysis by Brandt et al. (2014) demonstrated that top-down measurements — derived from atmospheric observations — generally exceeded industry-reported, bottom-up emissions inventories. Here, we reassess this issue by reviewing ten years of peer-reviewed studies published since that assessment to determine whether inventory accuracy has improved.

A total of 73 reported top-down–to–bottom-up emission ratios from 57 articles were compiled and analyzed. The majority of studies focused on methane emissions, while only 11 articles examined other O&NG-related pollutants, including volatile organic compounds (VOCs). Among studies published after 2014, 86% reported that bottom-up inventories underestimated emissions inferred from top-down observations, closely aligning with the 82% reported by Brandt et al. (2014). This consistency indicates that, despite increased scientific attention and regulatory focus, systematic underestimation of emissions in inventories remains largely unresolved.

Although extreme discrepancies (top-down/bottom-up ratios >10) were reported less frequently in recent studies, substantial underestimation persists at levels that are highly relevant for policy and mitigation strategies. North American studies showed larger underestimation factors (mean ratios of 2.59 – 3.75) compared to the global average, raising concerns about the accuracy of regional inventories used for national reporting and emissions mitigation planning. Comparisons involving United Nations Framework Convention on Climate Change (UNFCCC) national inventories yielded the lowest mean ratio (1.45), whereas other inventory types consistently produced mean ratios exceeding 2. A meta-analysis of carefully selected post-2014 studies suggests that global methane emissions from O&NG operations are underestimated by a factor of 2.50 ± 0.62.

For more than two decades, the Northern Colorado Front Range (NCFR) has experienced persistent spring and summer exceedances of the National Ambient Air Quality Standard for ozone. Previous research on ozone precursors and photochemistry has identified O&NG emissions as a significant contributing source. The second part of this work examines discrepancies in NCFR ozone precursor inventories, contrasting bottom-up estimates with values inferred from ambient air observations as reflected by the reviewed literature. While ambient monitoring data show signs of declining O&NG VOCs emissions and declining ambient nitrogen oxides, discrepancies between monitoring and inventories have been persisting. These comparisons further support the conclusion that emissions of ozone precursors, particularly O&NG VOCs, have been, and continue to be systematically underestimated in this region. Overall, these findings suggest that continued reliance on conventional bottom-up inventories may bias emissions baselines, weaken mitigation assessments, and hinder progress toward methane and ozone precursor reduction targets. Integrating top-down observations into inventory development and verification frameworks is therefore critical for improving transparency, accountability, and the effectiveness of O&NG-related climate and air quality policies.

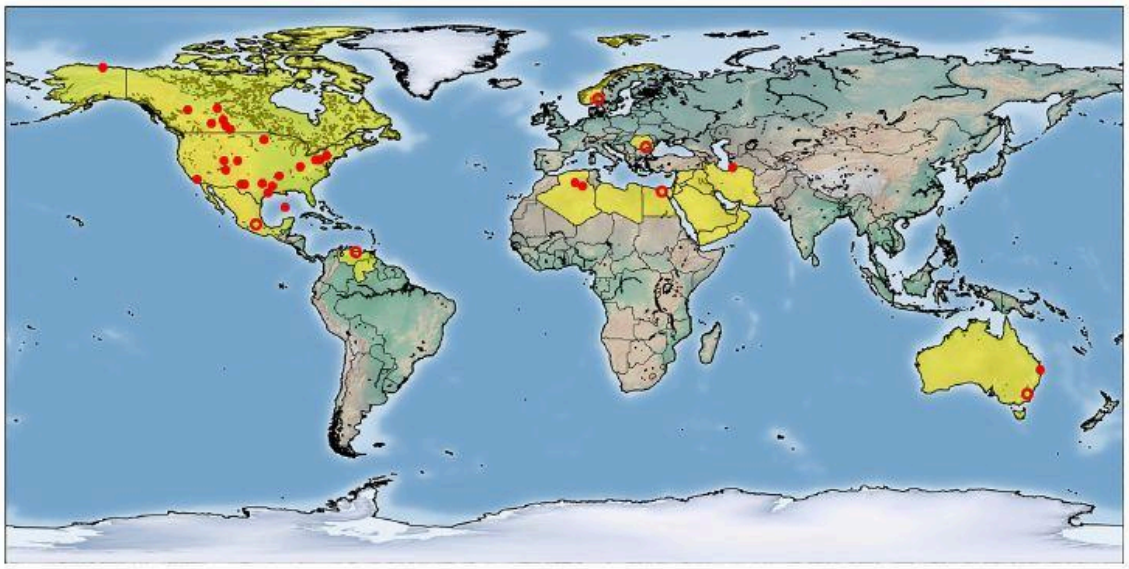


Figure 1. Regions (yellow) and locations (red markers) from where comparisons of bottom-up versus top-down oil and natural gas emission estimates were reported during 2015-2024 (Helmig and Caputi, 2025).

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Session 6:
Atmospheric Dynamics, Clouds, and Radiation

Potential Impacts of Deliberate Marine Cloud Brightening in the Arctic

David Clemens-Sewall (University of Colorado Boulder)
Co-authors: Marika Holland (NCAR)

Natural hazard mitigation and national security considerations are driving interest in research on geoengineering---deliberate perturbations in the Earth system for the objective of cooling our planet. It is critical to understand the potential risks and benefits of proposed geoengineering concepts as well as how we might detect if rogue actors were attempting to perturb the Earth system. We use a fully-coupled Earth system model (the Community Earth System Model version 2, CESM2) to examine the potential impacts of Marine Cloud Brightening (MCB) in the Arctic. MCB would consist of deliberately increasing the reflectivity and longevity of low, marine clouds by adding aerosols (such as from seawater) to the lower troposphere. On a pan-Arctic scale, we find that Arctic MCB perturbations could dramatically impact the physical and ecological systems and produce historically-unprecedented sea ice, upper ocean, and marine ecosystem conditions in the Central Arctic. On the periphery of the Arctic Ocean, including the GML Barrow Atmospheric Baseline Observatory (BRW), simulated conditions exhibit a high degree of interannual variability in both perturbed and unperturbed simulations. We use CESM2 simulations and the long term monitoring records at BRW and the adjacent Department of Energy Atmospheric Radiation Measurement facility to explore the potential detectability of Arctic MCB using long term monitoring sites and to provide local and historical context for the potential impacts.

Deforestation-Driven Clouds Amplify Top-of-Atmosphere Cooling in the Amazon

Tom Dror (CSL, NOAA CSL / CIRES)
Co-authors: Graham Feingold (NOAA - CSL)

The Amazon rainforest is a primary regulator of Earth's energy balance, yet the full biophysical impact of progressive deforestation, particularly when mediated by atmospheric responses, remains poorly constrained. Using two decades of multi-source remote sensing observations, we isolate the biophysical signals of forest loss to quantify an all-sky radiative forcing that integrates both surface and atmospheric effects. We find that in high-loss areas, forest removal results in a localized surface-brightening; however, this signal represents only a fraction of the total climatic response. When accounting for the coupled response of the atmosphere, specifically the formation of deforestation-driven clouds, the resulting top-of-atmosphere (TOA) cooling is significantly amplified. From a radiation perspective, incorporating these cloud responses doubles the TOA albedo compared to surface-brightening alone. These findings underscore the importance of cloud-mediated feedback in estimating the climatic impact of land-cover change and support their prioritized integration into climate modeling and land-management policies.

On the Effect of Clouds on the Aerosol Radiative Effect Across Cloud Regimes

Eshkol Eytan (Cloud, aerosol, and climate group, NOAA/CSL)
Co-authors: Graham Feingold (NOAA - CSL)

Cloud particles strongly modulate radiative transfer through the atmosphere across both the solar and longwave infrared spectra. Consequently, even relatively weak radiative effects of clouds on their surroundings can be substantial compared to clear-sky signals, with important implications for Earth's energy budget and for remote sensing applications.

Over the years, considerable research has focused on understanding radiative signatures in regions surrounding clouds, including contributions from three-dimensional radiative transfer, enhanced aerosol humidification, and subvisible or undetected cloud features. Recent work by Eytan et al. (2025) highlights the importance of these "cloud-influenced" regions by quantifying their radiative effects at the top of the atmosphere for the first time. In the solar, a local afternoon radiative effect of approximately -9 W m^{-2} over the ocean was reported, suggesting that a substantial fraction of the aerosol direct radiative effect is cloud-induced. In the longwave, a mean effect of about 1 W m^{-2} was found, comparable to the forcing associated with an additional ~90 ppm of CO_2.

In this presentation, we propose a new framework for assessing radiative fluxes by partitioning the sky into three categories: cloudy, pure clear-sky, and cloud-influenced clear-sky. We examine the contribution of cloud-influenced regions to all-sky top-of-the-atmosphere fluxes and investigate how the interplay among the three sky categories varies across cloud regimes and under different background aerosol conditions.

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Applying NOAA GML's Radiation, Aerosol, and Clouds (G-RAD) Division Observations and Products to Evaluate and Inform NOAA's NWP

Joseph Sedlar (CIRES and NOAA GML)
Co-authors: Vanessa Caicedo (CIRES)

NOAA GML's Radiation, Aerosol, and Clouds (G-RAD) division is internationally recognized as a leader in surface radiation and cloud observations, as well as the development of value-added data products. These long-term observations have been maintained operationally for decades through NOAA's SURFRAD and Baseline Observatory networks. Building on this foundation, G-RAD continues to advance the state of the art by developing high-level data products derived from these observations, while also designing and deploying next-generation instrumentation to enhance monitoring and understanding of energy transfer processes through Earth's atmosphere.

G-RAD's observational and analytical expertise is highly valued across NOAA line offices, particularly within OAR, where we collaborate closely with numerical weather prediction (NWP) model developers and cross-laboratory observational scientists. Over the years, sustained partnerships with the NOAA HRRR and RAP modeling communities have enabled unique observation-model evaluation studies. These efforts are rooted in G-RAD's long-term SURFRAD measurements, as well as our strong role as an interdisciplinary partner in shorter-term field campaigns. Through examples of G-RAD's observations and value-added data products, this poster highlights how these collaborations with model developers have contributed to measurable improvements in operational NWP performance. These advances are often linked to refinements in modeled physical parameterizations governing land-atmosphere energy interactions, cloud-radiation processes, and atmospheric boundary layer structure. While important challenges remain, continued cross-laboratory collaboration between modelers and observational scientists will be critical for future progress.

Using NOAA's SF6 Measurement Network to Characterize Atmospheric Transport Uncertainty and its Effect on Large Scale CO_2 Emissions Estimates

Jessica Lyons (Atmospheric Science, Colorado State University)
Co-authors: Andrew Schuh (Colorado State U. - CIRA)

Atmospheric transport models are an integral part of atmospheric flux inversions, which in turn are integral for understanding the emissions of important greenhouse gases such as methane and CO_2. As such, it is vital to evaluate the fidelity of transport models against observations and to compare such models against each other. Sulfur hexafluoride (SF_6) is a unique atmospheric tracer often used to evaluate transport. The observational record for SF_6 goes back to the 1990's and measurement platforms have expanded to now include flight campaigns, AirCores, and balloon measurements, making it possible to relate model performance directly to observations across the entire atmosphere. Schuh et. al (2019) showed an excess of SF_6 in both TM5 and GEOS-Chem at northern mid- to high-latitudes when compared to in situ observations at select marine boundary layer sites at those latitudes. It was proposed that this difference could arise from incorrect emissions, insufficient vertical mixing near the surface, or a combination of the two. Here we analyze TM5 and GEOS-Chem simulations of SF_6 against observations at several sites across the US using updated SF_6 emissions fields (Schuldt et al.,1983-2024). Preliminary analysis shows a buildup of SF_6 near the surface in both models as air moves west to east across continental US, moving towards higher emission areas. Simulations with the newer emissions agree with observations better. TM5 appears to move SF_6 emissions more efficiently from the surface than GEOS-Chem, although both appear to mix vertically too slowly. To provide further context for the positive bias in near-surface SF_6, we turned to inter-model comparisons. Zonally averaged SF_6 "curtains" comparing GEOS-Chem to TM5 imply a possible broad increase in near surface SF_6 bias in response to weaker vertical mixing. The ramification of the differences between these two is explored in the context of CO_2 flux inversions that are part of the OCO-2 v11 MIP.

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The critical role of AirCore in stratospheric circulation monitoring

Eric Ray (NOAA CSL and CIRES/CU)
Co-authors: Bianca Baier (NOAA - GML)

The large-scale stratospheric circulation, or Brewer-Dobson circulation (BDC), plays a key role in determining stratospheric trace gas and aerosol distributions, which, in turn, impact important radiative aspects of the whole atmosphere including the fate of long-lived chlorofluorocarbons and their associated ability to deplete stratospheric ozone. The BDC has consistently been predicted by chemistry-climate models to have sped up in recent decades and to continue to accelerate throughout the 21st century, although more gradually, in response to greenhouse gas increases and changes in ozone-depleting substances. However, verification of the trend has been difficult due to a paucity of measurements that allow us to infer the strength and variability of the BDC. Stratospheric trace gas observations from small balloons via the AirCore sampling technique from NOAA GML have provided a valuable new source of information about the BDC and how it is changing. In this presentation we will briefly show results from a pair of recent studies that rely on AirCore data that substantially change our understanding of the observed trend of Northern Hemisphere stratospheric mean age, which is the primary observed indicator of BDC trends. We will also show examples of how simultaneous trace gas measurements of multiple species from AirCores can refine numerous aspects important to the interpretation of the measurements, such as in the calculation of mean age, in the estimate of equivalent latitude and in idealized modeling that reveals the structure of BDC changes. Ongoing AirCore sampling is expected to continue to play a critical role in monitoring and understanding changes in the stratospheric circulation.

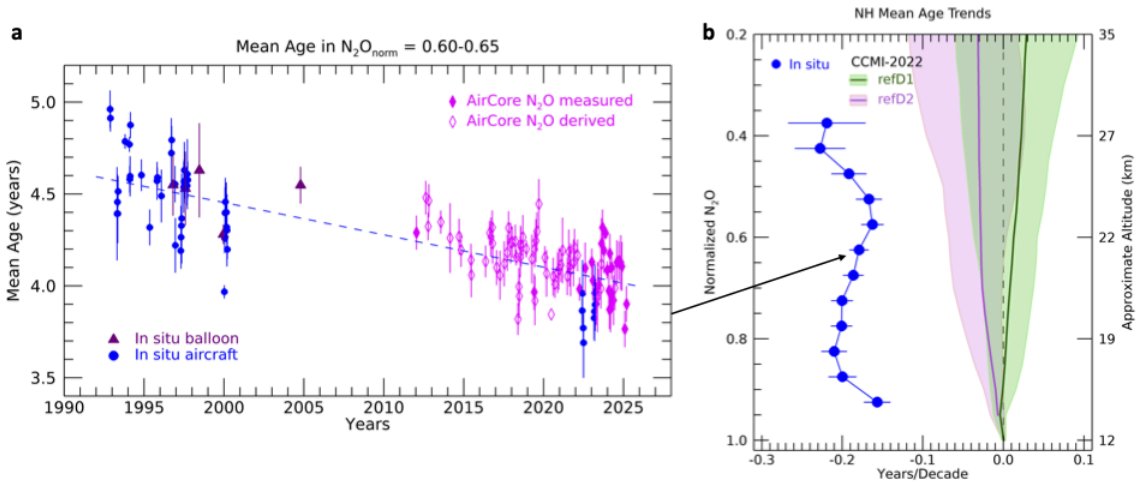


Figure caption: (a) Time series of mean ages derived from in situ SF_6 and CO_2 measurements taken from aircraft (blue), in situ balloon (purple) and AirCore (magenta) platforms. (b) Trend profiles as a function of normalized N_2O from in situ data (blue symbols) and CCMI-2022 model output from refD1 (green) and refD2 (purple).

Session 7:
Integrated Networks: Satellites, Aircraft, and Scale-Bridging

A New Approach for Leveraging the Complementarity of Diverse Satellite and In Situ Observations for Greenhouse Gas Tracking and other Atmospheric Composition Applications

Arlyn Andrews (SilverLining)

Data assimilation systems for greenhouse gas tracking, air quality, and other atmospheric composition applications have evolved substantially over the past few decades but are still hampered by model errors, inadequate process representation, simplistic statistical assumptions, and challenges around combining diverse datasets. For example, improved strategies are needed to optimally leverage the complementarity of sparse, well-calibrated and information rich in situ observations and globally comprehensive satellite observations that are more susceptible to systematic biases.

We present a novel model-data fusion approach for optimizing trace gas fields that incorporates geostatistical techniques such as kriging along with Bayesian inverse modeling. Key innovations include use of site and regional climatologies for gap filling and efficient implementation of flow-following isopleth-dependent error covariance matrices. We demonstrate the method using available surface-to-stratosphere in situ observations along with a suite of pre-existing model fields to produce "4-dimensional reference surfaces" for CO_2 and CH_4 with rigorously characterized uncertainties. These reference surfaces will enable improved evaluation and bias correction of satellite retrievals and model simulations.

The approach provides a framework for Observing System Simulation Experiments (OSSEs) for facility/urban/regional/global applications and can be expanded to include existing and candidate new satellite observations. We will present an analysis of the information content and constraints provided by expanded aircraft measurements corresponding to commercial aircraft sampling and additional routine profiling sites. We will consider implications for improved estimation of greenhouse gas emissions and removals and atmospheric growth rates and for satellite retrieval bias correction.

The Scientific and Societal Importance of the Orbiting Carbon Observatories

Christopher O'Dell (CIRA, Colorado State University)
Co-authors: Vivienne Payne (NASA - JPL)

In July 2014, under foggy skies, the second Orbiting Carbon Observatory (OCO-2) satellite successfully lifted off from Vandenberg Air Force in California into low earth orbit, following the failed launch of the original OCO satellite in 2009. It was followed by the installation of its near twin, OCO-3, on the International Space Station in 2019. Together, OCO-2 and OCO-3 measure and monitor two primary aspects of the earth's carbon cycle, the column-mean concentration of carbon dioxide (XCO_2), and Solar-Induced chlorophyll Fluorescence from terrestrial plants (SIF). The OCOs make these measurements with their high-spectral resolution near-infrared spectrometers, which measure the spectra of reflected sunlight in three spectral bands centered on 765 nm, 1610 nm, and 2060 nm wavelengths. OCO-2 and OCO-3 are funded and managed by NASA, and have been making measurements for over 11 and 6 years, respectively. Further, both instruments are healthy and should be able to continue observations for many years to come.

In this presentation, we will discuss the general importance of these measurements, along with the latest data improvements and scientific findings. They have led us to be able to better predict agricultural-relevant quantities such as crop yields and flash droughts. We have quantified mean biospheric uptake of CO_2 from dozens of the larger nation-states on earth, helping to better quantify their total carbon emissions. Crucially, this success has led to a large international effort to build next-generation satellite instruments based on the same technology, but with significantly enhanced capabilities related to spatial sampling and coverage. I will also discuss the critical complementarity of ground-based, aircraft, and space-based data; none alone has a complete picture of the earth's atmosphere, and all are vitally important to both continued monitoring and the pace of scientific discovery.

Acknowledgements:

This presentation represents the full OCO-2 and OCO-3 mission and science teams. OCO-2 and OCO-3 are funded by NASA's Earth Science Directorate.

Evaluation of Carbon Fluxes in East Tropical Africa from OCO-2 Satellite Retrievals and Global Inversion Models with In Situ Vertical Profile Measurements

Kathryn McKain (NOAA GML)
Co-authors: John Miller (NOAA - GML)

The sign and magnitude of the net carbon balance of tropical Africa is highly uncertain due to a lack of both in situ and remote sensing observations in the region. OCO-2 satellite retrievals increase the spatial coverage of CO2 data overall, but tropical data coverage remains low due to cloud cover, which also has strong seasonality. Previous work using global inversion models assimilating satellite CO2 data found tropical Africa was a much larger carbon source than predicted by terrestrial biosphere models or inversion models assimilating only in situ data. A recent simulation study demonstrated that the seasonal sampling bias of OCO-2 over tropical Africa, combined with prior flux models with too small seasonal amplitudes, could lead to net flux estimates that are biased high. However, satellite retrievals and inversion results for tropical Africa have not yet been evaluated with in situ observations from within tropical Africa.

We use 1.5 years of aircraft vertical profile measurements of CO_2 over Uganda to evaluate fluxes in eastern tropical Africa, as simulated by the ensemble of global inversion models participating in the OCO2 v11 Model Intercomparison Project (MIP). The sign, magnitude, and seasonality of observed CO_2 vertical gradients are used to evaluate regional-scale net CO_2 fluxes resulting from models with and without assimilation of satellite observations. Simultaneous measurements of CO, a tracer of biomass burning, and observed CO:CO_2 ratios, are used to disaggregate contributions from terrestrial ecosystem exchange and biomass burning to the net flux, and therefore evaluate the contribution of biomass burning to potential model biases. Lastly, observed and modeled free-troposphere values are also compared to investigate potential large-scale biases in models due to the lack of in situ measurements in the region from the long-running global network.

The Chestnut Ridge Supersite: A Revamped Observing System for Studying Land-Atmosphere Interactions and Feedbacks in a Southern Appalachian Forest

Temple Lee (NOAA / Air Resources Laboratory Atmospheric Turbulence and Diffusion Division)
Co-authors: Mauricio Toro (NOAA - ARL)

The proper representation of land-atmosphere interactions over complex terrain is an essential component of operational numerical weather prediction (NWP) models. As both the horizontal and vertical resolution of NWP models increases and NWP models are better able to resolve finer-scale atmospheric processes, proper characterizations of the surface layer and boundary layer over, for example, forested mountainous terrain, are becoming increasingly important.

In 2005, the NOAA Air Resources Laboratory Atmospheric Turbulence and Diffusion Division installed a 60-m micrometeorological tower at Chestnut Ridge near Oak Ridge, Tennessee. The site represents the continuation of a previous tower in the nearby Walker Branch watershed and is now one of the sites in the National Ecological Observatory Network (NEON). The Chestnut Ridge tower, which is part of NOAA's Surface Energy Budget Network (SEBN) and the AmeriFlux network (site ID: US-ChR), is located within a mixed-deciduous forest canopy representative of other forested regions in the southern Appalachian Mountains. Since the tower's installation, above-canopy meteorological and flux observations have been used to address a range of science questions on surface-layer processes over forests and complex terrain.

Since 2023, additional observations have been added to the site, which include an expanded multi-layer (i.e., both within and above the canopy) arrangement of eddy correlation systems for quantifying momentum, heat, moisture, and CO_2 fluxes; high temporal resolution observations of air temperature, humidity, wind, and radiation (including both incoming and outgoing shortwave and longwave); and soil temperature and soil moisture across multiple sampling depths. Additionally, a WindCube V2.1 wind lidar was installed about 5 km northeast of the tower to determine vertical profiles of wind and turbulence quantities, including turbulent kinetic energy, vertical velocity variance, and vertical velocity skewness over the lowest 300 m of the atmosphere. The lidar is complemented by other lidars in the region, operated by colleagues from the Oak Ridge National Laboratory, which are used to obtain vertical profiles of wind speed and direction and to infer boundary-layer depth. In our presentation we will summarize key recent research findings obtained using the new suite of observations from the site. We will also highlight how the site provides an ideal natural laboratory for other research collaborators across NOAA to study the physics and chemistry of the atmospheric boundary layer over complex, forested terrain.

The NOAA Balloon Baseline Stratospheric Aerosol Profiles (B2SAP) Dataset for In Situ Measurements of Stratospheric Aerosol

Katie Smith (NOAA CSL)
Co-authors: Alexandre Baron (CIRES)

A persistent aerosol layer exists between the tropopause and middle stratosphere, and characterizing the background state and variability of these stratospheric aerosols is essential for predicting the climate response after stratospheric perturbations. Understanding the size distribution of these aerosols is critical for determining the influence they have on the global radiation budget and their role in chemical and dynamical processes.

The Balloon Baseline Stratospheric Aerosol Profiles (B2SAP) project is an on-going, multi-year effort within the NOAA Earth's Radiation Budget (ERB) program to define background stratospheric aerosol abundances and variability using in situ measurements. The B2SAP dataset consists of aerosol size distribution observations from high-altitude balloons, at latitudinally dispersed locations. Regular, highly resolved vertical profiles from the surface to 29 km of aerosol data products such as: total aerosol concentration, particle size distribution, surface area concentration, effective radius, are used to build up a global picture of the stratospheric aerosol layer and its variability.

We present the B2SAP dataset spanning 2019 to the present and use it to characterize stratospheric aerosol properties and variability during periods without major stratospheric perturbations, as well as during several observed plume injection events. Using this dataset, we examine both short- and long-term variability and begin to investigate seasonal and shorter-timescale trends.

These observations can be used to constrain the global radiative budget and global climate models, validate and calibrate space-based sensors, as well as deepen our understanding of how perturbations (e.g. from explosive volcanoes, large wildfires) to the aerosol layer impact the radiative, chemical and microphysical properties of the stratosphere.

Acknowledgements:

Authors would like to thank the extended B2SAP team.

Using Commercial Aircraft to Monitor Urban Carbon Reservoirs

Colm Sweeney (NOAA)

Our current understanding of the carbon cycle relies on a limited network of direct and remote sensing systems for measuring atmospheric greenhouse gases (GHGs). While this has provided a general understanding of natural and anthropogenic GHG sources and sinks, it is insufficient for monitoring subtle emission changes caused by climate change, mitigation efforts, and interventions. To address this, a new network, integrating existing and emerging technologies, will be necessary. This network, enhanced through public-private partnerships, will enable verification of GHG emissions and uptake from global to local scales.

A prime example of these expanding private sector collaborations is the recent partnership between NOAA and United Airlines. This collaboration leverages commercial aircraft to provide up to eight daily atmospheric profiles at a fraction (1%) of the cost of comparable research aircraft. The benefits of these observations are magnified by their low cost, increased frequency, and the ability to frequently sample large metropolitan areas, which are often served by mid-size aircraft like the Boeing 737. These profiles are crucial for bridging the gap between ground-based direct measurements and satellite-based remote measurements, thereby facilitating GHG emission monitoring across all scales.

This presentation will offer an overview and update on a global initiative that utilizes a unique platform to enhance our capacity for GHG observation. Specifically, NOAA's agreement with United Airlines to carry a GHG analyzer in the EE-bay of their 737-900ER short-haul aircraft is expected to significantly expand measurements of CO_2, CH_4, CO, and water vapor in and out of major metropolitan areas worldwide. With 50 aircraft distributed among 10 different airlines, we anticipate sampling 200 metropolitan areas globally with a frequency of better than every 3 days. This will lead to a substantial reduction in the uncertainty of urban methane emissions, as well as providing critical constraints on regional GHG emissions and satellite retrievals through the unique characteristics of aircraft profiles.

POSTER SESSIONS

Session P1:
The Carbon Pulse: Ocean Sinks & Terrestrial Feedbacks

$\delta^{18}O$ of atmospheric CO_2 from the NOAA global monitoring network

Kerstin Braun (INSTAAR, CU Boulder)
Co-authors: Sylvia Michel (U. Colorado Boulder - INSTAAR)

The INSTAAR Stable Isotope Laboratory has a 36-year record of stable isotopologues of CO_2 from NOAA's Global Greenhouse Gas Reference Network (GGGRN). Measurements of carbon isotopes of atmospheric CO_2 ($\delta^{13}CCO_2$) have proven to be useful for partitioning the uptake of CO_2 between oceans and the biosphere, and tracking the variability in plant uptake of this important greenhouse gas. The isotopic composition of oxygen in CO_2 ($\delta^{18}OCO_2$) is routinely measured along with δ13CCO2. The main influences determining $\delta^{18}OCO_2$ values in atmospheric samples are exchanges of oxygen between CO_2 and water. Enrichment of ^{18}O is usually associated with isotopic exchange inside leaves during photosynthesis whereas deletion of ^{18}O is a result of interactions with soil water. Based on these processes, $\delta^{18}OCO_2$ is expected to display seasonal variability that lags behind cycles of $\delta^{13}CCO_2$ by about 2-4 months. However, at many locations in the GGGRN the interpretation of $\delta^{18}OCO_2$ is complicated by high variability in the measurement, usually with a bias toward more negative $\delta^{18}OCO_2$. The most likely explanation for this bias is oxygen exchange between CO_2 and water inside the flask as changes in temperature (for example during air transportation) cause condensation. Sampling systems that include condensing dryers have improved this issue at most humid locations within GGGRN, but a few sites remain insufficiently dried. Furthermore, some high latitude sites have highly variable $\delta^{18}OCO_2$ data despite low humidity.
Previous studies have suggested filtering of the data based on specific humidity at the time of sampling to mitigate the bias in $\delta^{18}OCO_2$, however, at many mid-latitude locations such filters would lead to the loss of a large proportion of the data mostly during the spring and summer. In this study we evaluate filtering of $\delta^{18}OCO_2$ based on weather data derived from hourly reanalysis in addition to statistical filters that are designed to account for the negative bias caused by post-sampling isotopic exchange in the flasks. We compare globally and zonally averaged $\delta^{18}OCO_2$ from different flagging and filtering regimes to see which maximizes data retention without introducing biases or water contamination artifacts.

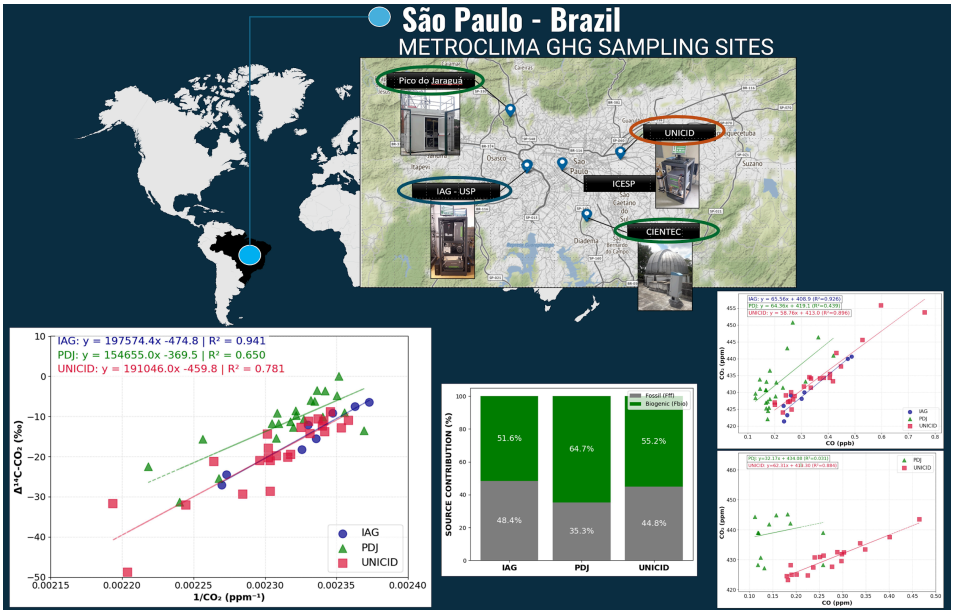
Characterizing CO_2 emissions with $\Delta^{14}C$-CO_2, CO_2, and CO in urban, suburban, and background sites of São Paulo

Leslie Morales (Meteorology, Sao Paulo University)

Emissions from urban cities currently account for up to 75% of anthropogenic greenhouse gas (GHG) emissions; taken as a line item, this represents the single largest human contribution to climate change. Consequently, reducing GHG emissions from cities has been identified as one of the most effective measures to address climate change. Among atmospheric tracers, radiocarbon (^{14}C) is considered the "gold standard" tracer to detect fossil emissions ($ffCO_2$) because fossil fuels are completely devoid of ^{14}C ($\Delta^{14}Cff$ = -1000 ‰) and their emissions impart a detectable dilution in the ratio of $^{14}C/^{12}C$ relative to clean background air. However, $\Delta^{14}CO_2$ measurement campaigns had thus far been limited to cities located in temperate climates such as Indianapolis, Los Angeles, and Heidelberg, even though most of the world's megacities are in subtropical/tropical climates.

In this study, we present $\Delta^{14}C$-CO_2 and CO_2 measurements from São Paulo, Brazil – a megacity with a subtropical climate and population of ~23 million. This measurement campaign took place during the local winter (July 2024). We collected 2.5 L glass flask samples from three sites: a suburban site at the Institute of Astronomy, Geophysics and Atmospheric Sciences (IAG) of the University of São Paulo, an urban site at a campus of the University of the City of São Paulo (UNICID), and a vegetated site in a protected area at Pico do Jaraguá (PDJ). Each site has a cavity ring-down spectroscopy instrument (Picarro) for CO_2 mole fraction measurements.

We use a Keeling plot analysis to distinguish between biogenic and fossil CO2 sources. Supplementary data on PM_{10}, $PM_{2.5}$, O_3, and NO_x from CETESB (São Paulo's Environmental Protection Agency) were incorporated to assess concentration anomalies during the campaign. The $\Delta^{14}C$-CO_2 intercepts from the Keeling plots show large biogenic contributions at all sites, even during winter -491.85 ‰ (Bio=55.2%, Ff=44.8%) at UNICID, -459.84 ‰ (Bio=51.6%, Ff=48.4%) at IAG, and -361.71 ‰ (Bio=64.7%, Ff=35.3%) at PDJ. The biogenic CO_2 likely originates from ethanol combustion in vehicles and respiration from urban vegetation, particularly at PDJ and IAG. The CO/CO_2 ratio suggests relatively inefficient combustion compared to typical values reported in the US, Europe, and Japan.



Acknowledgements:

These results were part of the São Paulo Research Foundation (FAPESP; grant no.2016/18438-0, METROCLIMA Project; FAPESP grant no. 2025/24222-0 and FAPESP grant no. 2024/01021-6).

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Advancing fire modeling capabilities for understanding terrestrial carbon exchange

Aleya Kaushik (CIRES University of Colorado Boulder / NOAA Global Monitoring Laboratory)
Co-authors: John Miller (NOAA - GML)

Fire is an important disturbance component of the terrestrial carbon cycle, and it is critical to understand spatiotemporal variations in fire occurrence and magnitude to better assess impacts on ecosystems and land-atmosphere carbon cycle exchanges. The magnitude and frequency of extreme fires have increased in recent decades despite recent reductions in total global burned area. Global earth system models use a variety of bottom-up techniques to simulate fire, while top-down models rely on satellite-based measurements of fire counts or fire radiative power. Here we present an updated fire model which combines fuel loads from a state-of-the-science terrestrial biosphere model with near-real-time burned area derived from satellite observations of fire counts. We compare our results with other global fire products that rely on different satellite measurements calibrated by external inventories, assessing both regional and temporal variations and their connections to environmental drivers such as soil moisture and atmospheric dryness. Finally, we evaluate the fire emissions from these disparate products within the context of atmospheric measurements of carbon monoxide and carbon-13 isotopes of carbon dioxide.

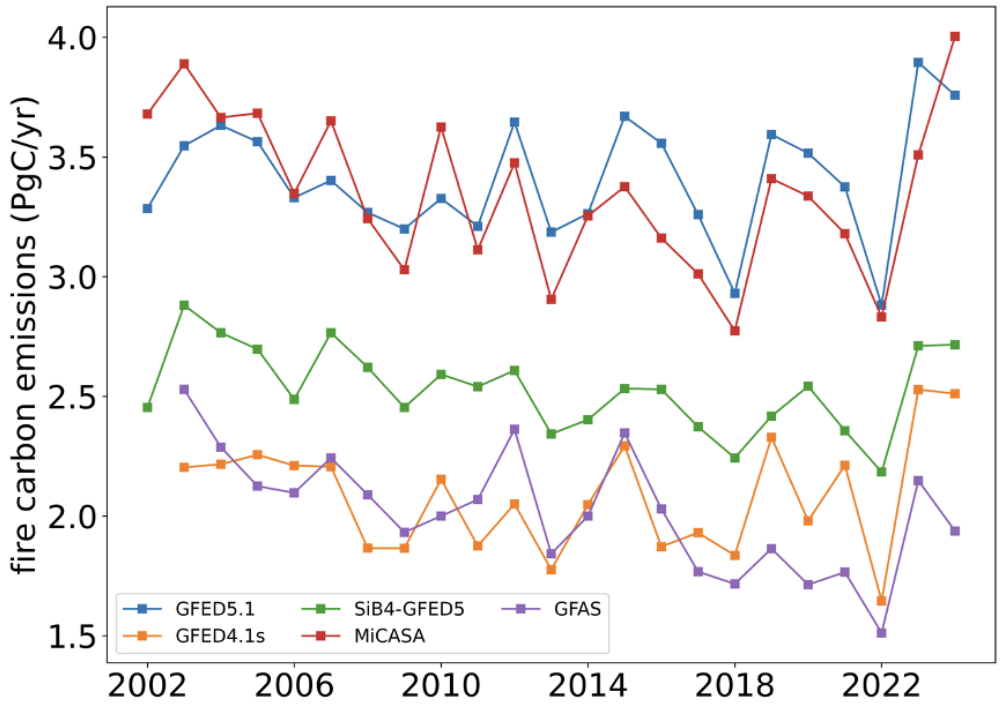

Figure: Comparing global fire carbon emissions from a variety of fire products with our recent fire model ("SiB4-GFED5") where we combine the capability of a bottom-up terrestrial biosphere model (SiB4) with burned area derived from satellites analogous to methodology used in GFED5.

Preliminary Sensitivity Tests of X-STILT Parameters for Tropical Ecosystem Applications in the Amazon Region

Yanxiao Liu (CU Boulder)
Co-authors: Bharat Rastogi (U. Colorado Boulder)

Accurately simulating atmospheric transport is critical for interpreting greenhouse gas signals in tropical ecosystems. While the X-STILT (X-Stochastic Time-Inverted Lagrangian Transport) model is widely used for satellite- and ground-based CO_2 observations, its performance in the Amazon remains underexplored due to the region's complex meteorology.

This study conducts preliminary sensitivity tests to determine the optimal X-STILT configuration for the Amazon Basin. We are currently evaluating how key parameters—specifically particle release height (MAXAGL), particle number (NUMPAR), and vertical receptor spacing (dh)—influence simulated footprints and transport characteristics. The primary goals of these tests are to: (1) assess model stability; (2) understand systematic/random errors caused by receptor configurations; and (3) balance computational efficiency with the accuracy required for deep atmospheric transport. These tests will establish a standardized configuration for X-STILT in tropical environments, providing a foundation for future research to constrain Amazonian carbon fluxes using satellite data.

Acknowledgements:

Thank Dien Wu for providing the model and technical support.

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What drove the response of ecosystem photosynthesis to 2023/24 Drought in the Amazon Tropical Forest

Ximeng Huang (Geography, University of Colorado Boulder)
Co-authors: Bharat Rastogi (U. Colorado Boulder)

The Amazon forest is one of the largest and most contiguous tropical forests in the world, sustaining high photosynthetic activity and playing an essential role in climate change mitigation. During 2023 and 2024, the Amazon Basin experienced an extreme drought, yet the response of ecosystem productivity remains unclear. Solar-induced fluorescence (SIF) is a proxy for vegetation photosynthesis, and multiple satellite-based SIF products have been developed in recent years. Here we apply direct instantaneous SIF retrievals from Tropospheric Monitoring Instrument (TROPOMI), to investigate the response of ecosystem photosynthesis to the 2023/24 Drought in the Amazonia. The drought affected 57.9% of the Amazon tropical forest in 2023, increasing to 71.1% in 2024. Drought extent peaked during transition seasons, specifically in October 2023, March 2024, and October 2024. Across the whole region, the spatially averaged SIF decreased by 0.86% in 2023 and 1.94% in 2024. The mean standardized SIF anomalies for SIF were -0.14 in 2023 and -0.41 in 2024, with a stronger decrease observed in the southern Amazon. Water storage has the significant correlation with SIF, with lower water storage associated with more negative SIF anomalies. Lower cloud cover during the drought years also contributed to the decline in SIF. Our findings reveal that drought-induced water availability plays a critical role in the variation of vegetation in tropical forests.

Hydrodynamics-informed Carbon monitoring in Tropical Coastal Wetlands Using Harmonized Landsat-Sentinel (HLS) Product

Ajay Devda (Ecosystem Science and Sustainability, Colorado State University)

Tropical wetlands hugely contribute to global ecosystem services, and are highly vulnerable due to climate change and anthropogenic activities. Continuous and accurate monitoring of wetlands can serve diverse objectives, including enhancing resilience, biodiversity, carbon credits, and sustainable development. The region's high tidal variation hampers the accuracy of universal remote sensing products, often leading to over- or underestimation of key ecological parameters. Consideration of hydrodynamics is crucial to the accurate estimation of ecological parameters through remote sensing products. Recognizing that existing biomass and GPP estimates often neglect hydrodynamic variation that disproportionately affects NIR reflectance, we propose novel correction strategies. Our study aims to evaluate landscape-scale restoration impacts and carbon flux dynamics, considering hydrodynamic changes across a transboundary wetland incorporating remote sensing, in situ data, and machine learning-based modeling approaches. To accurately assess hydrodynamics impacts, we utilized datasets containing biomass and hydrodynamic time series from mini-buoys and remote sensing indices, offering a robust dataset for calibrating and validating wetland resilience models. Our high-frequency (30-minute interval) water-level data from multiple monitoring stations revealed the impact of hydroperiod on wetland condition and resilience. We explored remote sensing models, including machine learning methods (XGBoost), to correct the estimate of wetland biomass, and assessed performance in the Sundarbans' unique tidal and hydrologically dynamic context. This work contributes to the development of a comprehensive Monitoring, Reporting, and Verification (MRV) framework for tropical wetlands and informs future climate mitigation strategies through data-driven mangrove restoration planning.

Acknowledgements:

We acknowledge the contribution of data-sharing partners, including the Living Delta Project, the NASA HLS Team, and TUM, Munich.

On the Utility of Ship-Based Atmospheric CO_2 Measurements for Constraining Air–Sea CO_2 Fluxes

David Munro (CIRES/NOAA GML)
Co-authors: Anna McAuliffe (CIRES)

Although variability in atmospheric carbon dioxide (CO_2) over the global oceans is roughly an order of magnitude smaller than variability in the surface ocean partial pressure of CO_2 (pCO_2), air–sea CO_2 flux estimates are nonetheless sensitive to the representation of atmospheric CO_2 in the marine boundary layer (MBL). Despite this sensitivity, most studies rely on zonally smoothed model output or data products rather than in situ ship observations for the atmospheric boundary condition, in part because of the need to filter contamination resulting from ship exhaust. Ship-based atmospheric CO_2 measurements—collected both by underway pCO_2 systems that primarily sample surface seawater and periodically measure the atmosphere, and by dedicated high-precision atmospheric systems—provide a direct means to resolve spatial and temporal gradients that are often absent in these products and to evaluate resulting regional biases.

We synthesize available ship-based atmospheric CO_2 observations from multiple platforms, including research vessels, commercial ships, and moorings distributed globally, and discuss the application of consistent quality control and data reduction procedures across datasets. These measurements are compared with widely used atmospheric CO_2 products, including the NOAA MBL reference and CarbonTracker planetary boundary layer fields, to assess their impact on air–sea CO_2 flux estimates.

We find that existing atmospheric CO_2 products underestimate variability in regions with strong gradients, such as near densely populated coastal zones, but also exhibit substantial regional biases across open-ocean basins. As a result, flux estimates derived using these products can differ significantly from those constrained by ship-based observations, with regional impacts on the order of 20% in some areas, while global-scale effects remain comparatively small.

These results demonstrate that expanded use of ship-based atmospheric CO_2 observations can substantially improve regional air–sea C flux estimates and provide an important observational constraint for model evaluation and atmospheric inversion systems. As part of ongoing efforts within the Surface Ocean Reference Observing Network (SOCONET), integrating these measurements into global synthesis frameworks represents a key step toward reducing uncertainty in ocean carbon uptake and its variability.

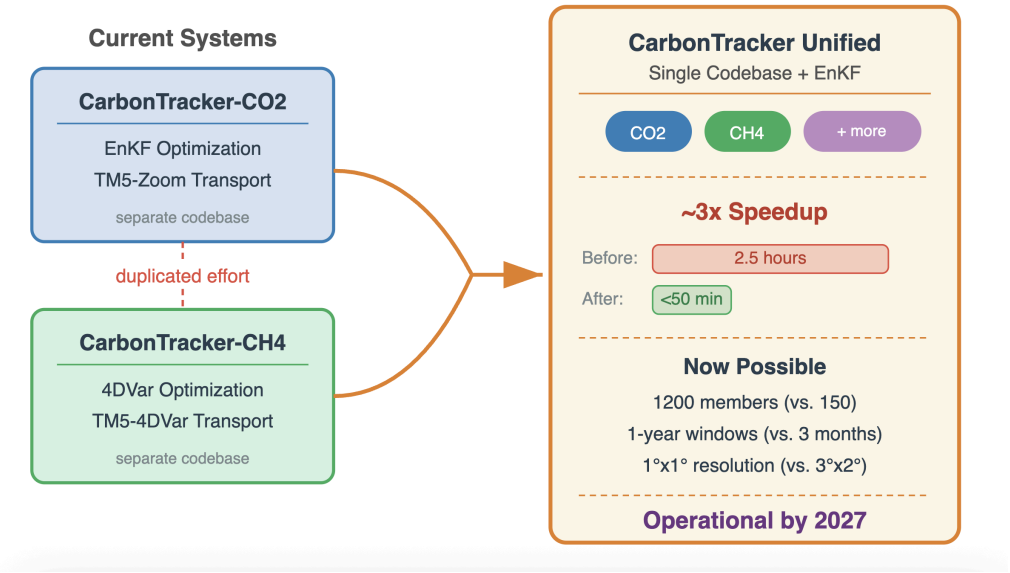
Toward a Unified CarbonTracker: Consolidating NOAA GML's CO_2 and CH_4 Flux Estimates

Ashley Pera (NOAA/CIRES)
Co-authors: Andrew Jacobson (CIRES), Lori Bruhwiler (NOAA – GML), John Miller (NOAA – GML)

NOAA's Global Monitoring Laboratory operates two global data assimilation systems: CarbonTracker-CO_2, which since 2007 has produced global estimates of surface CO_2 fluxes, and CarbonTracker-CH_4, introduced in 2014, which calculates isotope-aware methane fluxes. Both systems share the TM5 transport model but diverged into separate codebases when CarbonTracker-CH_4 adopted 4DVar optimization in 2022. Maintaining separate codebases has duplicated effort, prevented scientific advances from propagating between chemical species, and locked each system to its own state vector design.

We have developed a unified system that consolidates these branches into a single codebase using an ensemble Kalman filter for both CO_2 and CH_4. A prototype has been validated against prior CarbonTracker output and will form the basis of an operational system. Novel state vector configurations and the flux estimation of other gases such as OCS and halocarbons are now possible. Infrastructure modernization — a dedicated I/O server, shared-memory parallelism, and pre-computed diffusion caching — delivers an approximately 3x speedup, reducing a typical assimilation cycle from 2.5 hours to under 50 minutes. This enables operational testing of larger ensembles (up to 1200 vs. the current 150 members), longer windows (1 year vs. the current 3 months), and higher global transport resolution (1°x1° vs. current 3°x2°).

We have implemented a framework to evaluate proposed changes to the assimilation system — such as new optimization configurations or even observing networks — allowing rigorous, science-based estimates of the global inversion's uncertainty. This provides evidence-based guidance for network design decisions that directly affect global and national greenhouse gas monitoring quality. The unified architecture lowers the barrier to extending CarbonTracker to additional species and coupling with Earth system models, and its modular design makes it straightforward for new researchers to configure the system. We expect our annual CarbonTracker CO_2 and CH_4 releases to use this unified system by 2027.



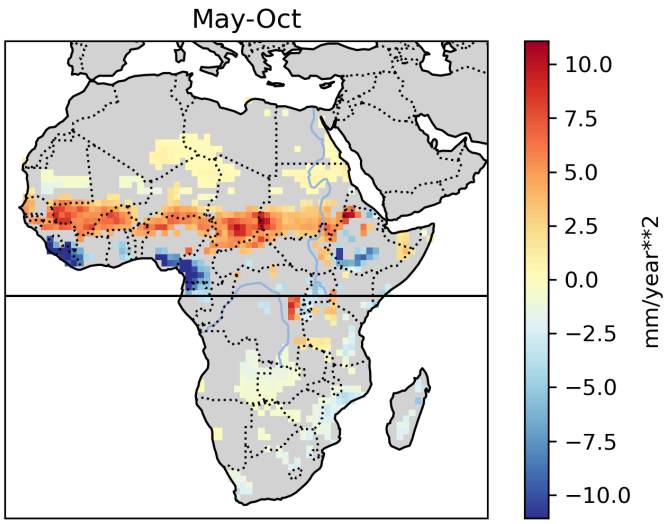
Session P2:
Ozone, Particulate Matter, and Air Quality

Northern Hemisphere Air Quality and Methane Emissions from Tropical Africa: Are they connected?

Lori Bruhwiler (NOAA Global Monitoring Laboratory)

A robust feature of atmospheric methane inversions is an increase in emissions from sub-Saharan Africa. Inclusion of 13C-CH4 data in NOAA GML's CarbonTracker-CH4 data assimilation/ inversion system (CTCH4) suggests that the increases are due to increases in microbial emissions. There are not adequate observational constraints to make conclusions about how much of the increases are due to microbial processes from agriculture and waste compared to natural wetland emissions. NOAA GML's CarbonTracker-CH4 inversion system shows that emissions from Tropical and sub-Saharan Africa have increased by ~12TgCH4/yr over 2000-2024. Estimated wetland areas and Total Water Storage from the GRACE satellite data show positive trends over this region. Finally, there is a strong precipitation signal as seen in the GCPC precipitation analysis. It therefore seems that increases in moisture are driving increases in microbial emissions, likely both natural and anthropogenic.

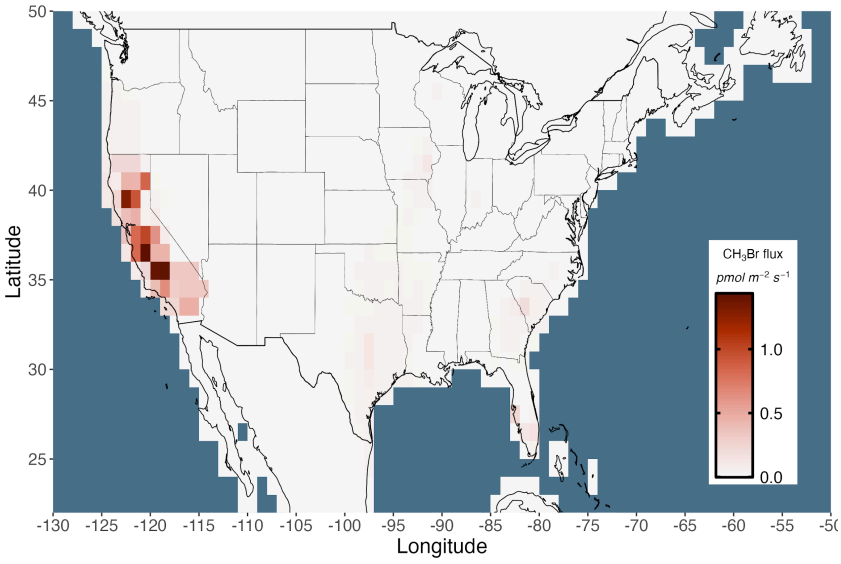
During the 1980s, sub-Saharan Africa experienced severe droughts, scientific consensus converged on ideas about desertification, including feedbacks from human activities such as grazing with the atmospheric water budget. However, in recent decades, this trend has turned around and the region has experienced extreme flooding events. Climate model studies using large ensembles of runs have demonstrated that changes in aerosol concentrations in Northern Latitudes can influence sea surface temperature gradients, with implications for the distribution of rainfall. Improvements in air quality in North America and Europe have led to decreased aerosol optical depth over past decades, with effects on SST gradients resulting in a northward migration of NH summertime precipitation. As air quality improvements are implemented in Asia, similar changes in SST could occur in the Pacific Basin with implications for changing precipitation, wetlands, and ultimately methane emissions. Here we explore how GMLs radiation, aerosol and greenhouse gas networks can be used to explore this problem.



A decline but no cessation of methyl bromide emissions from the United States over 2007-2018

Dylan Gaeta (CIRES/NOAA GML)
Co-authors: Scot Miller (Johns Hopkins U.)

Methyl bromide (CH_3Br) is an ozone-depleting substance (ODS) that by 2015 was globally phased out of use for most applications under the Montreal Protocol on Substances that Deplete the Ozone Layer. However, the Montreal Protocol includes exemptions for quarantine and pre-shipment (QPS) uses, and existing bottom-up inventories of CH_3Br consumption and/or emissions for the U.S. provide conflicting information on CH_3Br use over time. In this study, we use long-term atmospheric measurements of CH_3Br from the NOAA Global Monitoring Laboratory (GML) Global Greenhouse Gas Reference Network (GGGRN) to estimate CH_3Br emissions from the contiguous United States for years 2007-2018, a time period that encompasses the phase-out of most Montreal Protocol exemptions. Specifically, we assimilate tall tower, observatory, and aircraft flask-sample measurements of CH_3Br from the NOAA GGGRN and footprints from the NOAA CarbonTracker-Lagrange public data release in a geostatistical inverse model (GIM) to estimate spatially-gridded monthly and annual CH_3Br emissions and corresponding uncertainties. To help improve our inverse model estimate, we incorporate inventory data sets of CH_3Br production, consumption, and end uses from the United Nations Environment Programme (UNEP), the U.S. Environmental Protection Agency (EPA) National Emissions Inventory (NEI), and the California Department of Pesticide Regulation (CDPR) as predictor variables in the GIM. Overall, we find that California is the dominant source of CH_3Br emissions from the U.S., accounting for >50% of national emissions, both before and after the 2015 Montreal Protocol phase-out deadline. We find that U.S. CH_3Br emissions declined by ~1 Gg yr^{-1} (56.6%), down from a mean of 1.69 Gg yr^{-1} in 2007-2010 to a mean of 0.73 Gg yr^{-1} in 2015-2018. We observe a notably large decline in late summer/early fall emissions of CH_3Br in California, consistent with the 2015 phase-out of soil fumigation with CH_3Br for strawberry farming. Despite the reduction, CH_3Br emissions from the U.S. did not decline to zero after 2015, predominantly due to two ongoing exemptions: 1) QPS fumigation at/near international shipping ports and 2) fumigation for very select agricultural uses (e.g., strawberry nursery plants). Our work highlights the effectiveness of the Montreal Protocol in reducing CH_3Br emissions from most end uses, but it also highlights that CH_3Br emissions related to international trade and from agricultural uses like strawberry farming present an ongoing challenge.



Airborne measurements of bromoform and dibromomethane and the potential impact of changing oceans on their future emissions

Behrooz Roozitalab (ACOM, NSF NCAR)
Co-authors: Eric Apel (NCAR)

Bromoform ($CHBr_3$) and dibromomethane (CH_2Br_2) are two short lived halocarbons with predominant global emissions from oceans through an enzyme-mediated process in the presence of macroalgae or phytoplankton. Through convection and other transport processes, these emissions result in about 5 ppt of bromine reaching the upper troposphere and lower stratosphere (UTLS) with implications on the stratospheric ozone. Despite their importance and due to limited observations, there are still uncertainties in their emission magnitudes, sources, and abundances, both in the present day and future. In this presentation, we show our in-situ observations using the NSF NCAR Trace Organic Gas Analyzer with Time-of-Flight mass spectrometer (TOGA-TOF) in recent airborne missions including, but not limited to, the 2024 NASA ASIA-AQ (Airborne and Satellite Investigation of Asian Air Quality) campaign in Asia and the 2025 NSF-funded GOTHAAM (Greater New York Oxidant Trace Gas Halogen and Aerosol Airborne Mission) campaign in the northeast US. We compare our measurements with the available NOAA GML observations (i.e., CH_2Br_2). We also present our recently developed long term global oceanic emission inventory of $CHBr_3$ and CH_2Br_2 and their future impact on the UTLS bromine using the most recent halogen chemical scheme within the Community Atmosphere Model with chemistry (CAM-chem) model. Finally, we compare simulations with different oceanic emission inventories. A particular focus of this study was on the impact of future emissions. Our results suggest emission enhancements in the future with 0.47-1.13 ppt Br increase in the upper troposphere by 2100.

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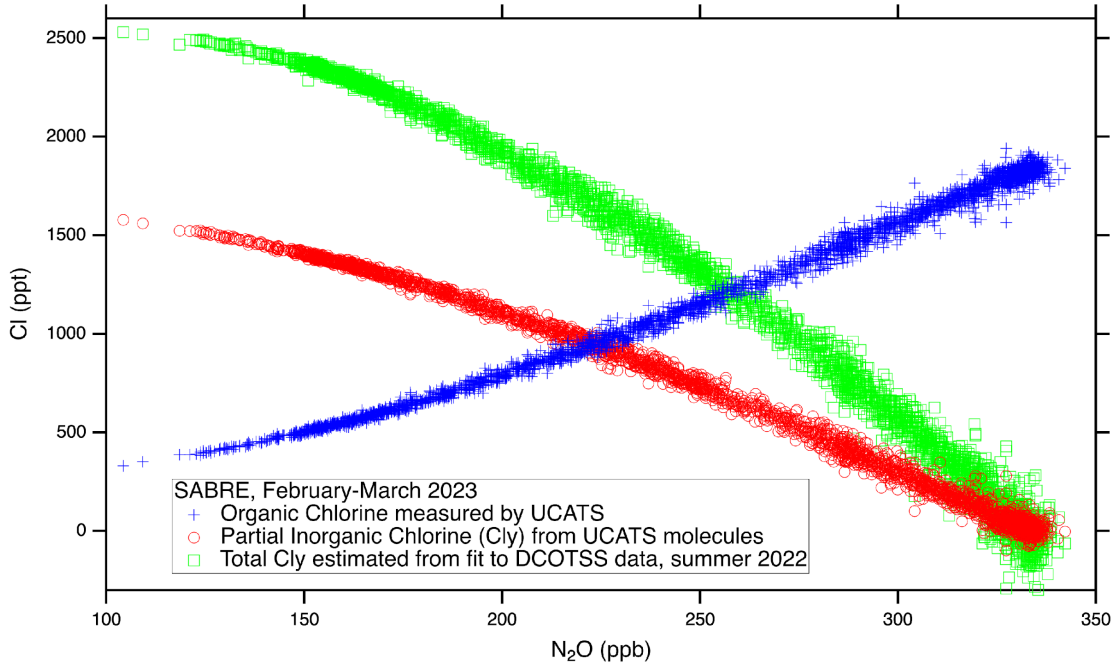
Halogen Compounds in the Northern Hemisphere Stratosphere: from Summer Midlatitudes to the Polar Vortex

Eric Hintsa (University of Colorado/CIRES and NOAA Global Monitoring Laboratory)
Co-authors: Fred Moore (CIRES)

The response of stratospheric chemistry and ozone to changes in water vapor and aerosols from volcanic eruptions, climate change, or geoengineering depends in part on the amount of reactive halogen compounds (primarily chlorine and bromine) in the atmosphere. We present results from the Stratospheric Aerosol processes, Budget and Radiative Effects (SABRE) mission, in which the NASA WB-57 aircraft flew in the lower stratosphere from Houston, TX and Fairbanks, AK in February-March 2023. The UAS Chromatograph for Atmospheric Trace Species (UCATS) measured CFC-11, CFC-12, CFC-113, and halon-1211, which account for more than half of the organic chlorine entering the stratosphere. Using techniques developed for the Dynamics and Chemistry of the Summer Stratosphere (DCOTSS) mission in 2021 and 2022, we estimate the amount of organic chlorine remaining in measured air parcels, and by difference, calculate the approximate amount of inorganic halogen compounds in each air parcel. This includes results at mid- and high latitudes, and air sampled inside remnants of the Arctic polar vortex in 2023.



Global Monitoring Laboratory- Wildfire Research Mobile Monitoring Systems

Mark Kutchenreiter (CIRES, GML GRAD; NOAA Affiliate)
Co-authors: Ben Sheffer (CIRES)

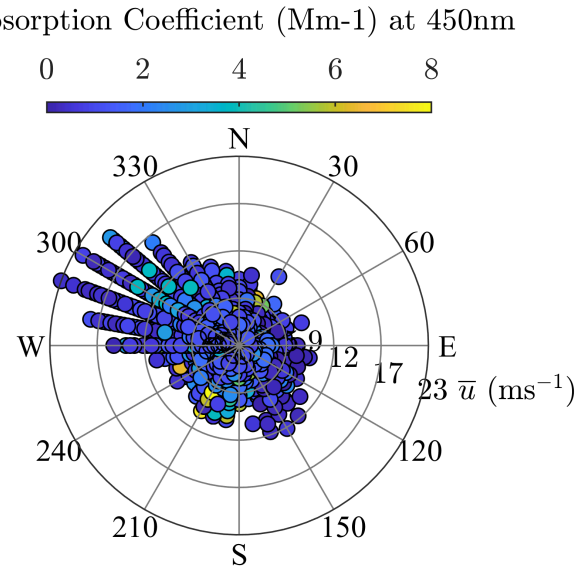
Understanding wildfires requires an interdisciplinary approach due to the complex feedbacks between weather, climatic conditions, and air quality processes. The NOAA Global Monitoring Laboratory (GML), Global Systems Laboratory (GSL), Air Resources Laboratory (ARL), and Physical Sciences Laboratory (PSL), with CIRES participation, have partnered to build fixed boundary layer observation facilities and two CLAMPS (Collaborative Lower Atmospheric Mobile Profiling Systems) mobile units equipped with similar instruments. In addition, the GML GRAD group is preparing the SMOLDER (Situational Measurement and Optical, Detection of fire Emissions and Radiative impacts) mobile monitoring unit that will include aerosol, radiation, meteorological, and air quality monitoring instruments. Research area highlights associated with these mobile facilities includes: tracking smoke plumes, aerosol/smoke detection, smoke impacts on surface radiation, plus satellite and model evaluations. Recognizing the increasing threats of wildfire and its potential negative impact on communities, the FY22 Bipartisan Infrastructure Law (BIL) Provision 15 provided funding for "observation and dissemination of infrastructure used for wildfire prediction, detection, and forecasting." In addition to several other fire weather initiatives, NOAA Research is using funding from the BIL to help fill the fire weather observation gap specifically in complex terrain where weather is more unpredictable.

The influence of local meteorology and air mass source region on aerosol light scattering and absorption measurements at Appalachian State University

Thomas Batalia (Physics and Astronomy, AppalAir/Appalachian State University)

Optical properties of aerosols are dependent on meteorological conditions in source regions, and contribute to meteorological systems like radiative forcing. Lower tropospheric aerosol optical properties have been measured near-continuously at Appalachian State University's AppalAIR facility (APP) since 2009, as part of NOAA Federated Aerosol Network (Sherman et al., 2015). Aerosol light scattering and other aerosol properties related to loading have decreased over this 17 year period, largely due to decreases in regional sulfate aerosol resulting from amendments to the Clean Air Act. However, the inter-annual variability is large, due to meteorological influences and episodic wildfire smoke. The scattering decreases and variability are largest during the summer months, when the APP site is episodically influenced by long distance smoke transport.

This presentation uses multi-wavelength scattering coefficient, absorption coefficient, and particle number concentration measurements from AppalAIR along with local meteorology measurements to examine the meteorological influences on aerosol optical properties at APP over the 2010-2025 period. NOAA HYSPLIT air mass backtrajectories are also used for the summer 2023 to examine the Canadian wildfire influence and for an NSF-funded multi-season field campaign (June 2024-August 2025), which included new measurements of cloud condensation nuclei, particle size distributions, and equivalent black carbon mass concentrations. Overall, the wind dependence of scattering and absorption depends on season. High number concentrations of mostly small particles from new particle formation occur during spring and fall are primarily associated with long distance transport from the northwest, through the Ohio River Valley. While scattering coefficient is mostly influenced by regional sources, absorption coefficient is largely influenced by local traffic, along with occasional wildfire transport.



Acknowledgements:

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Optimizing Ozone Profile Sampling Frequency for Trend Calculations

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This study presents a methodology for optimizing observation strategies for ozone trend analyses by leveraging ozonesonde and model data during periods of high-intensity sampling, such as those occurring during field campaigns. Through random subsampling of data from these intensive periods, we determine the sampling frequency necessary for reliable trend computation as a function of altitude, season, geographic location, and record duration. As the global community compiles tropospheric ozone trends (e.g., the Tropospheric Ozone Assessment Report, TOAR, and follow-on TOAR-2) and continues to monitor the recovery of the stratospheric ozone layer, understanding the frequency of data collection required to compute reliable ozone trends is critical for the design of future operational and field campaign sampling strategies. In particular, this study demonstrates that to yield similar ozone trend uncertainties, the required profile frequency 1) in the tropics is up to a factor of three lower than that in the midlatitudes; 2) in spring and fall at midlatitudes is up to a factor of three greater than in summer, 3) in the troposphere is up to a factor of five greater than in the stratosphere, and 4) model results from MERRA2 appear useful in identifying sampling frequency requirements in places without intensive in situ campaign periods.

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Session P3:
Methane & Trace Species: Sources, Sinks, and Isotopes

First look at the NOAA GML CO flask measurements on the X2025 calibration scale

Gabrielle Petron (Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA)
Co-authors: Andrew Crotwell (CIRES)

The NOAA carbon monoxide (CO) measurement program for tropospheric (and mostly background) air samples was started by Paul Novelli in the late 1980s. The sample collection procedure, early versions of the instrumentation and analytical system and the initial calibration reference scale were described in prior publications [1-5].

In 2003, NOAA became the World Meteorological Central Calibration Laboratory (WMO CCL) for CO. In this role, NOAA GML maintains the WMO CO calibration scale made of sets of primary standards and disseminates it to other laboratories in the form of calibrated whole air standards.

In 2026, the NOAA GML Central Calibration Laboratory revised the CO calibration scale to more accurately correct the CO drift in 2011 (current) primary standards, to improve the assignments of historical primary and secondary standards and to also improve the transparency of the scale prior to 2011.
NOAA discrete air sample CO measurements from 1993 to present are now available on the revised calibration scale, X2025. We will briefly show how the revised scale impacts the CO measurement results and use these revised measurements to reevaluate how the distribution of CO in the global background atmosphere has changed over the past three decades.

Acknowledgements:

This research was supported in part by the NOAA cooperative agreement NA22OAR4320151, for the Cooperative Institute for Earth System Research and DataScience (CIESRDS). The statements, findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the views of NOAA or the U.S. Department of Commerce.

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Investigating the capability of atmospheric δD-CH4 in reducing the uncertainty in the global methane budget

Santanu Halder (NOAA GML)

Methane (CH_4) is a potent greenhouse gas that has been increasing rapidly in the atmosphere since 2007, following a stable period during 2000-2006. It is essential to understand its budget, including changes from both emissions and sinks. The potential sources and sinks are relatively well understood; however, their relative contributions to atmospheric CH_4 remain poorly known. The inverse models that assimilate both atmospheric CH_4 and $\delta^{13}C$ measurements point to a dominant contribution to the rapid increase from microbial emissions. Recent research using box modeling has shown that atmospheric δD (proportional to the D/H ratio of CH_4) has the potential to further improve our understanding of methane sources and sinks. In this presentation, we will further explore the utility of δD using three-dimensional simulations and comparisons with observations between 2011 and 2022.

Atmospheric $\delta^{13}C$ has proven to be a useful tracer in distinguishing between fossil fuel and microbial emissions. On the other hand, the lack of spatio-temporal signatures of CH_4 sources gives rise to considerable uncertainty in the global CH_4 budget. Atmospheric δD reacts with OH differently than $\delta^{13}C$, so atmospheric δD could be helpful to constrain the atmospheric CH_4 sink. Additionally, the ΔD signature of most emissions varies strongly with latitude, providing a different constraint than $\Delta^{13}C$. We will compare globally distributed atmospheric δD measurements to simulations forced by surface fluxes calculated using the CarbonTracker-CH_4 data assimilation system, as well as newly constructed maps of δD source signatures. By construction, the CarbonTracker fluxes (CT2025) already agree relatively well with global observations of CH_4 and $\delta^{13}C$. However, CarbonTracker fluxes are tied to assumed methane loss rates and $\delta^{13}C$ fractionation factors as well as prior spatial distributions of surface fluxes, such as tropical wetland extent. The series of δD simulations and comparisons with observations we will present allow us to test these assumptions against δD observations.

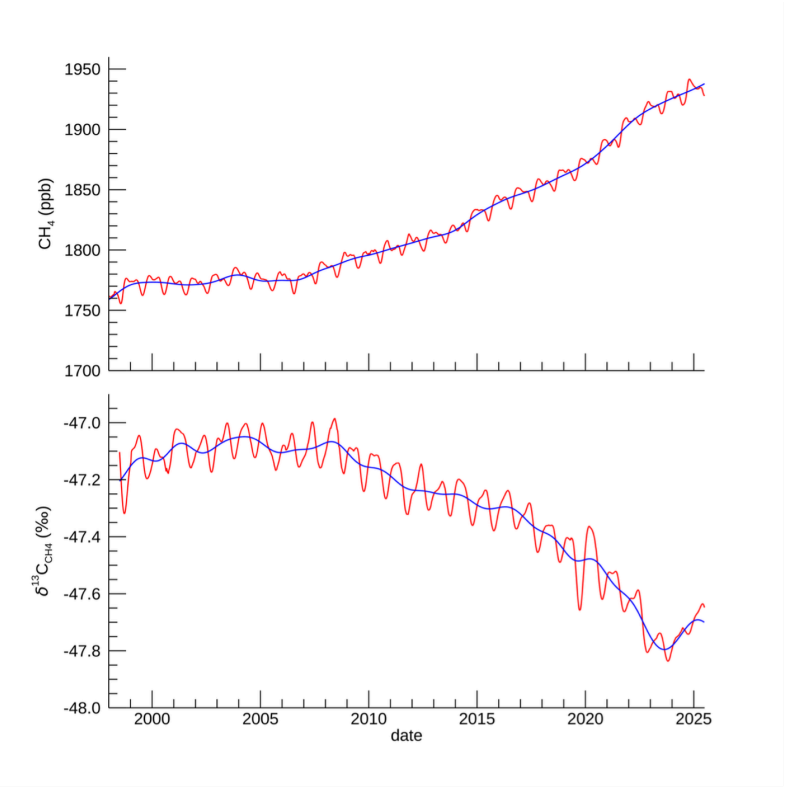
Preliminary results using CT2025 fluxes show that simulated atmospheric δD generally agrees with observations, indicating the overall quality of the CarbonTracker inversion results. However, the CT2025 fluxes overestimate observed δD at Northern Hemisphere sites and are comparable at Southern Hemisphere sites. In contrast, the "Ch4only" scenario, which does not include $\Delta^{13}C$ data constraints, greatly underestimates observed atmospheric δD. "Mic+" and "TropWL+" scenarios, which have enhanced microbial emissions relative to CT2025, show improved agreement with observed δD in the Northern Hemisphere, including reproducing the observed long-term global means and latitudinal gradients of CH_4, $\delta^{13}C$. These δD results suggest a potential avenue for improvement in the standard CarbonTracker fluxes. All simulations show minimum atmospheric δD one month earlier than observations in the Southern Hemisphere; the model also exhibits a smaller seasonal cycle amplitude than observations in the Northern Hemisphere, indicating the possibility that the seasonality of CH_4 sinks in our standard inversions can also be improved. In this study, we will demonstrate the extent to which atmospheric δD can be a potential tracer to refine our present understanding of the global CH_4 budget.

Trend in atmospheric $\delta^{13}C\text{-}CH_4$ suggests methane growth in 2024 and 2025 was driven by increased fire and fossil fuel emissions

Ben Riddell-Young (CIRES, NOAA GML)
Co-authors: John Miller (NOAA - GML)

Understanding the drivers of trends in atmospheric methane (CH_4) is crucial for assessing the effectiveness of mitigation efforts for this potent greenhouse gas. The isotopic composition of CH_4 ($\delta^{13}C\text{-}CH_4$ and $\delta D\text{-}CH_4$) provides a powerful constraint on these trends because major CH_4 sources have distinguishable isotopic signatures and each sink fractionates isotopes differently. The inverse relationship between atmospheric CH_4 growth and declining $\delta^{13}C\text{-}CH_4$ and $\delta D\text{-}CH_4$ over the past two decades has been predominantly driven by increasing emissions from microbial sources: wetlands, agriculture, and waste (Basu et al., 2022; Fujita et al., 2025; Riddell-Young et al., 2025). However, this relationship shifted beginning in 2023, with $\delta^{13}C\text{-}CH_4$ now increasing as CH_4 has continued to rise (see figure). Estimates of $\delta D\text{-}CH_4$ trends over this period remain limited due to sparse observations in 2024 and 2025.

Here, we use a suite of box models to interpret recent trends in atmospheric CH_4, $\delta^{13}C\text{-}CH_4$ and $\delta D\text{-}CH_4$. We find that while the surge in CH_4 growth rate from 2020 to 2022 was driven by increased microbial emissions, consistent with satellite-based inversion studies (Lin et al., 2024; Ciais et al., 2026), the smaller CH_4 increase since 2023 reflects a reduction in microbial emissions relative to 2020–2022 and an increased contribution from isotopically enriched sources: biomass burning and/or fossil fuel emissions. We leverage the simplicity of box models to perform comprehensive uncertainty analyses and evaluate sensitivity to key parameters in the CH_4 budget, including source signatures, sink fractionation and OH variability, to evaluate which post-2022 emissions scenarios are most consistent with observations. Additional $\delta D\text{-}CH_4$ observations in 2024 and 2025 will help further refine the relative contributions of fire and fossil fuel CH_4 emissions to recent CH_4 growth.



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Deuterium measurements of atmospheric methane from the NOAA global flask network and inter-laboratory intercomparisons

John Ortega (INSTAAR, University of Colorado)
Co-authors: Sylvia Michel (U. Colorado Boulder - INSTAAR)

Since 2005, the global surface methane mole fraction has increased from approximately 1760 to 1925 ppb. During this same time period, the hydrogen and carbon stable isotope ratios of methane (δ^2HCH_4 and $\delta^{13}CCH_4$) have decreased at rates of -6.0 ‰ yr^{-1} and -0.7 ‰ yr^{-1} respectively (Riddell-Young, 2025). The combination of the methane mole fraction and its stable isotope ratios provides important information about source and sink processes for this radiatively important trace gas. There is currently a focus on mitigating methane emissions because it has a global warming potential 27-30 times greater than CO_2 over a 100 year timeframe (IPCC 2021), and it is easier to control than CO_2. The INSTAAR Stable Isotope Lab (SIL) at the University of Colorado has maintained a continuous record of $\delta^{13}CCH_4$ measurements from globally distributed surface sites since 1998. Our measurements of δ^2HCH_4 are more limited, due to measurement challenges. However, we have recently dedicated efforts to refining the various steps necessary for this measurement: extracting 20 nanomoles of methane from air followed by chromatographic separation, converting methane into carbon and hydrogen, and performing the isotope ratio analysis. Here we present sample data and quality control metrics from surface sites and calibration cylinders since mid-2024, demonstrating substantial improvements in instrument performance since earlier SIL efforts in past decades. Our system can now reliably measure δ^2HCH_4 using approximately 250 mL of flask air from NOAA Global Greenhouse Gas Reference Network (GGGRN) sites. Part of each measurement set involves analyzing a calibration cylinder using identical treatment to the flask samples. From these measurements, we have calculated a repeatability of ~1.3 ‰ over a 5 month time period. Recent data from GGGRN surface sites are shown below in Figure 1. Consistent delivery of high precision of δ^2HCH_4 measurements will allow us to improve our understanding of methane sources and sinks. We have also sent air from network flasks to collaborators at the Institute for Marine and Atmospheric research Utrecht (IMAU, Netherlands). Starting in 2022, four sites (BRW, MLO, SMO, CGO) were chosen to transfer the remaining air from the glass flasks into FlexFoil bags and then shipped to Utrecht. This initially provided δ^2HCH_4 measurements while the INSTAAR system was being refined. As the INSTAAR δ^2HCH_4 measurements have come online, we have continued to send a subset of these samples for additional comparisons of our δ^2HCH_4 measurements. This poster will assess the comparability of our δ^2HCH_4 measurements between the laboratories.

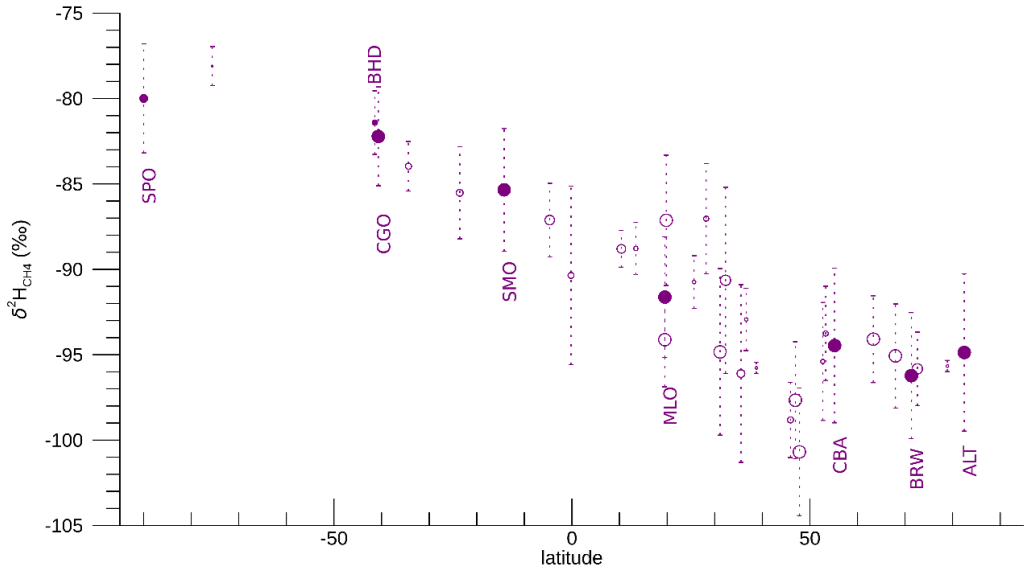

Figure 1: INSTAAR Stable Isotope Lab δ^2HCH_4 results from GGGRN sites sampled during 2024 until early 2026 showing a latitudinal gradient. Sites that are designated for δ^2HCH_4 measurement are indicated by their three letter codes: SPO (South Pole), Baring Head (New Zealand), CGO (Cape Grim, Tasmania), SMO (American Samoa), MLO (Mauna Loa, Hawaii), CBA (Cold Bay, Alaska), BRW (Barrow, Alaska), and ALT (Alert, Canada). Other data shown are from additional network sites used to test the system. Symbol sizes are proportional to the number of measurements.

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Towards Mitigation Scale: Supporting Methane Emissions Management by Connecting Spatial Scales with Satellites

Betsy Farris (Environmental Engineering, University of Colorado Boulder)
Co-authors: Daven Henze (U. Colorado Boulder)

With the increasing availability of satellite instruments capable of measuring methane, we aim to develop tools and methods that integrate open-source satellite data with ground-based measurements to better monitor landfill emissions. The team plans to collaborate with landfill operators to deploy and evaluate both low-cost and advanced ground-based monitoring techniques for measuring methane and volatile organic compounds (VOCs) from landfills. Additionally, we will evaluate our estimates with ground sampling from a former Department of Energy project across two oil and gas basins—the San Joaquin Valley and Denver-Julesburg Basin.

In this initial study, we explore how the TROPOspheric Monitoring Instrument (TROPOMI), with its high precision and daily revisit, can be leveraged in atmospheric inversions to estimate emissions. We use the open-access Integrated Methane Inversion (IMI) tool to assess the feasibility of regional emission estimates across different spatial and temporal scales. Additionally, we investigate how oversampling TROPOMI data can enhance spatial resolution at the cost of reducing temporal resolution, aiding background concentration estimation, as well as seasonal and long-term trend analysis. Finally, we evaluate the role of plume mapping instruments in resolving emissions from individual landfills and other interfering sources. The findings from this study will inform best practices for using open-source satellite data in supporting landfill management and improving the integration of satellite and ground-based sensing for more effective emissions monitoring and mitigation. In future work, we will look beyond landfill management to apply our methods to other sectors.

Application of oxidation flow reactors to methane: understanding isotopic effects during atmospheric oxidation and potential for mitigating dilute emissions

Jianghanyang Li (INSTAAR, University of Colorado Boulder)

Atmospheric concentrations of methane (CH_4) have been increasing rapidly since 2007, primarily driven by increased microbial emissions. Uncertainties in the global CH_4 budget due to poorly constrained isotopic effects of its atmospheric oxidation, together with the lack of effective mitigation technologies for dilute emission sources, remain significant challenges. In this work, we investigate CH_4 oxidation chemistry in an oxidation flow reactor (OFR) using a combination of laboratory experiments and detailed radical chemistry modeling. Our work shows that OFRs equipped with low-pressure mercury lamps can sustain OH concentrations several orders of magnitude higher than ambient levels using only water vapor, oxygen, and UV radiation. This reduces CH_4 lifetimes from years to minutes or hours. Across a wide range of CH_4 concentrations, humidity levels, and temperatures, CH_4 oxidation in the OFR is dominated by OH, with negligible contributions from non-OH pathways. We then evaluate the feasibility and energy efficiency of adapting OFRs for mitigating dilute CH_4 emissions. While existing small-radius OFRs exhibit poor energy efficiency, our modeling demonstrates that increasing reactor radius and improving 185 nm radiant efficiency can enhance overall energy efficiency by more than an order of magnitude. OFRs with radii of 60-120 cm can achieve energy efficiencies comparable to state-of-the-art photochemical mitigation technologies at CH_4 concentrations between 100 and 1000 ppm, a regime that represents a substantial fraction of global anthropogenic methane emissions. Together, these results establish OFRs as an excellent platform for fundamental studies on isotopic effects of methane oxidation and highlight their potential for mitigating methane emission hotspots from dilute sources.

Global monitoring capabilities with NDACC HR-FTIR: from retrieval optimization to model evaluation and extreme events

Ivan Ortega (Atmospheric Chemistry Observations & Modeling, NCAR)
Co-authors: James Hannigan (NCAR)

High-resolution Fourier Transform Infrared (HR-FTIR) solar absorption observations within the Network for the Detection of Atmospheric Composition Change (NDACC) provide long-term ground-based records of atmospheric composition, spanning multiple decades and a broad range of tropospheric and stratospheric trace gases, enabling global-scale assessments of trace gas trends, model performance, and satellite validation. Here we present an overview of capabilities currently being developed and applied at NCAR using NDACC FTIR measurements, illustrated through three complementary projects:

(1) we present advances in retrieval strategies for methane (CH_4), including sensitivity to spectroscopy databases and inversion methods. Validation with independent AirCore and aircraft profiles demonstrates robust performance in both total and partial columns, and these optimized products are used to evaluate CAM-Chem simulations, improving constraints on tropospheric and stratospheric processes (chemistry) and emission scenarios.

(2) we present long-term carbonyl sulfide (OCS) trends derived from a global NDACC FTIR network retrieval framework spanning 1986–2025. The results reveal vertically resolved, non-monotonic behavior, including a pronounced shift toward negative growth rates after ~2016, followed by a renewed increase beginning in 2024. Stratospheric variability is interpreted using N_2O as a dynamical tracer, providing improved constraints on the global sulfur budget.

(3) we demonstrate the network's capability to characterize tropospheric composition changes associated with wildfire activity using multi-species FTIR observations (CO, HCN, H_2CO, NH_3, C_2H_2, C_2H_6, and CH_4). These long-term records capture both baseline variability and extreme enhancements, and comparisons with CAM-Chem highlight strengths and limitations in representing fire emissions, transport, and impacts on atmospheric oxidation.

Together, these three projects highlight NDACC FTIR as a powerful capability being developed at NCAR for long-term, vertically resolved monitoring of atmospheric composition, supporting improved model evaluation, trend analysis, and attribution of both gradual changes and extreme events.

Session P4:
Atmospheric Dynamics, Clouds, and Radiation

A Machine Learning Derived Integrated Dataset of SURFRAD Radiation, Cloud, and Boundary Layer Height Observations for Land-Atmosphere-Cloud Interactions

Vanessa Caicedo (GML)
Co-authors: Joseph Sedlar (CIRES)

Accurate estimation of boundary layer height (BLH) remains challenging due to inconsistencies among thermodynamic, turbulence, and aerosol-based retrieval methods, as well as differing definitions of BLH. To address these limitations, we developed a machine learning-based framework that leverages integrated surface radiation, cloud, and meteorological observations from the NOAA Surface Radiation (SURFRAD) Network. A Random Forest (RF) model is trained to estimate BLH based on thermodynamic BLHs derived from radiosondes. The model incorporates key predictors including lifting condensation level height, aerosol gradients, surface energy flux proxies, and seasonal variability. By integrating radiative, surface meteorological, and aerosol-based signals, the thermodynamically trained RF model bridges gaps between traditional and aerosol-based retrieval methods.

Using long-term SURFRAD observations combined with newly developed machine learning-derived BLH and cloud classification products, we create a value-added dataset linking boundary layer structure with cloud-radiation interactions across diverse climate regimes. This dataset provides a new pathway for examining land-atmosphere-cloud coupling, enabling characterization of relationships among boundary layer evolution, cloud regimes, and surface radiation. It also supports evaluation and improvement of boundary layer representation in weather and climate models, with important implications for atmospheric composition, surface emissions, and the development of convection, clouds, and precipitation.

Cloud-driven stochastic variability sustains radiative bimodality in the Arctic winter: insights from long-term Arctic observations

Jung-Sub Lim (CIRES, University of Colorado / NOAA CSL)
Co-authors: Graham Feingold (NOAA - CSL)

Wintertime Arctic surface longwave radiation exhibits two preferred states, a cold, clear regime and a heat-trapping opaque-cloud regime. The occupancy within these two states strongly regulates the surface energy balance, with important implications for sea-ice loss and Arctic climate. The dynamical origin of this bimodality is unclear, and reanalysis products such as ERA5 and climate models tend to collapse toward a single intermediate state. By applying a stochastic differential equation framework to 27 years of high-temporal-resolution observations from Utqiaġvik, with independent support from additional Arctic records including MOSAiC and Ny-Ålesund, we decompose net longwave flux variability into a mean restoring tendency (drift) and state-dependent fast variability (diffusion). We show that a pronounced enhancement of sub-hourly cloud-driven variability in the transition range reshapes the single-well drift potential, thereby creating the two regimes. This variability peak arises from nonlinear coupling between fluctuations in cloud liquid water path and longwave emissivity saturation, and is confined to winter, when shortwave forcing is absent and thin mixed-phase clouds dominate the cloudy state. ERA5 represents the mean restoring tendency well but strongly underestimates this state-dependent variability, consistent with its unimodal bias. Across six CMIP6 models, intermodel differences in bimodality are more strongly associated with differences in fast cloud variability than with differences in mean-state drift. These results identify unresolved state-dependent cloud variability as a key ingredient of Arctic winter radiative bistability and provide a concrete observational target for evaluating and improving high-latitude cloud and radiation representations in Earth system models.

INITIAL CHARACTERIZATION OF CLOUD CONDENSATION NUCLEI ACTIVITY IN THE SOUTHEASTERN UNITED STATES

Ben Sykes (Physics and Astronomy, Appalachian State University)
Co-authors: James Sherman (Appalachian State U.)

Within global climate forcing projections, aerosol-cloud interactions (ACI) remain a major source of uncertainty, with key contributions arising from uncertainties in aerosol activation as cloud condensation nuclei (CCN). Regional characterization of CCN activity would facilitate further research into processes dictating ACI, but long-term studies remain limited and are especially scarce in the southeastern United States (SE US). This area is of particular interest, as local aerosols have likely contributed to a lack of regional warming over the past century. Improving our understanding of aerosol properties and CCN behavior in this region will be important for refining climate modelling across all scales.

To address this gap, we investigate how aerosol size distributions, chemical composition, and meteorological parameters influence CCN activity. Using a TSI Scanning Mobility Particle Sizer (SMPS) in tandem with a DMT Cloud Condensation Nuclei Counter, we can directly relate particle size distribution to CCN spectra. Consistent with Köhler theory, preliminary results highlight a positive correlation between particle size and CCN activity, as periods with a predominance of larger particles contained a higher fraction of aerosols able to act as CCN.

Chemical composition, through its influence on hygroscopicity, further modulates an aerosol's ability to act as CCN. Initial observations indicate that a higher organic fraction of aerosols weakens the relationships between size distributions and CCN spectra. To better understand these effects, measurements from an Aerodyne ToF Aerosol Chemical Speciation Monitor, combined with regional data from the U.S. EPA Air Quality System, will be used to further characterize CCN activity as a function of aerosol chemistry.

Ongoing work integrates these measurements with meteorological conditions, seasonal variability, and regional events to develop a comprehensive framework for CCN characterization. Utilizing the available instruments at the Appalachian Aerosol Interdisciplinary Research (AppalAIR) sites, this study aims to generate a regionally representative data set to improve our understanding of how aerosol variation governs CCN activity in the SE United states.

Acknowledgements:

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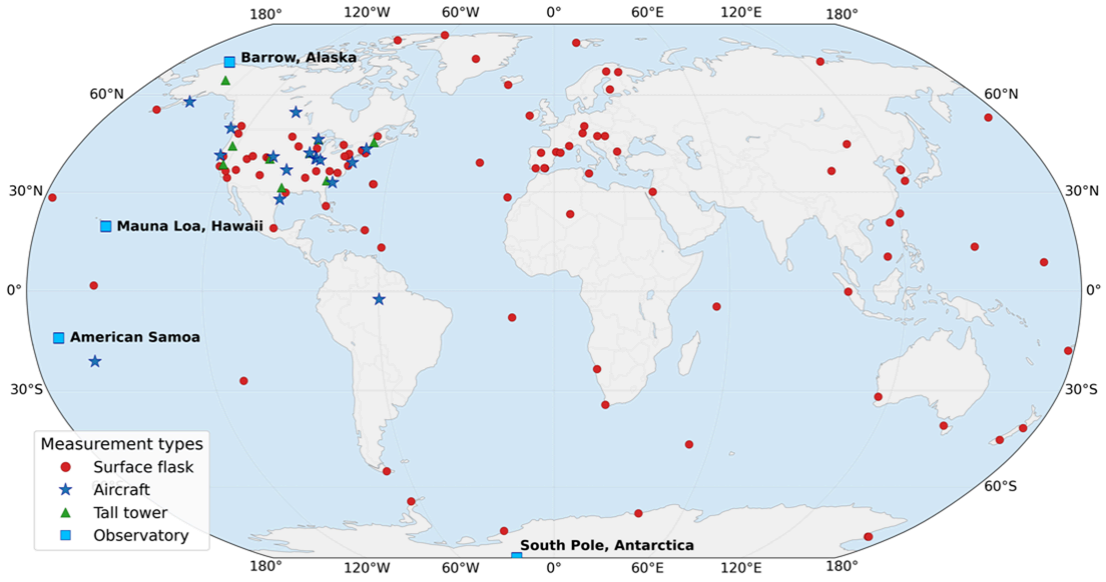
Session P5:
Integrated Networks: Satellites, Aircraft, and Scale-Bridging

NOAA GML's Greenhouse Gas Reference Network Management, Logistics, and Importance

Eric Moglia (GML, NOAA/CIRES)

Beginning in 1967, the NOAA's Greenhouse Gas Reference Network (Figure 1) has provided spatially and temporally consistent data for use by scientists, modelers, and organizations around the world. The network focuses on the collection and analysis of background air samples for CO_2, CH_4, N_2O, SF_6, CO, isotopes of CO_2 and CH_4, and halo- and hydro-carbons. Air samples are collected in 2.5 L glass flasks at surface sites and in 0.7 L glass flasks contained in Programmable Flask Packages (PFP) at aircraft and tall tower network locations.

This extensive global network requires meticulous group oversight including daily preparation and logistical planning, equipment management, quality control, ongoing international communication, and extensive data management. The majority of these daily operations occur in the Flask Logistics Lab. It is here that equipment is prepared for the field and where 12,000 – 15,000 yearly flask-air samples are received, cataloged, and routed to various analysis laboratories. This presentation will discuss the importance of the network, daily management operations, and logistics.



Quantifying the effects of long-term storage on measurements of carbon dioxide from air samples in flasks

Joshua Mauss (OBOP, NOAA GML/CIRES)
Co-authors: Brittany Verbeke (CIRES)

Collecting samples of air in glass flasks forms the backbone of NOAA GML's Global Greenhouse Gas Reference Network (GGGRN). The operational complexities of collecting flask samples from over 80 sites across the world means that some samples will remain in storage for extended periods of time before measurement. For example, samples collected from the South Pole, one of NOAA's Atmospheric Baseline Observatories, can be stored for up to a year before analysis. To quantify the drift in major greenhouse gases over storage periods, flasks were filled with calibrated tank air and measured at a series of intervals consistent with common storage times from sites across the GGGRN. These measurements were compared to control flasks measured immediately and the tank calibrations to quantify a drift rate for CO_2, with plans to quantify the drift rate of CH_4, CO, H_2, N_2O, and SF_6 in the future. Preliminary results show that flasks in Programmable Flask Packages (PFPs), which are used at aircraft and tower sites, leak CO_2 at a rate of up to .009 ppm/day, likely through diffusion across PTFE O-rings. Samples in flasks collected by the Portable Sampling Units (PSUs), which are used at surface sites, do not exhibit this noticeable leak rate on storage timescales under six months. By quantifying a drift rate in storage, these tests aim to provide a correction factor for measurements made on GGGRN flasks so that more accurate greenhouse gas data can be measured regardless of the operational challenges that confront operating the GGGRN.

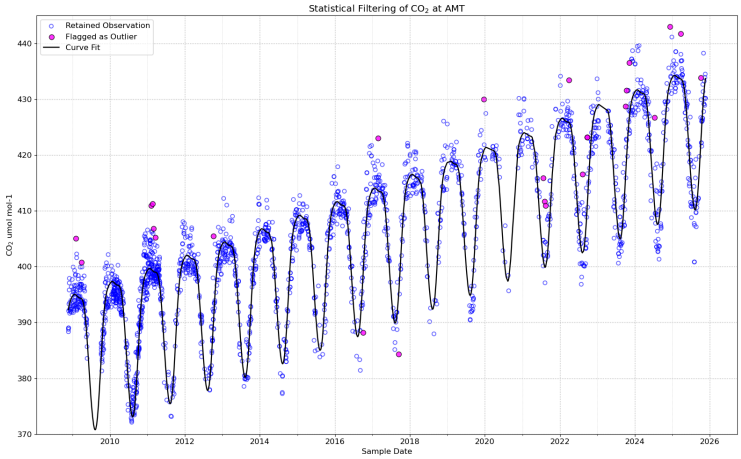
Statistical Flagging of Longterm Records of Multiple Gases from Flask Samples Collected at Continental Tall Tower Sites

Emily Kaiser (Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder)
Co-authors: Kathryn McKain (NOAA - GML)

The NOAA Global Monitoring Laboratory (GML) has conducted in situ measurements and discrete air sampling at a network of continental tall towers since the 1990s. Discrete samples are collected automatically using Programmable Flask Packages (PFPs), typically at the same time every day or every few days. The towers reach heights of up to 500 m and are located at elevations ranging from 2.0 to 4200 masl, with daytime sampling within the continental boundary layer. Samples are analyzed in the GML Boulder laboratories for over 50 gases, including long-lived greenhouse gases, ozone depleting substances, and other important trace gases. They are intended to provide regionally representative (O(103) km) measurements of the lower atmosphere composition across North America, including in areas influenced by both natural processes and anthropogenic activities in the continental interior and on both the Atlantic and Pacific coasts.

This poster describes a statistical filtering approach for multi-gas PFP flask data, specifically for measurements of CO_2, CH_4, CO, N_2O, SF_6, and H_2, at 20 tower sites. The primary goal of the filtering method is to accurately identify and flag outlier mole fractions, likely related to local flux processes, while preserving signals representative of regional-scale processes, prior to data release. We describe how this filtering procedure detects anomalous data points and characterizes patterns and typical behavior across the network.

The statistical filtering method expands on the NOAA GML curve fitting/smoothing procedure introduced by Thoning et al. (1989) and relies on fitting time series curves for each gas at every site. Outliers are identified using a threshold for residuals relative to the fitted curve. For sites with inconsistent records or significant sampling gaps, the standard curve-fitting approach is modified to use the fitted function directly in place of a smoothed curve. When applying this method to the tall tower PFP dataset, over the full record up to the present, approximately 2–4% of observations are flagged as outliers. We will present examples of filtered and unfiltered datasets, including preliminary results in which outlier identification for a single gas is based on outliers for other gases. Overall, statistical filtering allows for a consistent, documented, and reproducible approach to the identification of outliers in continental data time series.



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Sensor Life Cycle Management for Traceable Measurements in National Ecological Observatory Network (NEON)

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Sustaining scientifically defensible ecological observations at national scales requires more than extensive infrastructure—it demands intentional alignment between scientific questions, measurement strategies, and long-term data stewardship. The National Ecological Observatory Network (NEON) was designed to address continental-scale ecological change over decades, relying on thousands of in-situ sensors deployed across diverse environments to quantify atmospheric, terrestrial, and aquatic processes.

In this work, we describe how explicitly defined science requirements serve as the organizing principle for NEON's sensor selection, calibration, and life cycle management. Rather than treating instruments as interchangeable components, we frame sensor choice as a scientific decision driven by intended data use, uncertainty tolerance, and analytical scale. This approach enables effective integration of both lower-cost sensors and high-precision instruments, ensuring each is deployed where it provides meaningful scientific value.

Science-driven requirements also establish expectations for traceability and uncertainty, shaping NEON's comprehensive quality assurance framework. Central to this framework is an in-house Calibration and Validation Laboratory that anchors measurements to nationally and internationally accepted standards. Complementary strategies—such as full uncertainty propagation, interlaboratory comparisons with federal partners, systematic evaluation of emerging technologies, and assessment of sensor drift—support consistency across space, time, and evolving hardware.

Through practical examples, we demonstrate how these processes have informed sensor population management, guided responses to obsolescence, and strengthened confidence in long-term data products. We conclude with lessons learned from operating a large, heterogeneous sensor network at scale, emphasizing how grounding technical decisions in core scientific questions enables NEON to deliver measurements that remain reliable, comparable, and scientifically relevant across generations of ecological research.

CAO Tower Meteorological Deployment and Opportunities

Sara Morris (GML, NOAA)
Co-authors: Philip Handley (CIRES) and Jon Kofler (CIRES)

On January 15, staff from the Global Monitoring Laboratory's (GML) Observatory and Global Network Operations division completed installation of meteorological (MET) instruments at the lab's Colorado Atmospheric Observatory (CAO) tower in Byers, CO. The team installed the tower-MET system at three heights—30m, 100m, and 508m. The instruments will measure temperature, relative humidity, wind speed, and wind direction. Despite setbacks, shifting priorities, and budget challenges, the team persevered, confirming the structural integrity of the booms and aligning measurements and data collection methods. This work supports the long-term vision for GML's tower network.

GML operates several measurement programs: Semi-continuous measurements are made at four baseline observatories, 57 surface sites, 14 aircraft sites, and 14 tower sites. Starting in the 1990s, GML began taking measurements from TV, radio, and cell phone towers (ranging from 100 to 600 meters) to expand the lab's long-term monitoring of carbon cycle gases over continental areas. At these tower sites, GML makes continuous, regionally representative measurements of carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4). These air samples are shipped back to the Boulder, Colorado, laboratory for analysis of CO_2 and more than 50 other gases. In 2024, GML began updating its aging field measurement equipment, by deploying single high-precision analyzers that integrate measurements of CO_2, CH_4, and CO into a single instrument. This initiative represents the initial phase of a multi-year plan aimed at ultimately upgrading to a new trace gas measurement system, designated as "NextGen." The Colorado Atmospheric Observatory tower was added to the network in 2024 and serves as the first fully NextGen testbed site.

Next steps include facilitating collaborations with the NOAA Office of Marine and Aviation Operations (OMAO) and other stakeholders to utilize the site and its measurements as a cal/val testbed for drone and fixed wing copter comparisons.

Photo Credit: Jonathan Kofler

NOAA's Mauna Loa Atmospheric Baseline Observatory – Site Status and Redevelopment Project Updates

Christine Smith (NOAA Global Monitoring Laboratory)
Co-authors: Brian Vasel (NOAA - GML)

NOAA's Mauna Loa Atmospheric Baseline Observatory (MLO), often regarded as the "premier atmospheric science site on earth", is located at 11,141 ft altitude on the north slope of the Mauna Loa Volcano on Hawaii's Big Island. The site is home to numerous high-profile climate data sets including the "Keeling Curve" that first documented the rise in carbon dioxide in our global atmosphere by the Scripps Institution of Oceanography (SIO). The free tropospheric air, remote location, and minimal influences of vegetation and human activity at MLO are ideal for monitoring constituents in the atmosphere that cause climate change.

In November 2022, the Mauna Loa Volcano erupted and lava flowed over the access road and destroyed power lines servicing MLO. In partnership with the University of Hawai'i (UH), GML was able to quickly facilitate an emergency agreement to allow NOAA to set up their collection of CO_2 and flask sampling at the UH facility on Mauna Kea. NOAA added solar panels and battery backup to several MLO buildings, allowing roughly one third of MLO's instruments to operate without grid power. Minimal site access was facilitated by weekly to bi-weekly helicopter flights. The MLO Access Road was re-established in March 2026, allowing regular site access to continue.

NOAA is beginning an extended period of site redevelopment for the MLO campus, which includes replacing numerous small, aging research facilities within its 8-acre property. Starting in spring 2026, the first phases of the project will begin with replacing the existing tower, constructing a new small building at the base of the tower to house clean air science, upgrading the interior and exterior of the Keeling Building, replacing a number of smaller buildings and reworking the site's power and grounding infrastructure. These upgrades are part of a multi-phased master plan to streamline MLO's facilities, making MLO a more effective and efficient research campus to house NOAA and partner scientific research for decades to come.

Deploying and Testing a Next Generation In-Situ Measurement System at NOAA's South Pole Atmospheric Baseline Observatory

Janelle Hakala (GML/OBOP, CIRES/NOAA)
Co-authors: Philip Handley (CIRES)

Continuous, in-situ measurements of carbon dioxide (CO_2) have been taken at the South Pole Observatory (SPO) since 1975, currently utilizing a LI-COR 6262 NDIR gas analyzer. In 2023, the Global Monitoring Laboratory (GML) began developing "NextGen"—a new in-situ measurement platform designed for standardized deployment across all NOAA observatories and tall towers. During the summer of 2025, a NextGen system centered on a four-species Picarro gas analyzer was assembled for deployment at the South Pole. This system replaces the legacy LI-6262 NDIR, expanding the site's capabilities to include continuous methane (CH_4) and carbon monoxide (CO) monitoring alongside CO_2. Following its arrival and installation at the NOAA Atmospheric Research Observatory (ARO) between November 2025 and February 2026, the NextGen system is currently running in parallel with the LI-COR system for inter-comparison and validation. This poster describes the NextGen architecture and presents early measurement results and side-by-side performance comparisons as the timeline for transitioning to NextGen as the official SPO record is determined.

Southern Hemisphere Additional Ozonesondes (SHADOZ) Network Updates and Tropospheric Ozone Trends for the TOAR-II Activity

Debra Kollonige (ADNET Systems, Inc. / NASA GSFC)
Co-authors: Anne Thompson (UMBC - GESTAR II)

The Southern Hemisphere Additional Ozonesondes (SHADOZ) network provides high-quality, long-term tropical ozonesonde-radiosonde data to establish accurate climatologies, evaluate satellite and model products, and assess long-term tropospheric and stratospheric trends for the scientific community. Its core focus is maintaining reliable, consistent ozone profile data from 16 operating sounding stations in the tropics and subtropics. The SHADOZ network, jointly operated by NASA-Goddard Space Flight Center (GSFC), NOAA's Global Monitoring Lab (GML) and international partners, now has over 11,000 ozone and pressure-temperature-humidity (P-T-U) profiles with 100m vertical resolution at the SHADOZ archive (https://tropo.gsfc.nasa.gov/shadoz/Archive.html) with data from 1998-2026. The focus of this presentation is an update on the SHADOZ Project and Data Archive activities including: (1) the recent release of historical ozonesonde data from 2 new SHADOZ stations, Palau and Quito (Ecuador), with ~10 years of ozonesonde launches on the archive, (2) the success of hosting virtual regional SHADOZ station meet-ups in 2026, organized by the NASA-GSFC team, to foster improved communication with station Principal Investigators and staff, (3) the improvement of data findability and access through DOIs and new data formats, and (4) the results from the newly published 25-year tropospheric ozone trends from the SHADOZ network (Thompson et al., 2025; Van Malderen, et al., 2025), important for evaluation of model and satellite products as a part of the International Global Atmospheric Chemistry (IGAC) Project Tropospheric Ozone Assessment Report (TOAR-II) Activity. This presentation summarizes our successes in maintaining continuity of long-term global ozonesonde records in the tropics and subtropics and ensuring that the best quality ozone data reach end users.

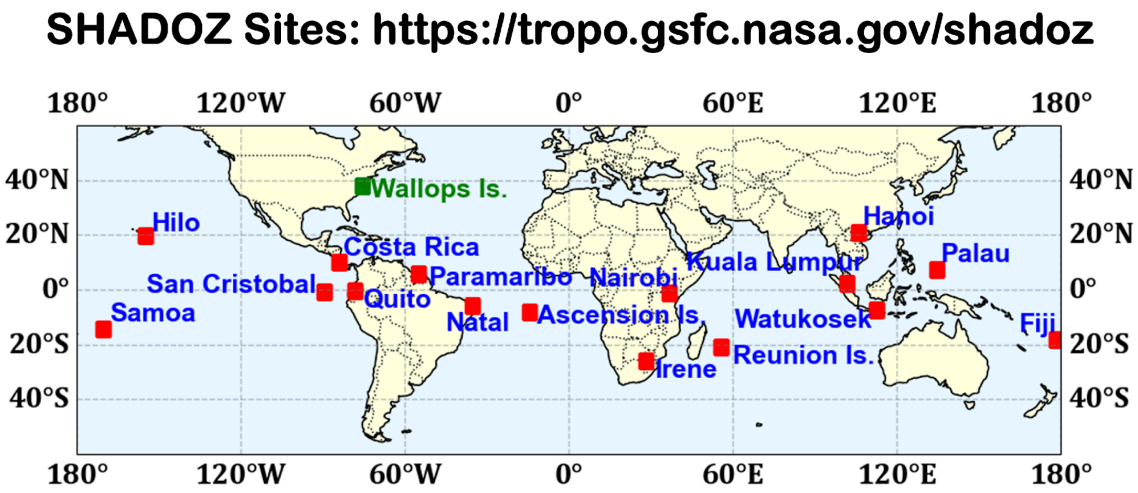

Figure caption: Map of 16 SHADOZ ozonesonde stations across the tropics and subtropics (red squares) and the Wallops Island, VA station (green square; also managed by the NASA GSFC team). All SHADOZ datasets are accessible at: https://tropo.gsfc.nasa.gov/shadoz/Archive.html. The Wallops Island data is available at: https://tropo.gsfc.nasa.gov/shadoz/Wallops.html.

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Design and Implementation of a Relational SQL Database for Ozone and Water Vapor Measurements

Peter Effertz (NOAA GML, Cooperative Institute for Research in Environmental Science)
Co-authors: Alex Fritz (CIRES) and Elizabeth Asher (CIRES)

NOAA GML's long-term atmospheric ozone and water vapor records are critical for understanding Earth's radiative balance and the impact on human health and the economy. The Ozone and Water Vapor Division (OZWV) high-quality observational data records include balloon-borne Frost-Point Hygrometer and ozonesonde instruments, ground-based Dobson spectrophotometers, and surface UV photometers. Historically, these multi-decadal datasets have been stored in disparate, heterogeneous formats (such as netCDF and legacy ASCII files) across isolated file directories. This decentralized approach poses significant challenges for cross-platform data integration and for the domestic and international collaboration required for long-term climate trend assessments. To address these critical data management bottlenecks, we present the design, implementation, and deployment of a robust, centralized relational database tailored specifically for OZWV's unique data needs. Utilizing the GML MySQL data server, we developed a normalized schema optimized for multidimensional atmospheric profiles and surface measurements. We will explore the use of tables for essential metadata, data versioning, data quality flags, flight logs, and instrument histories. Plans for data pipelines and APIs written in Python to import historic datasets and future datasets in near-real time will be detailed. The transition to a SQL-based infrastructure will fundamentally transform the group's analytical workflows. Complex queries spanning multiple decades, various instruments, and/or specific monitoring sites that previously required computationally expensive, time-consuming file-parsing scripts can now be executed in seconds. By including the OZWV records in the GML SQL database, we hope to accelerate our understanding of the changing atmosphere by reducing the time and cost associated with data ingestion. We hope to empower both GML scientists and our external data users to find and access our data, a key step toward making our data FAIR (findable, accessible, interoperable, and reusable).

Global Calibration Activities of the Dobson Network Based on the World Primary Standard Spectrophotometer D083

Glen McConville (DEPT. OF COMMERCE NOAAESRL)

This presentation provides an overview of the current status of the global calibration activities for Dobson spectrophotometers. To maintain the long-term quality and consistency of the Dobson total ozone observation network, the World Dobson Calibration Center conducts regular intercomparisons using the reference instrument D083. We report on recent calibration activities, including the calibrations performed and the long-term stability of the reference instrument D083.

The primary calibration sites are the Mauna Loa Observatory (MLO), USA, and the Izaña Observatory, Spain, which serve as key locations for maintaining traceability of Dobson measurements worldwide. Recent calibration activities carried out in Japan are presented, together with earlier calibration campaigns conducted in Australia.

In addition, results of comparisons between Dobson and Brewer spectrophotometers at the Izaña Observatory are reported, providing further insight into the consistency between the two independent ground-based ozone observing systems.

Future calibration campaigns planned for Argentina and Africa will also be discussed. These activities contribute to sustaining and strengthening the global Dobson observation network and ensuring the long-term consistency of total ozone measurements.

Ground-based validation of the operational satellite ozone products: an assessment of ozone recovery and processes impacting its short-term variability

Irina Petropavlovskikh (CIRES)
Co-authors: Brandon Noirot (CIRES)

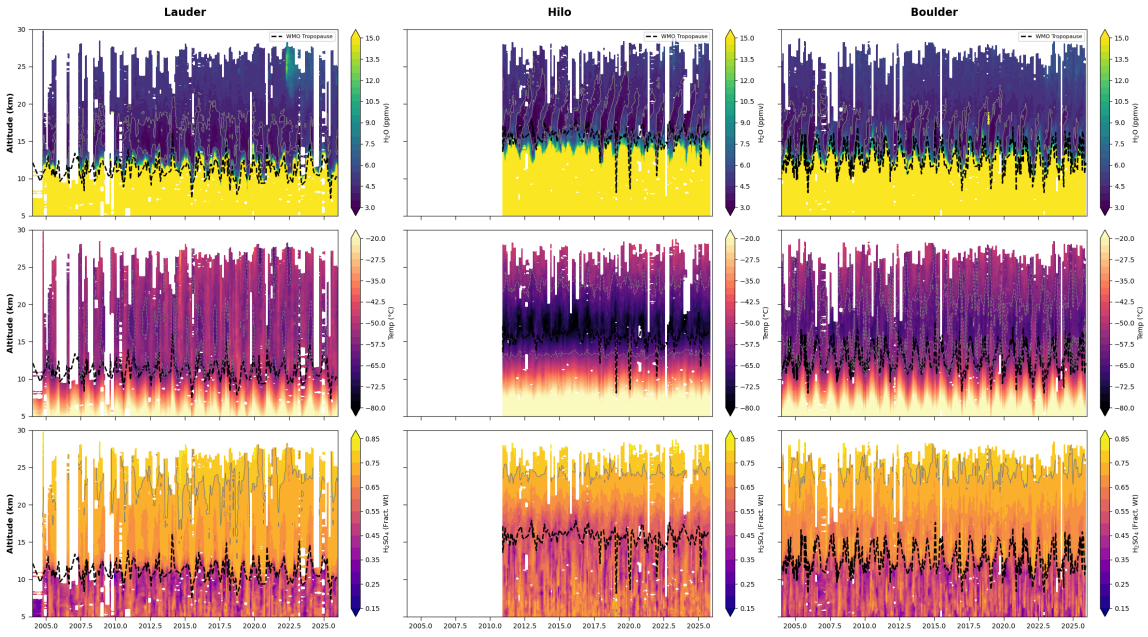
Over the last 40 years, NOAA and collaborators (i.e. at U. of Colorado and internationally) continuously collected, calibrated, and quality-assured ground-based (GB) and in situ ozone vertical profile observations in support of the Montreal Protocol and international agreements to track stratospheric ozone recovery. These datasets provide a reference for the operational products collected by the Ozone Mapping and Profiler Suite (OMPS) instruments flying on Suomi NPP, NOAA-20, and NOAA-21 satellites as part of the Joint Polar Satellite Systems (JPSS) for tracking daily changes in atmosphere, oceans and land. The NOAA OMPS instrument operationally produces ozone profiles and ozone column that extend the long-time record of NOAA SBUV observations, with data available daily and globally. The NOAA GML ground-based observations are used to assure the stability of ozone satellite records and in support of the combined long-term global satellite records (i.e. COHesive ozone record) which are important for climate research and predictability of the future Earth. This presentation provides an overview of the OMPS ozone profile retrieval evaluation using the NOAA ground-based ozonesonde and Dobson measurements as the reference for 2022-2025 period of study when observations from all three satellite observational platforms are available. The ultimate goal is to assess the long-term stability of NOAA-supported satellite records for contributing to the detection of stratospheric ozone recovery and its interannual variability.

Improving Sulfuric Acid Percent Weight A Priori Assumptions for Satellite Retrievals: Insights from Boulder, Hilo, and Lauder NOAA FPH Records

Elizabeth Asher (University of Colorado)
Co-authors: Emrys Hall (NOAA - GML)

Global satellites monitor aerosol optical properties and are used to interpret changes in stratospheric aerosol loading. NASA satellite retrievals for the Ozone Mapping and Profiler Suite-Limb Profiler (OMPS-LP) and the Stratospheric Aerosol and Gas Experiment III onboard the International Space Station (SAGE III-ISS) assume a constant a priori sulfuric acid (H_2SO_4) weight fraction (0.75 H_2SO_4/0.25 H_2O) to derive aerosol extinction (OMPS-LP) and particle size distribution parameters (SAGE III-ISS). However, the thermodynamic equilibrium of H_2SO_4/ H_2O aerosols depends on ambient temperature and the partial pressure of water vapor.

Here, we use long-term Global Ozone and Water vapor (GlO_3W) records from NOAA frost point hygrometer (FPH) and radiosonde soundings over Boulder (CO), Lauder (NZ), and Hilo (HI) to explicitly calculate the ambient H_2SO_4 weight fraction in the stratosphere. Our analysis reveals considerable seasonal and potentially latitudinal variability that deviates considerably from the 0.75 assumption. We explore the sensitivity of satellite products to these changes in particle composition and investigate the primary thermodynamic drivers responsible for the variability in H_2SO_4 weight fraction. These results have implications for improving satellite retrievals as well as the agreement between different satellites and the agreement between satellites and calculated extinction from in situ (balloon-borne or aircraft) measurements of aerosol number and size.



Acknowledgements:

We would like to acknowledge our colleagues in Lauder, NZ, Panny Smale, Richard Querel, as well as our colleagues in Hilo, HI, Matthew Martinsen, David Nardini, and Darryl Kuniyuki for their assistance with NOAA FPH soundings at these sites.

An Improved Analyzer for High-Precision and Low-Drift N_2O, CO, $^{13}CO_2$ Ambient Monitoring

Alexis Badder (Picarro)
Co-author Joyeeta Bhattacharya (Picarro)

Recognized by their critical contributions to greenhouse gas emissions, N_2O and CO have recently risen to the focus for ambient monitoring, where high precision and low drift specifications are both essentially desired to ensure data integrity for long term measurements. In response to the growing needs of the monitoring community, Picarro has launched a new N_2O/CO analyzer – PI5310 that integrates our renowned mid-infrared laser-based cavity ring-down spectrometry (CRDS) technology with significant software and hardware enhancements, as well as sought-after new features to better serve the remote monitoring use cases. Alongside N_2O/CO, this analyzer also has an improved $^{13}CO_2$ data channel which supports clear isotopic discrimination of CO_2 sources and pathways, helping to separate background atmospheric CO_2 from fluxes driven by biological or combustion processes (when used in conjunction with Picarro's near IR greenhouse gas analyzer like G2401 or G2301). This improved PI5310 analyzer will continue to provide simultaneous real-time sub-ppb measurements of ambient N_2O, CO, and $^{13}CO_2$ with much improved precision and drift performance that exceeds the specification requirements of the Integrated Carbon Observation System (ICOS), which will be reviewed in detail in this paper. Additionally, to further explore the measurement capability and comprehensively utilize the potential of its spectroscopy in which the $^{13}CO_2$ is well captured, the PI5310 analyzer was set up alongside the CO_2 and CH_4 measurements by a Picarro G2401 analyzer to characterize its performance in $^{13}CO_2$ measurements in comparison with a Picarro iso-carbon analyzer G2201-i. The experimental set up and preliminary evaluation results are also summarized and discussed in this paper.