GLOBAL MONITORING DIVISION

2018-2022 Research Plan

Taking the pulse of the planet

EARTH SYSTEM RESEARCH LABORATORY
Global Monitoring Division

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Earth System Research Laboratory
Global Monitoring Division
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Global Monitoring Division Research Plan: 2018 – 2022

GMD VISION

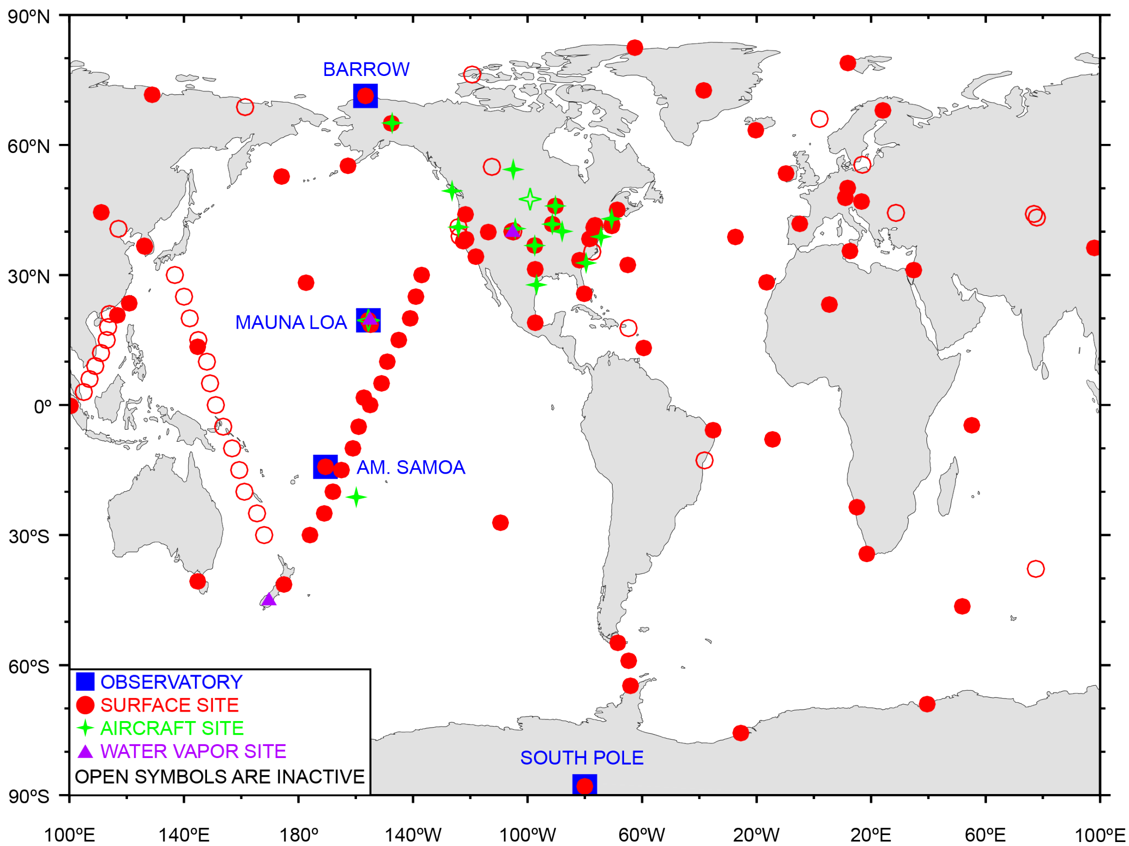
Society using the best possible information to inform decisions on climate change, weather variability, carbon cycle feedbacks, and ozone depletion

GMD MISSION

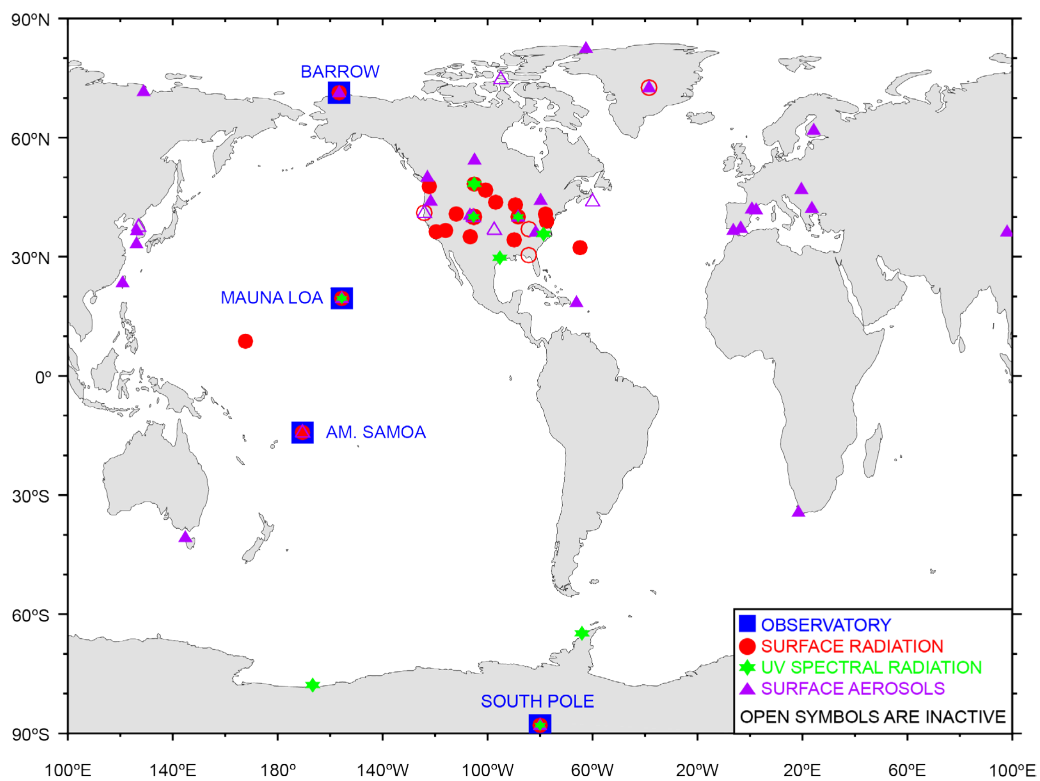
To acquire, evaluate, and make available accurate, long-term records of atmospheric gases, aerosol particles, clouds, and surface radiation in a manner that allows the causes and consequences of change to be understood

Global Monitoring Division Observational Networks

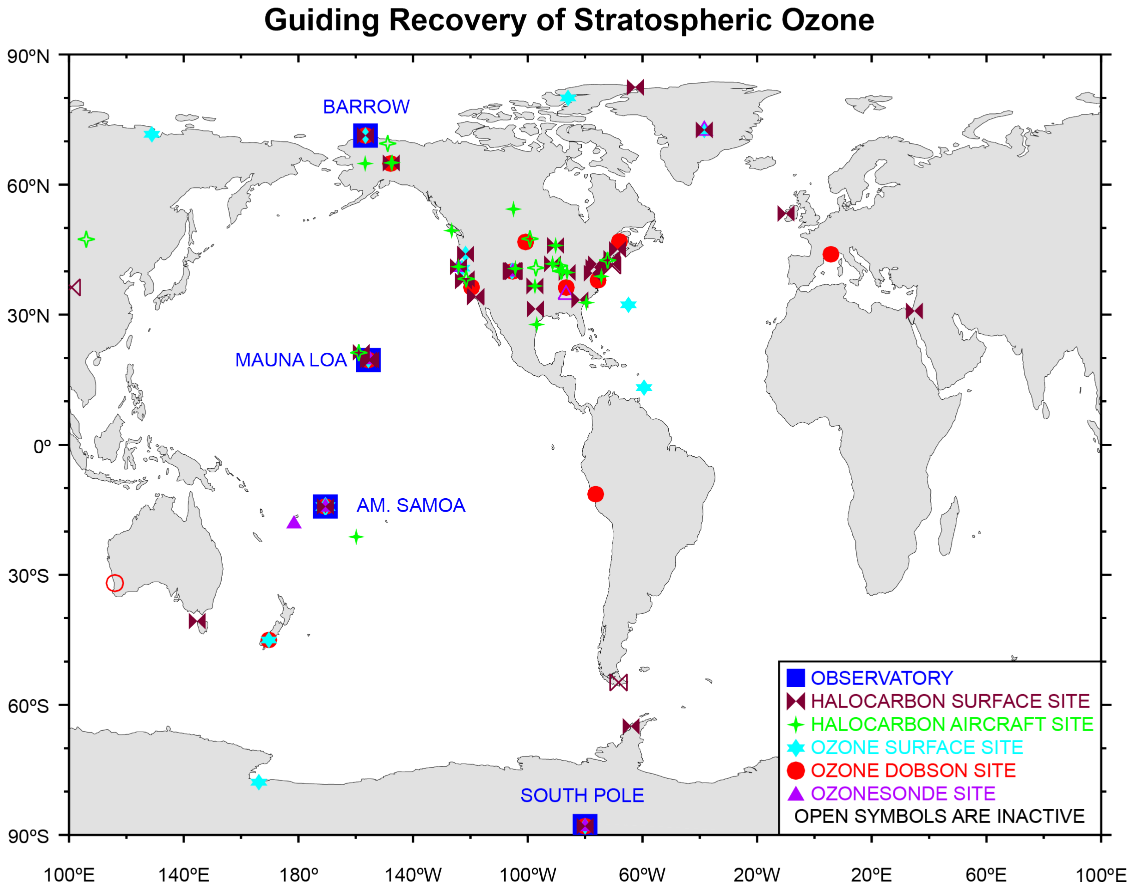
Tracking Greenhouse Gases and Understanding Carbon Cycle Feedbacks



Monitoring and Understanding Changes in Surface Radiation, Clouds, and Aerosol Distributions



Global Monitoring Division Observational Networks



These three maps show the observational sites and networks that address the three GMD research themes described in this Research Plan.

Message from the Director

The mission of NOAA's Global Monitoring Division has always been to provide high-quality, long-term records of atmospheric composition in a manner that allows the causes of change to be understood. This requires not only measurement and monitoring, but also evaluation, analysis, and publication of results. And it requires active engagement with partners at all levels. Today, GMD works with 67 countries around the world to obtain and analyze data, and has representatives on a number of national and international advisory groups and governing bodies. The Division's 100+ publications in 2017 average about 4.5 per PhD-level scientist, underscoring GMD's productivity and the value of partnerships we leverage.

While the value of sustained observations has always been recognized by the scientific community, their importance is not always clear to policy makers, resource managers, and even the general public, all of whom are more readily attracted to the latest widget or sensational finding. Long-term, surface-based and in situ observations are the foundation of Earth System science. They are essential for understanding our changing climate and concomitant feedbacks, and they are indispensable for ensuring that satellite retrievals do not drift over time or succumb to internally driven error and bias. Model analyses and predictions depend fundamentally upon sustained, representative observations to be grounded in reality.

This Research Plan underscores the relevance and importance of GMD's observations by demonstrating how our research aligns with internationally acknowledged Grand Challenges in Earth System science. The three themes of "Tracking Greenhouse Gases and Understanding Carbon Cycle Feedbacks", "Monitoring and Understanding Changes in Surface Radiation, Clouds, and Aerosol Distributions", and "Guiding Recovery of Stratospheric Ozone" show that alignment and capture all that we do. The first two themes support universally accepted World Climate Research Programme (WCRP) Grand Challenges, and the third addresses a specific requirement in the Clean Air Act of 1990 which, in and of itself, constitutes a Grand Challenge. The work required to address these three themes positions us well to continue advancing understanding of radiative forcing, climate sensitivity of CO_2, renewable energy options, climate intervention decisions, air quality, arctic processes, and long-range transport, all of which remain compelling issues and all of which require our long-term observations to resolve. As our records continue, they grow in value. Our job is to ensure both.

James H. Butler
Director

GMD Research Accomplishments

Global Monitoring Division (GMD) scientists have unique and globally recognized expertise in making sustained atmospheric observations, interpreting those observations, and communicating their findings to other researchers, policy makers, and the public. Some research accomplishments of the past decade are noted in this section.

Tracking Greenhouse Gases and Understanding Carbon Cycle Feedbacks

Human perturbation of Earth's carbon cycle, through the massive introduction of old carbon from fossil fuel sources into the modern atmosphere-land-ocean system, has altered and will continue to alter our climate. Exacerbating this has been the addition of other greenhouse gases (GHGs) to the atmosphere, which together continue to drive planetary warming and climate change. Much of GMD's research focuses on addressing these issues by providing high-quality, long-term observations of the gases driving climate change and targeted efforts at understanding their influences on Earth and the carbon cycle. To address these issues, GMD scientists have done the following:

- documented the global atmospheric distribution and varying trends of carbon dioxide (CO_2) and methane (CH_4) for decades, including identifying the Northern Hemisphere terrestrial biosphere as a large sink for carbon dioxide,
- determined the amount of methane and pollutant emissions from oil and gas extraction at major oil and gas plays in the United States (U.S.),
- determined that the ocean and terrestrial biosphere continue to absorb half of all fossil fuel-CO_2 emissions, even as emissions increase over time,
- ascertained that the ability of the atmosphere to cleanse itself of organic pollutants such as methane, volatile organic compounds, hydrochlorofluorocarbons, and hydrofluorocarbons is fairly robust and invariant from year-to-year,
- discovered a strong correlation between carbonyl sulfide (COS) and carbon dioxide concentrations throughout the atmosphere that provides insight into processes influencing carbon uptake by the land biosphere and how it might respond to changes in climate,
- determined a large reduction of the atmospheric lifetime (from 3200 to 850 yr) of sulfur hexafluoride (SF_6), a Kyoto Protocol GHG, based on modeling and balloon observations of a mesospheric sink,
- annually updated how concentrations of CO_2 and a multitude of non-CO_2 GHGs are increasing global climate forcing, and
- measured a 25% increase in stratospheric water vapor over Boulder since 1980 that would have enhanced the rate of surface warming during the 1990s by 30%.

Monitoring and Understanding Changes in Surface Radiation, Clouds, and Aerosol Distributions

The exchange of energy at Earth's surface is where weather begins and climate change is expressed. This exchange is strongly influenced by changes in the distributions of clouds and aerosols in Earth's atmosphere, which in turn are driven in part by perturbations from greenhouse gas and aerosol emissions and changes in atmospheric circulation. Understanding the variability in this complex system is one of the most difficult of the World Climate Research Programme (WCRP) Grand Challenges to address, yet extremely important if weather predictions and climate projections are to be improved at all scales. Such understanding begins with high-quality, well distributed, long-term observations of Earth-system characteristics that drive the system, most notably radiation at Earth's surface and changes in atmospheric constituents. To address these points, GMD scientists have done the following:

GMD Research Accomplishments (cont.)

- measured a large 12 W m^{-2} increase in net radiation over the continental U.S. over the last two decades and determined the mechanism to be a persistent decrease in cloud cover,
- contributed substantial improvements in the accuracy of broadband shortwave irradiance measurements by quantifying infrared loss from instrument sensors,
- provided surface irradiance data for Numerical Weather Prediction (NWP) model diagnosis and improvement that has resulted in a temperature bias reduction of ~70% at the 2-meter level over the U.S. Great Plains,
- documented a downward trend in surface aerosol light scattering of ~2% yr^{-1} (40-50% total decrease) at sites in the continental U.S. over the period 1993-2017 with a similar trend found in aerosol optical depth (AOD),
- discovered a consistent discrepancy between aerosol absorption optical depth (AAOD) from surface-based remote sensing and in situ vertical aerosol optical profiles, with the implication that the common use of AAOD retrievals to constrain model simulations of global black carbon concentrations should be done with caution, and
- used aerosol number concentration and size distribution measurements at network sites to investigate new particle formation and evaluate and improve the parameterization of aerosol processes in global models.

Guiding Recovery of Stratospheric Ozone

Monitoring stratospheric ozone (O_3) and the compounds that deplete it is not only a Congressional requirement for NOAA, but also a valuable tool for understanding changes in the Earth system owing to changes in climate and other influences. The Montreal Protocol on Substances that Deplete Stratospheric Ozone sets a path forward for a major global environmental success story, but it will take decades before the desired outcome is reached. Guiding recovery of stratospheric ozone requires high-quality, long-term observations, which is GMD's main forte, but also careful analyses of the data obtained to understand the influences of changes in circulation and climate on this recovery. To this end, GMD scientists have done the following:

- reported the turnaround of ozone-depleting chlorine (Cl) and bromine (Br) in the atmosphere in the 1990s and 2000s, tracked stratospheric ozone declines since the mid-1980s, and continued to monitor the progress of international protocols to guide ozone-layer recovery,
- identified potential threats to ozone-layer recovery due to a few controlled chemicals not declining as expected and increases in other chemicals for which production is not controlled,
- quantified emissions and emission trends of ozone-depleting substances (ODSs) and their substitutes over the U.S., providing, for the first time, observation-based evidence on the success of the Montreal Protocol on controlling ODSs on a national scale,
- provided high-quality records from the GMD ozone network that verified stratospheric ozone recovery in the mid-northern latitudes since 2000, signs of stratospheric ozone recovery in Antarctica, and signs of total column ozone recovery at multiple stations in the GMD network,
- identified a reversal of the long-term increase in baseline tropospheric ozone entering the U.S. from the Pacific, and
- showed that the mean Brewer-Dobson circulation (BDC) can be quantified over timescales of sub-annual to decadal changes by using a technique that combines datasets of measured age of air mass tracers (CO_2 and SF_6), tracers of photolytic loss with large stratospheric gradients (nitrous oxides, halons, and chlorofluorocarbons (CFCs)), and observed winds.

GMD Leadership

GMD scientists play a critical leadership role in the global atmospheric monitoring community by

- developing and disseminating methods for highly accurate and precise monitoring of important atmospheric gases and surface radiation,
- assisting researchers and institutions throughout the world in establishing and maintaining gas, aerosol, and radiation monitoring programs using precise and accurate instrumentation, and providing proven methods and consistent sampling protocols,
- creating, maintaining and distributing globally recognized World Meteorological Organization (WMO) calibration scales, so that diverse observing systems throughout the world can be achieved and provide trusted and compatible data,
- providing data critical for evaluating and validating greenhouse gas, ozone, and water vapor retrievals from satellites,
- providing global, high-quality data for evaluation of global and regional atmospheric transport models,
- providing data that are used extensively throughout the world to improve understanding of the human influence on atmospheric composition and biosphere-atmospheric processes, and
- serving on numerous national and international advisory committees to help ensure the integrity of coherent observing systems and to support their relevance to policy and resource decision-making.

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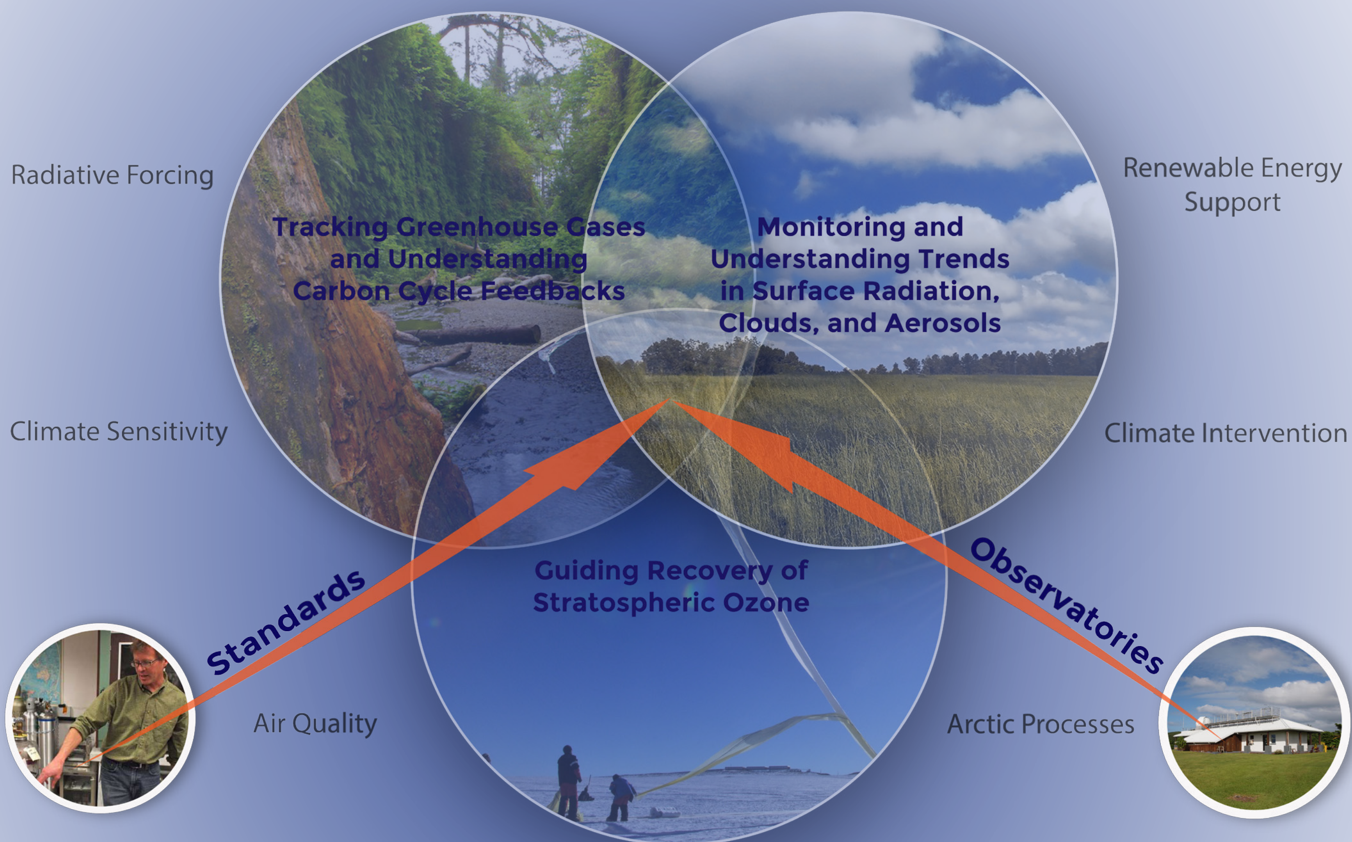
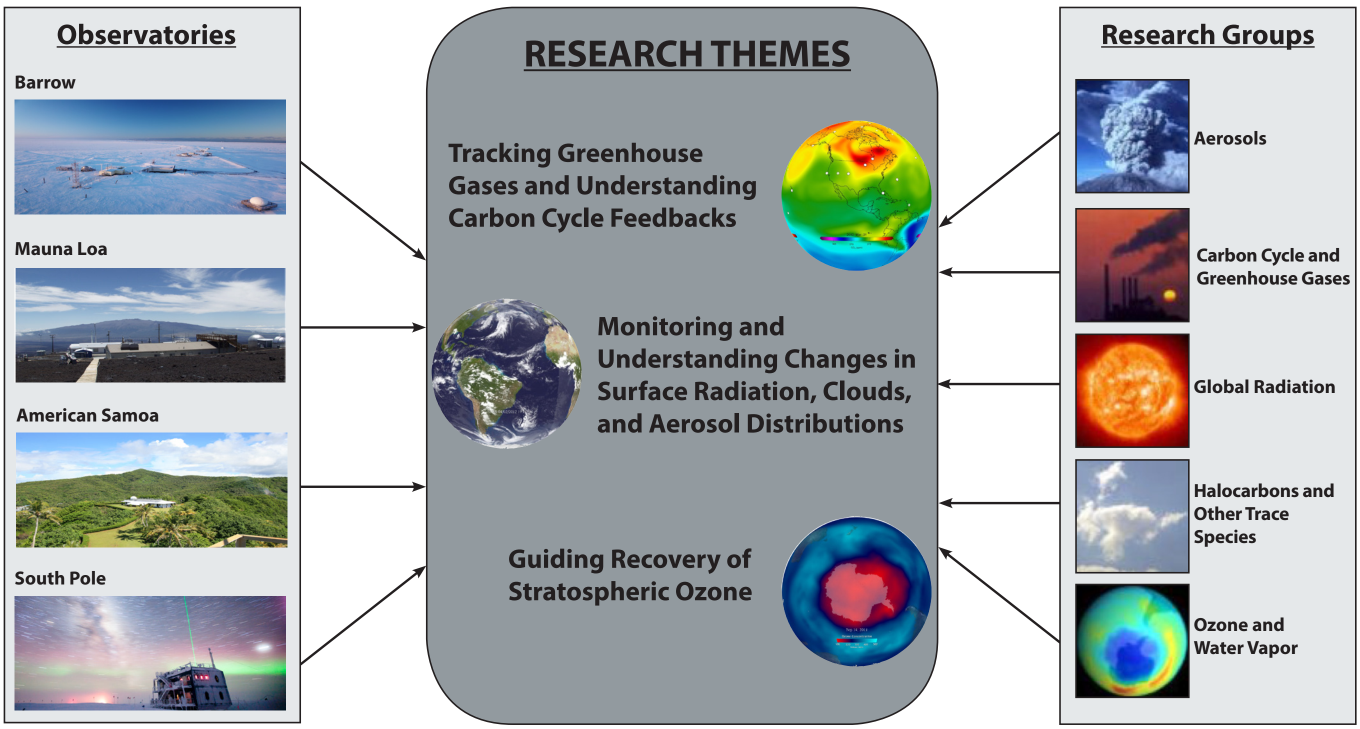
GMD Research Structure and Products



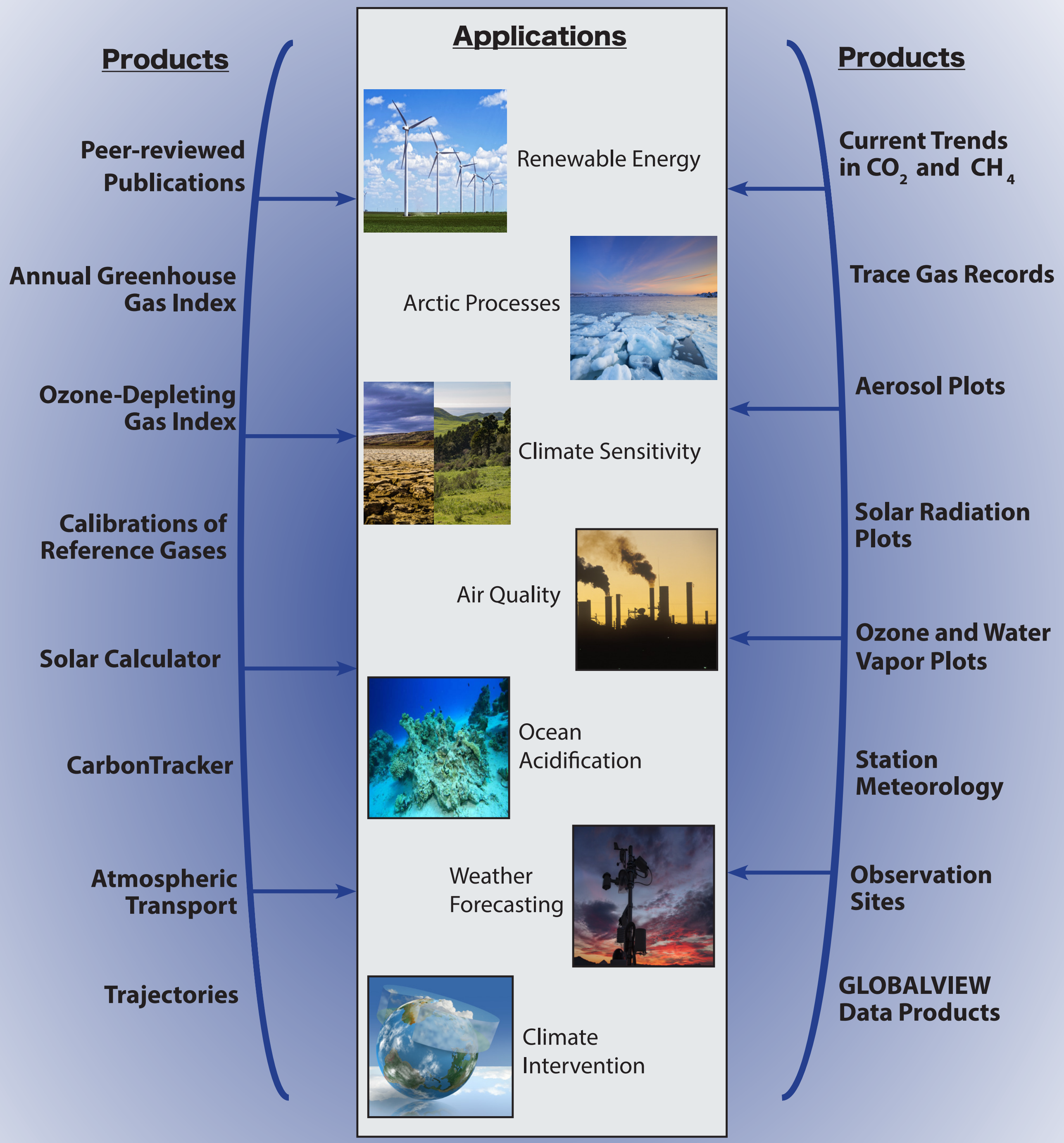
GMD Research Structure

Research emanating from GMD's networks addresses three major challenges including greenhouse gas and carbon cycle feedbacks, changes in clouds, aerosols, and surface radiation, and recovery of stratospheric ozone. GMD's five research groups – Carbon Cycle and Greenhouse Gases (CCGG), Halocarbons and other Atmospheric Trace Species (HATS), Ozone and Water Vapor (OZWV), Aerosols (AERO), and Global Radiation (G-RAD) – make and analyze observations, applying their expertise to address these themes. The unique observing systems operated by each research group come together at GMD's four baseline observatories, which serve as the backbone of the GMD observing system. However, most of the measurements from each group are made at other locations, including collaborator sites, sites in other networks, and on ships and aircraft. GMD's research groups work together in developing and maintaining their observing networks and, especially, in understanding, interpreting, and publishing results.



GMD's observations and research are critical to sustaining and preserving long-term observing records around the world. Because of the geographic coverage of GMD's observing systems, consistent high quality, and relevance to ongoing scientific endeavors, GMD's influence reaches well beyond monitoring, research, and scientific publications. Ultimately, GMD provides numerous products and services in support of the scientific community and society; fundamental, world-class data sets and analyses for national and international assessments; calibration, quality control, and observing sites to support international networks; leadership in national and international organizations; data for the validation and evaluation of satellite and modeling products; and improved forecasting for renewable energy resources. Tying research to applications results in the development of a variety of products supporting society.

Sample GMD Products and Applications



GMD's products range from long-term datasets of atmospheric composition to interactive atmospheric data visualizations, indices, and trends. These products have many applications.

Legislative Drivers for GMD Measurement Programs

There are 29 legislative drivers that instruct and guide the Global Monitoring Division measurements and data reporting. The seven that are most relevant are as follows:

- National Climate Protection Act of 1970
- National Climate Program Act of 1978
- Clean Air Act of 1990
- Global Change Research Act of 1990
- Global Change Prevention Act of 1990
- United Nations Framework Convention on Climate Change of 1992
- Montreal Protocol on Substances that Deplete the Ozone Layer, 1987, as amended and adjusted

The Global Change Research Act of 1990 called for a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change. This and the Clean Air Act of 1990 brought climate and ozone research to the forefront and GMD's mission was strengthened with both of these pieces of legislation. The Clean Air Act specifically required NOAA and NASA to monitor stratospheric ozone and the compounds that deplete it.

GMD's mission, vision, and research support the broader objectives of the Department of Commerce, NOAA, and Office of Oceanic and Atmospheric Research (OAR) strategic plans and OAR corporate priorities, and are consistent with the NOAA Research Plan. Specifically, GMD's research contributes directly to the Climate Adaptation and Mitigation and Weather-Ready Nation goals and indirectly to Healthy Oceans and Coastal Communities. GMD's long-term observations and analyses are foundational to the OAR goals of describing and understanding the state of the climate system and how it is evolving; they are essential for understanding what causes climate variability and change on global to regional scales; they support understanding how climate affects seasonal weather and extreme events; and they are used by GMD scientists and partners to understand the connectivity among atmospheric composition, chemistry, ecosystems, climate, and weather.

GMD's reach, however, goes far beyond its position within the agency structure. Owing to the high quality and relevance of its measurements, calibrations, and quality control efforts, GMD's contributions are crucial to several aspects of the U.S. Global Change Research Program (USGCRP). They are central and absolutely necessary to the World Meteorological Organization's (WMO) Global Atmosphere Watch (GAW) Programme, a major component of atmospheric composition measurements in the Global Climate Observing System (GCOS), and captured in the broader mission of the Global Earth Observation System of Systems (GEOSS).

GMD's research priorities address two of the major WCRP Grand Challenges focused on climate forcing -- greenhouse gases and carbon cycle feedbacks, and radiation, cloud, and aerosol forcing. GMD provides leadership on a number of advisory committees and steering groups within these broader organizations to assist in achieving and sustaining relevant, high-quality observations in the service of science.

GMD National and International Linkages

Owing to the global monitoring mandates that GMD operates under and the need to work with partners in carrying them out, GMD has dozens of national and international partners, expanding its reach to hundreds of long-term observing sites. In addition to the four NOAA Atmospheric Baseline Observatories, many of the sampling sites operated by GMD's research groups involve cooperative partners. These networks of GMD-driven observations are further strengthened through the linkages GMD maintains with its domestic and international partners to expand global observations and ensure their high quality. The number of in situ observing or sampling sites reliant on GMD's calibrations, analytical capabilities, and/or expertise in quality control can be estimated as follows:

- greenhouse gases (204 sites in 45 countries)
- surface and stratospheric ozone (66 sites in 12 countries)
- aerosols (27 sites in 12 countries)
- solar radiation (44 sites in 5 countries)
- ozone-depleting halocarbons and other trace gases (70 sites in 20 countries)

GMD has served over the decades as the core of the WMO GAW Programme, which has been able to expand on GMD's strengths through the establishment of international Quality Assurance Centers, Regional Calibration Centers, Twinning Training Programs to build capacity, Scientific Advisory Groups, and coalitions of experts in the various areas of atmospheric composition. GMD scientists work as leaders and participants in all WMO GAW activities to ensure connectivity, quality, and relevance of global observing systems.

GMD supplies calibration standard reference gas mixtures to 245 different organizations in 36 countries, World Standard total column ozone calibrations for 33 global sites, and instrument specifications and software to coordinate and inter-compare aerosol measurements at 27 global sites and solar radiation calibrations (64 agencies in 27 countries).

Finally, over the past five years GMD has had official collaborations with 561 separate agencies, companies and universities. Data downloads from GMD's FTP site that require logging onto a GMD server numbered one-half million in 2017. Although there is no accurate method to count the number of data downloads obtained through the "Anonymous Web Server", it is likely many times larger than the tracked FTP server.

GMD Workforce

The Global Monitoring Division maintains a federal workforce together with scientists from the University of Colorado's Cooperative Institute for Research in the Environmental Sciences (CIRES) and Colorado State University's Cooperative Institute for Research in the Atmosphere (CIRA). CIRES and CIRA Research Scientists and technical staff work side-by-side with NOAA federal scientists and technicians in GMD's laboratories and in the field, sharing both the research efforts and the presentation of results at conferences and in publications. The collaboration with CIRES and CIRA and other institutions such as the University of Colorado's Institute of Arctic and Alpine Research (INSTAAR) provides GMD access to a more expansive range of expertise in the academic community. Because of challenges facing the process of recruiting federal scientists, GMD also uses contract companies to employ a number of information technology and administrative staff.

GMD staff collaborate with scientists, engineers, and technicians from many universities and agencies in the collection of samples and operation of instruments at the numerous field sites beyond the four observatories. Additionally, GMD is involved in synergistic projects around the world – projects including designing instruments, making measurements at the observatories, and conducting studies from manned and unmanned aircraft, ships, tall towers, temporary field sites, vehicles that are modified to take samples when in motion, and on commercial airlines. GMD scientists are actively engaged in the scientific analysis of their data, leading to the publication of results on the web, in peer-reviewed publications, and international assessments.

Global Monitoring Division Staff - 2017


Uinta Basin


WARNING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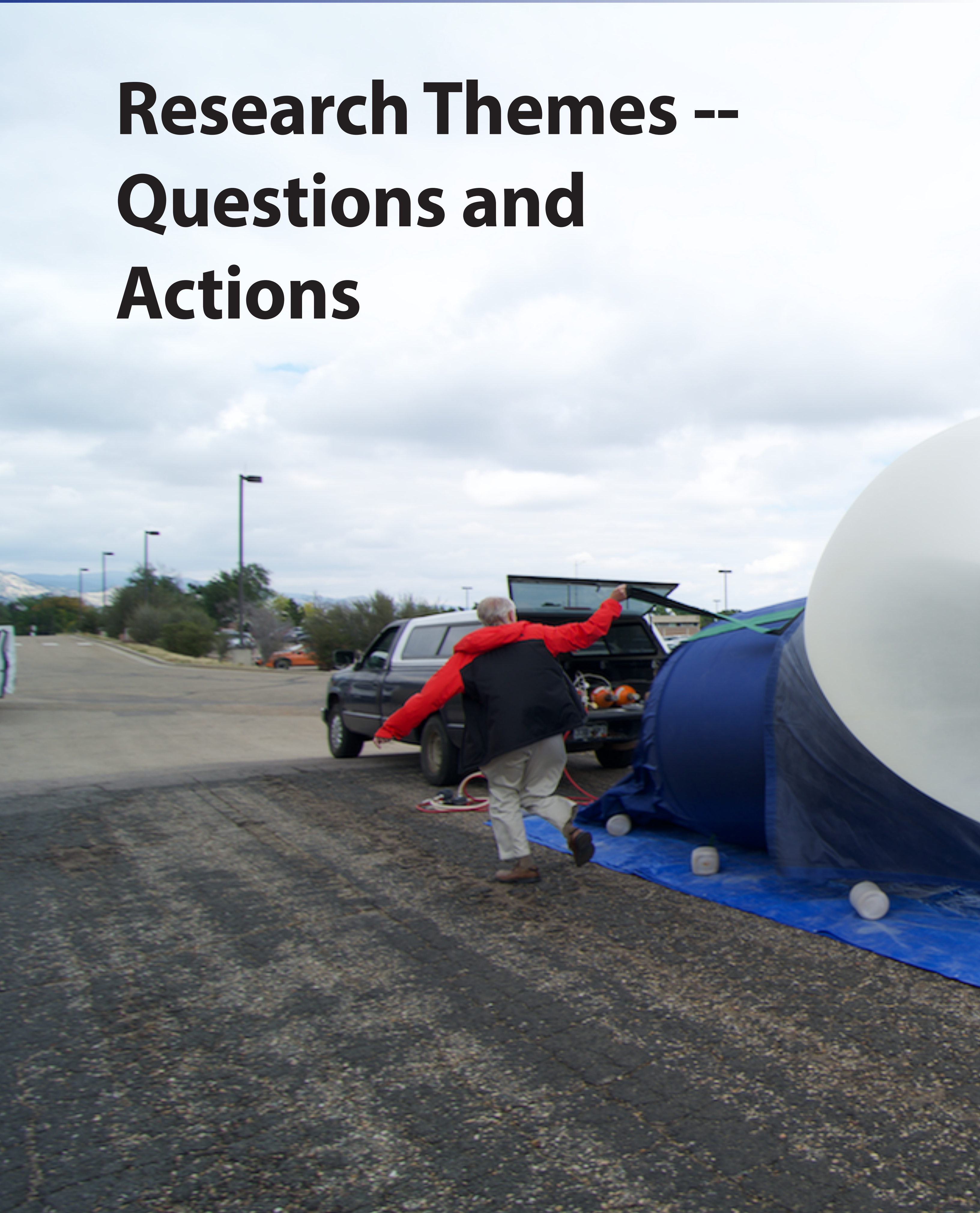
Research Themes -- Questions and Actions

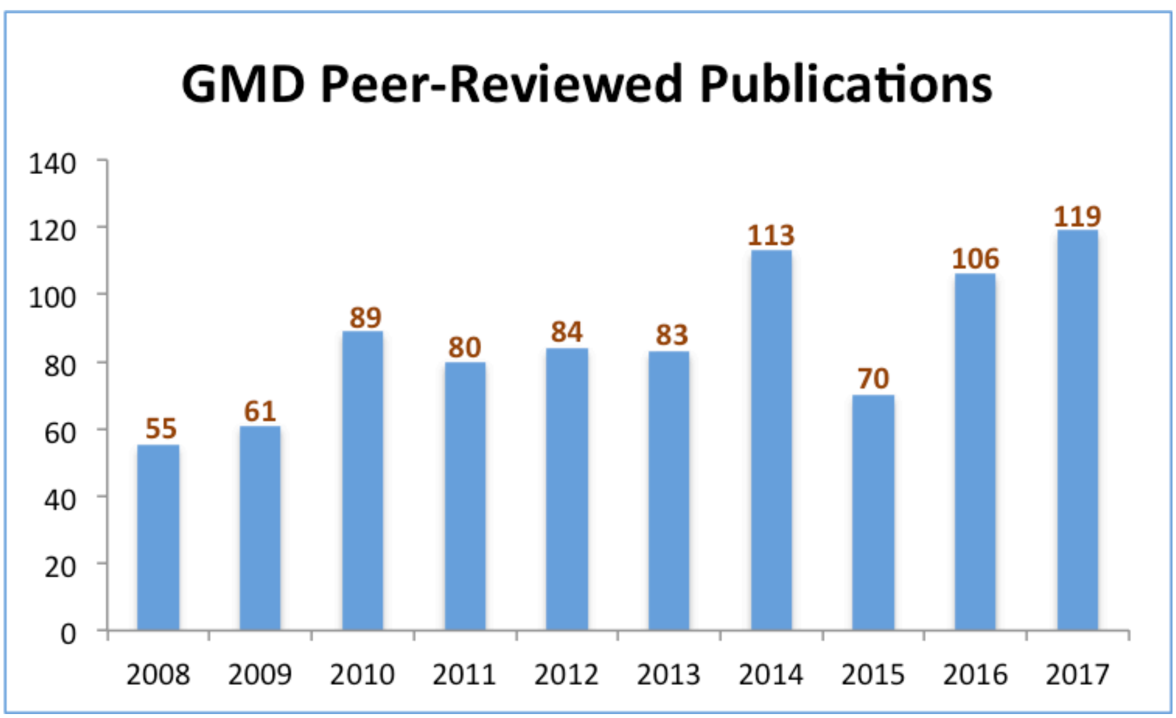


Research Themes -- Questions and Actions

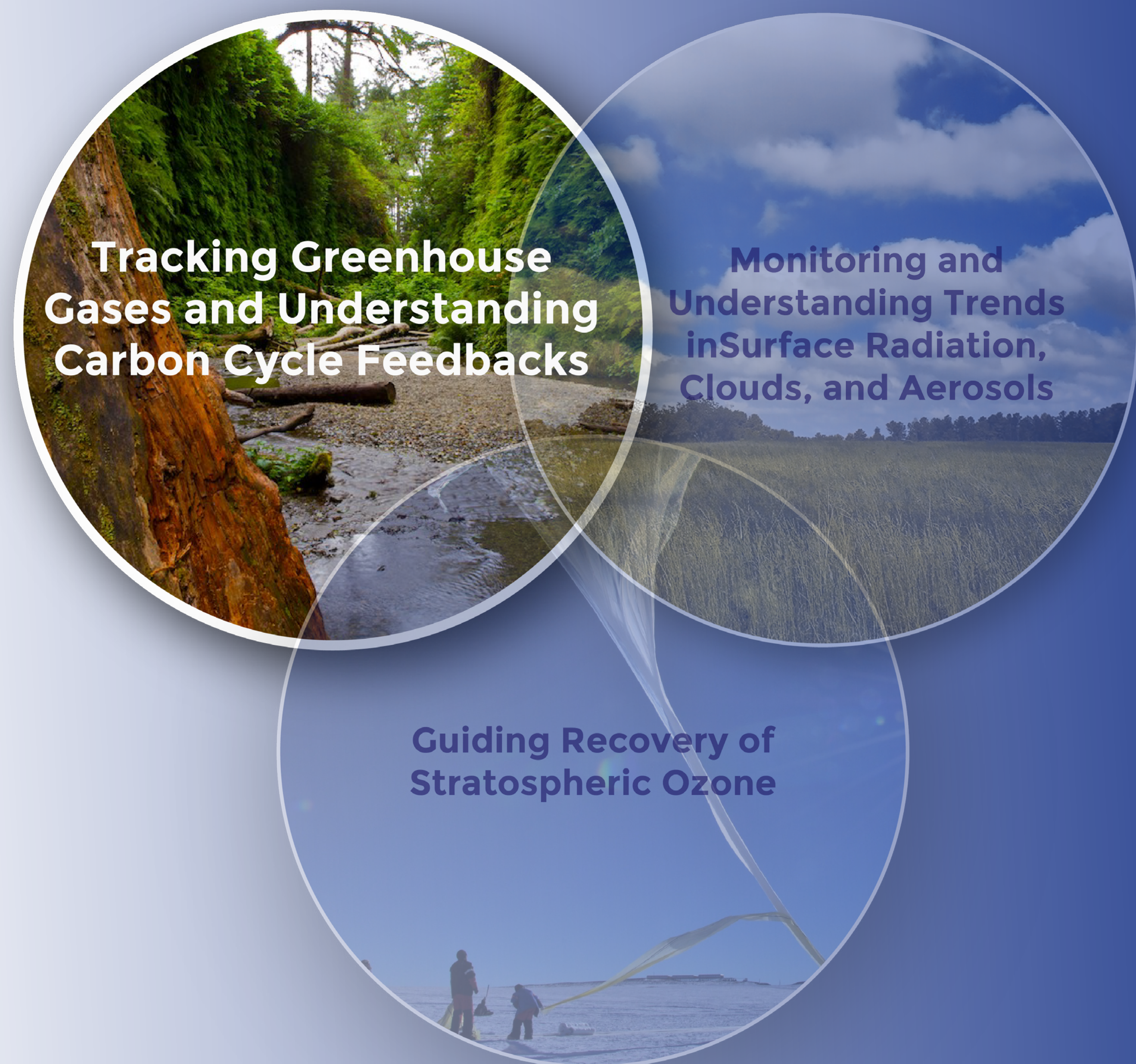
The ultimate drivers of GMD's observing systems and research are scientific questions that can be addressed by engaging the unique skills, capabilities, and observations of GMD. GMD's comprehensive networks provide accurate long-term measurements of greenhouse gases (GHGs), aerosols, surface radiation, clouds, and ozone-depleting gases. This is done to establish a basis for tracking GHGs and carbon cycle feedbacks; variability in surface radiation, clouds, and aerosols; and the recovery of stratospheric ozone under the Montreal Protocol, the three themes of our research. These topics are essential for improved understanding of the underlying causes of Earth's changing climate. GMD's long data records greatly improve understanding of the processes that impact on the budgets of GHGs, ozone, and radiation on timescales of days to centuries.

Fundamental actions common to all GMD research questions:

- Maintain existing global and U.S. observing networks (Observations Section, p. 39), including baseline observatories, regional networks, as well as tall tower, shipboard, aircraft, and balloon platforms.
- Sustain, improve, and disseminate measurement standard scales and protocols to help ensure the quality of GMD's measurements and to assure the use of the accurate scales throughout the global scientific community.
- Make all data and products freely available to scientists, the general public, and policy makers in a manner that is easy to understand. Keeping our measurements and research transparent to all helps to ensure their relevance and usefulness.
- Analyze and synthesize our data and disseminate results via peer-reviewed publications and international syntheses such as the WMO/UNEP Ozone Assessments and the IPCC Assessment Reports. Scientific publications are the essential building blocks of assessments and environmental policy. GMD has made significant contributions in the published literature with 860 peer-reviewed publications in the past decade and participation in national and international assessments.



Research Theme 1: Tracking Greenhouse Gases and Understanding Carbon Cycle Feedbacks



Research Theme 1: Tracking Greenhouse Gases and Understanding Carbon Cycle Feedbacks

Today's anthropogenic climate change is largely driven by increasing greenhouse gases in the atmosphere, modified to some extent by the distribution of aerosols and aerosol properties. To understand the influence of changing atmospheric composition on climate change and minimize its eventual magnitude, society needs the best possible information on the trends, distributions, emissions and removal of greenhouse gases. It is necessary to develop a solid, scientific understanding of their natural cycles, and how human management and the changing climate influence those cycles. Our atmospheric measurements can also provide fully transparent and objective quantification of emissions, supporting national and regional emissions reduction policies and generating trust in international agreements.

The NOAA Global Monitoring Division is a world leader in producing the regional to global-scale, long-term measurement records that allow quantification of the most important drivers of climate change today. Global monitoring of atmospheric greenhouse gases, in particular carbon dioxide (CO_2), has been part of NOAA's mission for over 50 years. GMD provides and interprets high-accuracy measurements of the history of the global abundance and spatial distribution of a suite of long-lived greenhouse gases. The spatial distributions, together with models of the winds and mixing (derived from weather forecasts) allow us to infer time-dependent patterns of emissions and removals that are consistent with our observations. The measurements are accurate and precise because of calibration, they stand on their own, and can be used far into the future with better models. They are also used to compare with satellite retrievals of column-averaged GHGs that cannot be calibrated, but still need to be used in tandem with calibrated data.

NOAA measurements of climatically important gases began in the late 1960s and expanded in the mid-to-late 1970s for CO_2, nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and upper atmospheric water vapor. Over the years other gases and isotopic ratios have been added, including methane (CH_4), carbon monoxide (CO), hydrogen (H_2), numerous hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), methyl halides, and sulfur hexafluoride (SF_6). GMD produces and maintains global standards for most of the climate-relevant gases. The use of common standards enables measurements by different methods, and by different countries and organizations to be used together, greatly increasing the value of the international cooperative measurement system.

By creating an unassailable and well documented record of GHGs in the atmosphere, GMD will continue to

- track the magnitude and location of major natural sources and sinks of GHGs.
- provide early warning of feedbacks and surprises in how human activities and a changing climate affect the carbon cycle.
- provide the international scientific community with calibrated reference gas mixtures, and provide leadership in quality control and data management. Calibrated measurements are the foundation of any GHG observing system.
- compare remote sensing retrievals with a dense network of calibrated measurements near the surface and in the vertical column. Retrievals of GHGs fundamentally cannot be calibrated and even very small systematic errors ("biases") can corrupt estimates of sources and sinks to an extent that is not acceptable. Bias removal down to unprecedented low levels is required for all long-lived greenhouse gases. Therefore, GHG measurements on commercial aircraft (up to 11-14 km altitude) need to be developed and AirCore (page 54) needs to be operationalized to cover the entire atmospheric vertical column (up to 30 km).
- improve inverse modeling techniques and our CarbonTracker data assimilation system.

To help society mitigate emissions on regional, national and international scales, GMD will

- provide an objective and transparent measure of the degree of success of mitigation policies by developing methods to quantify emissions from urban areas.
- quantify contribution of fossil fuels to CH_4 emissions on global and regional scales, such as oil and gas production regions.

Question 1: How will oceanic and terrestrial carbon sources and sinks influence and respond to a changing climate?

Relevance: The two-way interaction between carbon sources and sinks and climate is a first-order uncertainty in predicting climate in the 21st century and beyond. Understanding the past trajectories and current state of GHG sources and sinks is a prerequisite for predicting those in the future.

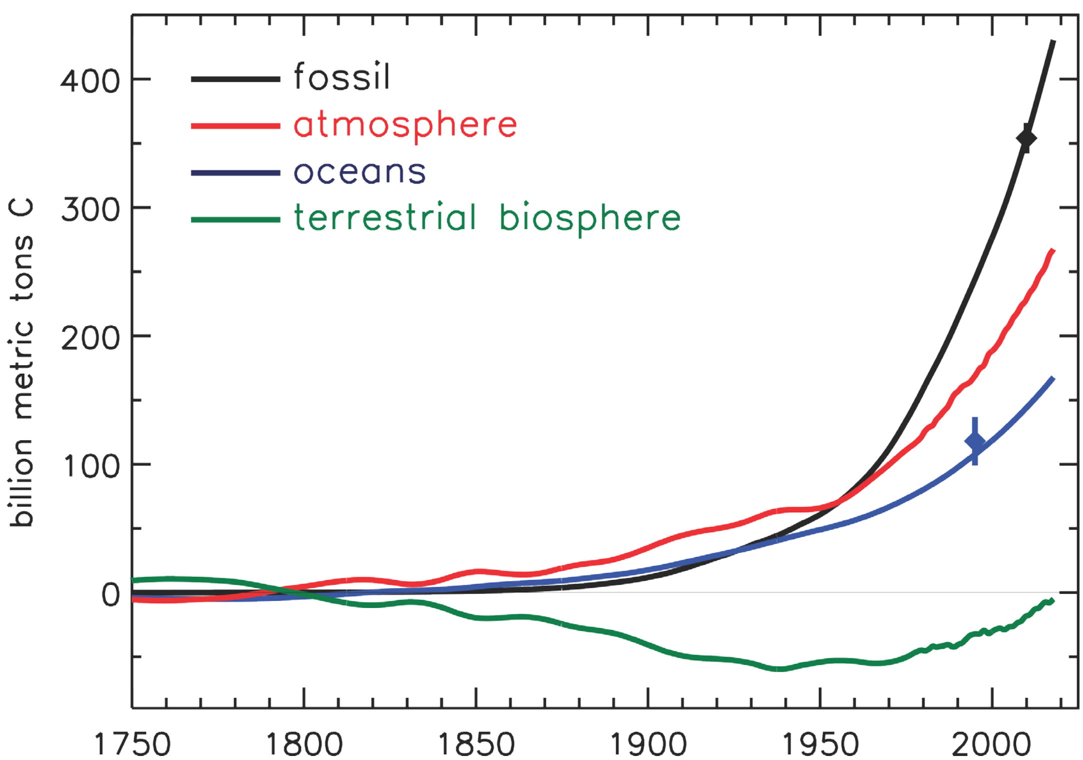
Actions Taken: GMD has used its long-term atmospheric observations of GHGs to quantify present day sources and sinks for three decades. Among other methods, we employ the CarbonTracker data assimilation systems for CO_2 and CH_4 to calculate global, continental, and regional sources and sinks. In order to improve the accuracy of our continental and regional source and sink calculations, we have increased the density of measurements over the U.S. and improved the resolution and quality of the atmospheric models we use to interpret the data.

What we've discovered: Global CO_2 sinks have stayed roughly constant as a fraction of emissions over the past 50 years. U.S. sinks absorb about one third of U.S. fossil fuel emissions, though with large variability. Global CH_4 emissions have increased since 2007 after having been steady for the preceding decade. Our measurements of CH_4 isotopes imply that increased leaks from oil and gas operations are very likely not the main cause. Thus far, we have seen no evidence for dramatic increases in CH_4 emissions from Arctic warming.

Kathryn McKain (NOAA GMD / CIRES) on the NOAA Twin Otter aircraft in August 2016 for a campaign to measure methane emissions from the Prudhoe Bay Oil Field and Arctic Tundra on the North Slope of Alaska.

Future Actions:

- Transition the CarbonTracker data assimilation systems to a higher spatial and temporal resolution atmospheric transport model in order to improve representation of continental observations that are critical for estimating terrestrial carbon fluxes.
- Explore the use of remote sensing data, aircraft observations, and observations of other atmospheric species that can help to improve GHG constraints.
- Cleanly separate the contribution of fossil fuel burning from all natural sources and sinks by using measurements of $^{14}CO_2$ in the atmosphere.
- Seek to restore weekly airborne GHG measurements in the U.S. and collaborate with other groups (Earth Networks, National Ecological Observatory Network [NEON], etc.) to increase the number of tower-based GHG measurements, thereby improving the resolution and accuracy of source and sink estimates over the U.S.
- Take steps to initiate automated measurements of CO_2 and CH_4 on commercial airliners and expand the use of the AirCore vertical profiling system.
- Increase the number of measurements of GHGs in the Arctic and tropics in collaboration with regional institutions in order to develop early warning systems for these global "hot spots".
- Increase analysis of biospheric CO_2 tracers like carbonyl sulfide (COS) and $^{13}C/^{12}C$ of CO_2 in order to better understand the role of climate extremes in controlling carbon sources and sinks.



Known cumulative changes in fossil fuel carbon emissions and observed atmospheric carbon increase (zero corresponds to the pre-industrial atmosphere). An empirical model of air-sea CO_2 exchange calculates cumulative oceanic uptake with parameters chosen to fit ocean observations (blue diamond in 1994) as well as the rate of increase in the oceans during the last two decades based on atmospheric O_2/N_2 observations. Changes in the terrestrial biosphere are derived from mass balance of the other three.

Impact: Expanding the number, location, and kinds of greenhouse gas measurements, and improving data assimilation tools will lead to better estimates of North American and global emissions. That will allow for earlier detection of possible carbon cycle – climate feedbacks, including possible changes in emissions from the rapidly warming Arctic. Improved understanding of the North American and global carbon cycles (and budgets of other GHGs) will enhance predictive capability of carbon cycle and climate models, and allow for better informed policy decisions. Vertical atmospheric profiles will improve our ability to derive sources and sinks through better quantification of air mixing between the boundary layer and free troposphere, and in and out of the stratosphere. Better air transport and much denser vertical in situ measurements will help evaluate remote sensing retrievals.

Question 2: What are the anthropogenic inputs of CO_2, CH_4 and other GHGs into the atmosphere?

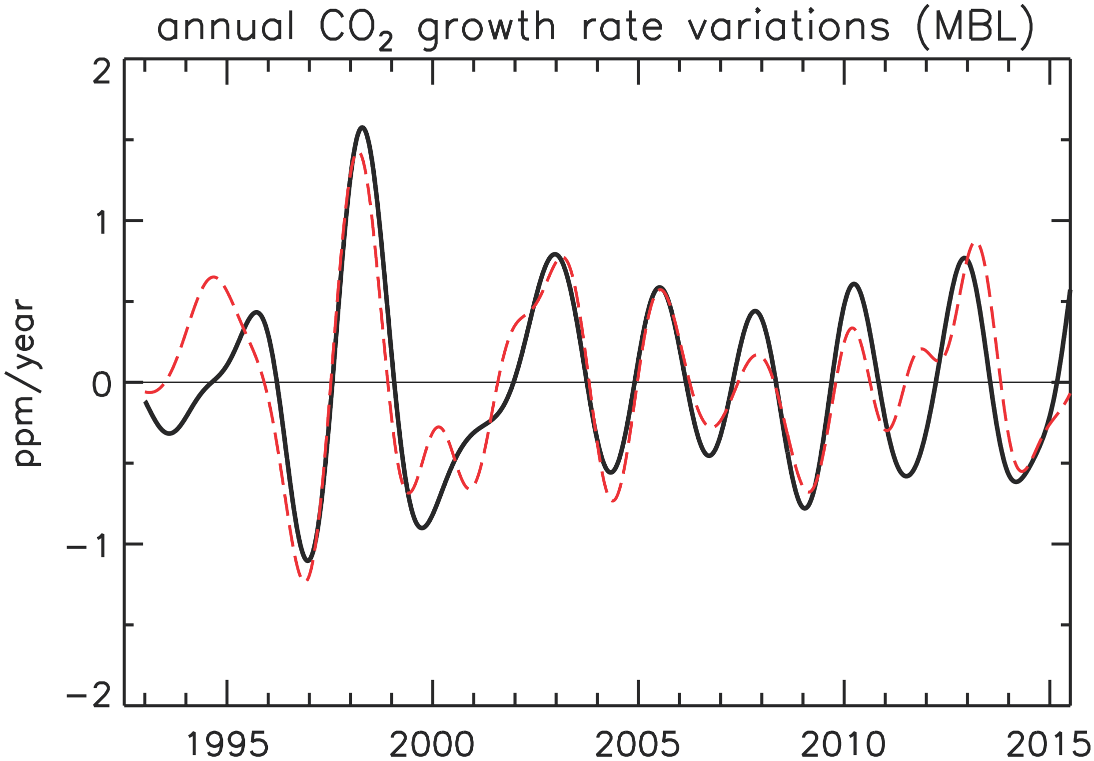
Relevance: These GHG emissions are responsible for anthropogenic climate change, yet the world currently relies only on self-reported, accounting-based approaches to determine emissions. Further, understanding carbon cycle response to climate change requires separation of human and ecosystem influence. We are developing techniques that allow objective and transparent quantification of emissions using atmospheric data.

Actions Taken: In addition to the long-term measurements of GHGs mentioned above, GMD has measured the atmospheric content of species like $^{14}CO_2$, CO, and other gases directly related to anthropogenic emissions, especially in the North American part of our network. These measurements have been used to estimate emissions of a variety of different trace gases. For example, in the case of anthropogenic methane emissions in the U.S., we have conducted short duration (weeks) intensive campaigns in and around oil and gas extraction regions. Longer duration (years) studies have also been performed around cities in order to estimate fossil fuel-CO_2 emissions. We have done Observation System Simulation Experiments (OSSEs) to help design the observational and modeling frameworks needed to most effectively use atmospheric data to estimate emissions.

What we've discovered: Atmospheric measurements of the strong GHG SF_6 have shown that inventories (from "bottom-up" accounting) greatly underestimate global emissions. Increases of CH_4 emissions over the U.S. have been, at most, modest during the last decade. Based on our $\delta^{13}C$ data, global emissions of CH_4 from fossil fuel use are a larger fraction of total anthropogenic emissions than previously believed, while the recent increase of atmospheric CH_4 is likely not due to increased fossil fuel emissions. Our estimate for U.S. HFC-134a emissions is consistent with the EPA inventory, while our observations for CCl_4 indicate that U.S. emissions are more than a factor of ten larger than the EPA's Toxics Release Inventory.

***Future Actions*:**

- Begin estimating U.S. fossil fuel-CO_2 emissions using CO_2 and $^{14}CO_2$ observations as part of the CarbonTracker data assimilation system.
- In collaboration with University of Colorado, INSTAAR, seek to expand the limited set of $^{14}CO_2$ observations over the U.S and East Asia to provide an improved quantification of fossil-fuel-CO_2 emissions and other greenhouse gases (e.g., halocompounds).
- Develop and implement data assimilation systems that use measurements of multiple gas mole fractions and isotopic ratios in order to determine anthropogenic contributions.



Smoothed, detrended annual mean growth rate of CO_2 derived from the Marine Boundary Layer (MBL) subset of sites (black line) and the same CO_2 growth rate derived from the observed $^{13}C/^{12}C$ ratios of CO_2 at the MBL sites, assuming that the isotopic signature is characteristic of photosynthesis by land plants (dashed red line). The fairly close match between the lines demonstrates that the CO_2 growth rate variations are almost entirely due to terrestrial ecosystems, not to the oceans.

Impact Determining emissions of GHGs using atmospheric observations will allow for independent evaluation of "bottom-up" inventory-based techniques. As has already been demonstrated, this may allow us to detect errors in the existing inventories. The atmospheric approach will also allow for closer to real time estimates of emissions, and will improve the partitioning of total sources and sinks into their anthropogenic and natural components.

Question 3: How will upper tropospheric and lower stratospheric water vapor respond to a changing climate?

Relevance: Changes in water vapor abundance near the tropopause exert a strong influence on climate. For example, if the 25% increase in stratospheric water vapor observed over Boulder between 1980 and 2010 is representative of a global trend, it would be responsible for enhancing the rate of surface warming by 30% during the 1990s.

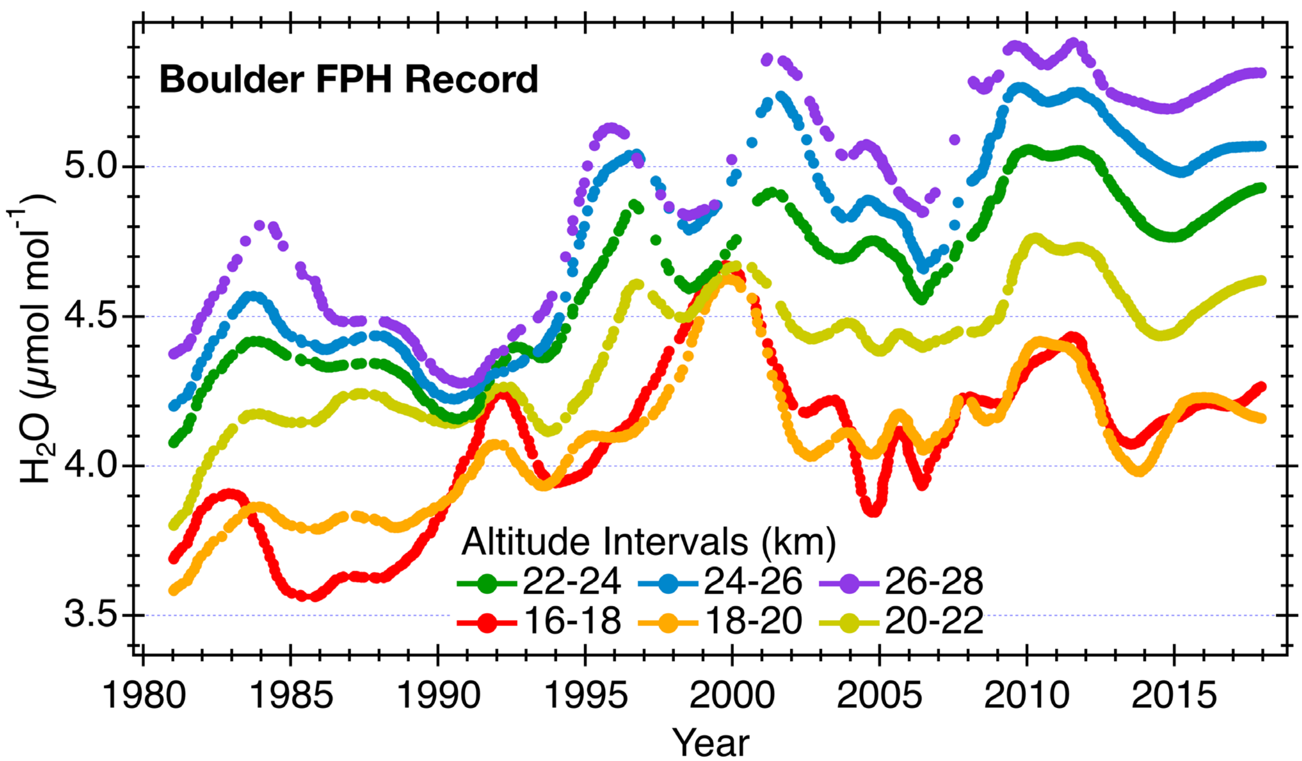
Actions Taken: Monthly water vapor soundings with balloon-borne frost point hygrometers (FPHs) were initiated in 1980 at Boulder and in 2004 at Lauder, New Zealand. Realizing a compelling need for water vapor vertical profiles in the tropics, monthly FPH soundings began in 2010 at Hilo, Hawaii. Time series of stratospheric water vapor mixing ratios produced from these soundings were analyzed for long-term trends and compared to measurements by satellite-based water vapor sensors. The Hilo data also help us better understand interannual changes in the tropical tropopause layer (TTL) that are driven by dynamical processes like the Quasi-Biennial Oscillation (QBO), the El Niño-Southern Oscillation (ENSO) and the Brewer-Dobson circulation (BDC).

What we've discovered: Stratospheric water vapor over Boulder has increased by approximately 25% since 1980. Only one-third of this long-term trend can be attributed to increasing amounts of methane entering the tropical stratosphere where it is oxidized to water vapor suggesting this may be a strong climate feedback. Satellite-based measurements of stratospheric water vapor provide better spatial coverage of the globe than FPH soundings but are often fraught with biases and temporal drifts, and, so far have been unable to provide reliable, long-term trends. The value of the near-global satellite records can be greatly enhanced once their biases and drifts have been characterized using FPH profiles.

Future Actions:

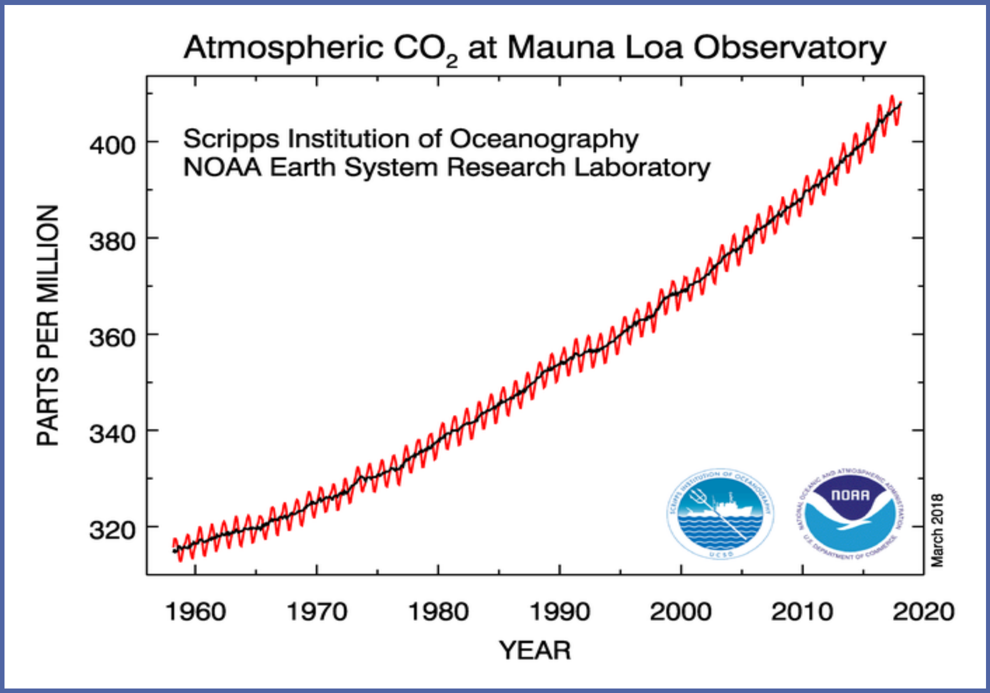
- Continue to monitor water vapor in the upper troposphere and lower stratosphere and attribute interannual and longer-term changes to the QBO and the ENSO, and potentially to changes in the BDC driven by climate change.
- Evaluate biases and drifts in satellite-based measurements of stratospheric water vapor to enhance the value of these near-global data sets.
- Establish an FPH sounding site in the tropical western Pacific region to monitor changes in the amounts of water vapor entering the stratosphere through the tropical tropopause.
- Continue to coordinate with the GCOS Reference Upper-Air Network (GRUAN) to help ensure continuity among in situ observing systems.

Impact: It is imperative that we understand all significant drivers of Earth's climate, including changes in stratospheric water vapor that may be indicative of a strengthening of the BDC. Our ever-increasing reliance on satellite-based measurements of upper atmospheric water vapor (and other trace gases) must be accompanied by greater efforts to detect and characterize their biases and temporal drifts.

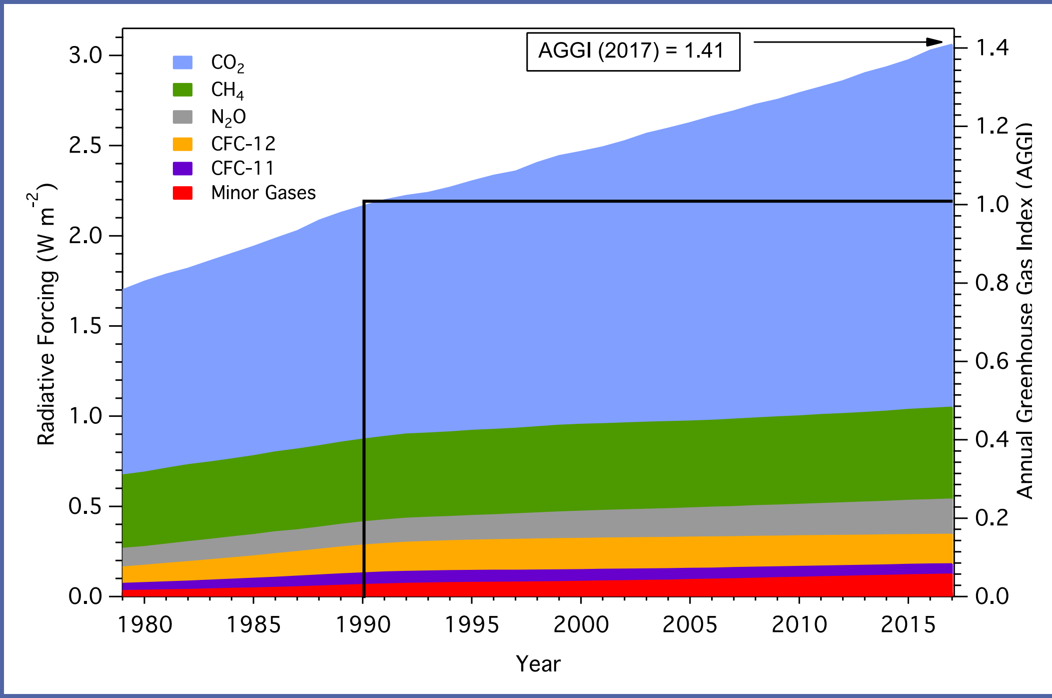


Smoothed time series of stratospheric water vapor mixing ratios in six altitude bins over Boulder, Colorado. Each data point represents a uniquely measured vertical profile by a balloon-borne FPH. This record exhibits a 25% increase in stratospheric water vapor from 1980 through 2017.

Two National Indicators of Climate Change

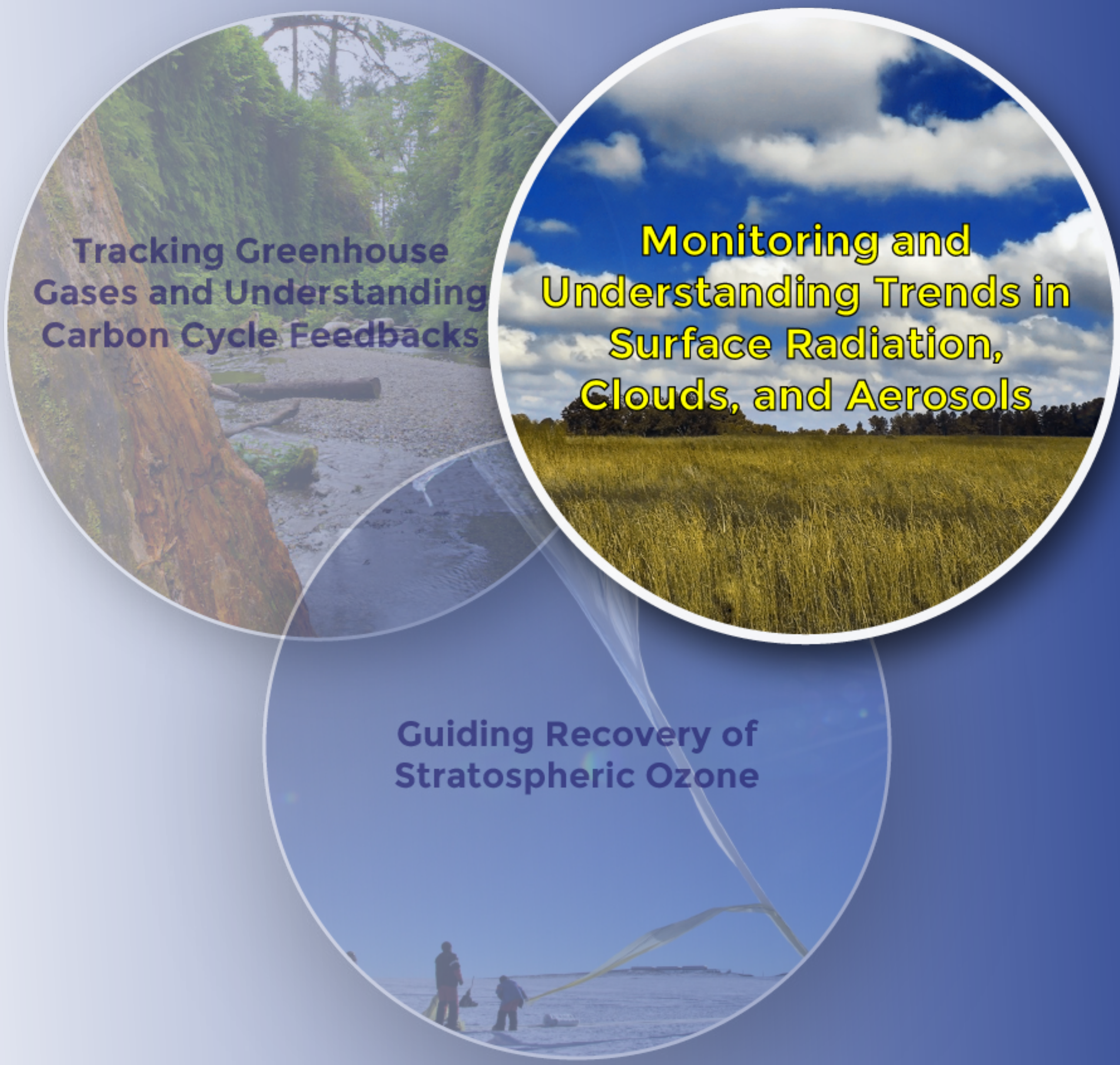


Full record of monthly average CO_2 at Mauna Loa Observatory. Starting in 1974, there are two independent records, from Scripps and from NOAA. Over the entire record the mean difference is 0.11 ppm, with the standard deviation of monthly differences 0.18 ppm (less than the line thickness in the figure), underscoring the robust value of this record. (The global record, based on observations from up to 40 marine boundary layer sites since 1980, is a USGCRP National Climate Indicator and updated each year.)



Greenhouse gas forcing from long-lived atmospheric gases has increased more than 41% between 1990 and 2017. The Annual Greenhouse Gas Index (AGGI), largely representative of what humans have done to accelerate global warming, is a USGCRP National Climate Indicator that is updated each year. (AGGI value based on data available at time of publication.)

Research Theme 2: Monitoring and Understanding Changes in Surface Radiation, Clouds, and Aerosol Distributions



Research Theme 2: Monitoring and Understanding Changes in Surface Radiation, Clouds, and Aerosol Distributions

Changes in the radiative energy balance at Earth's surface and at the top of the atmosphere result from forcing by greenhouse gases, aerosols, and related changes in the global atmospheric circulation. The distribution of clouds is the primary influence on the surface radiation budget and is sensitive to changes in circulation, but the nature of the response of different cloud types in different climatic regions is uncertain. Cloud radiative properties are also sensitive to aerosol particles which are highly variable in space, time, and composition. The role of aerosol particles in radiative forcing is complex and can be either positive or negative and they can influence the climate directly via long term changes in light absorption and scattering. The uncertainty in cloud responses to climate forcing constituents, either through direct interaction with aerosols or through circulation changes, is the primary factor limiting our ability to narrow estimates of the climate sensitivity (the warming resulting from a change in a climate forcing agent).

GMD observatories host long-term measurements of globally representative, climate-critical radiation variables such as the continuous measurement of the solar energy reaching Mauna Loa Observatory that began in 1958, the longest such record on Earth. Broadband measurements of incoming and outgoing solar and terrestrial radiation are made across the U.S. and at global baseline observatories to quantify the surface radiation balance and to track changes in cloud radiative properties. GMD has focused on the direct radiative effects of aerosol particles with measurements of aerosol optical properties that began in the 1970s. In response to the finding that anthropogenic aerosols create a significant perturbation in the earth's radiative balance on regional scales, GMD expanded its aerosol research program to include stations for monitoring aerosol properties in regions where significant aerosol forcing was anticipated.

To support these measurements, GMD maintains calibration facilities tied to the world standards and also shares calibration services with collaborators worldwide. GMD and its national and international partners have made substantial improvements in the accuracy of both solar and infrared measurements over the past 25 years, allowing detection of small changes in the radiation balance that have dramatic consequences for weather and climate. GMD also provides leadership to the international aerosol and surface radiation monitoring communities by providing technical expertise, calibrations, sampling and measurement protocols, and open source data acquisition, processing, visualization and editing software.

Question 1: How does the surface radiation budget and its components vary in space and time?

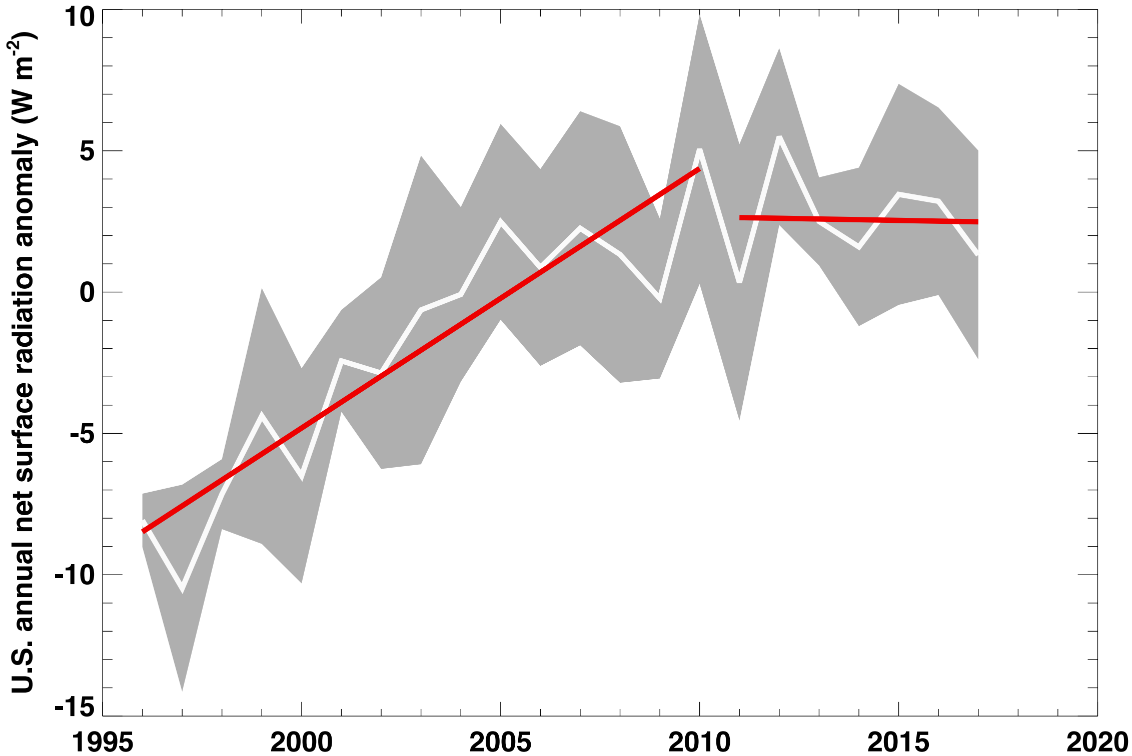
Relevance: The surface radiation budget (SRB) represents the energy available at Earth's surface for driving winds, heating the atmosphere, and evaporating water, and thus plays an appreciable role in driving weather patterns over the short-term and global circulation and climate over the long-term.

Actions taken: GMD makes long-term, continuous, high frequency, climate-quality measurements of the SRB and its components at several locations across the continental U.S. and representative locations around the globe. These observations are a major part of the cooperative, international GCOS Baseline Surface Radiation Network (BSRN, under the WCRP umbrella) that serves as the premier archive of accurate radiation measurements over the globe.

What we've discovered: Monitoring of the SRB has revealed decadal changes in 'Dimming' and 'Brightening', i.e., decreasing and increasing trends in the downwelling shortwave radiation, as the primary drivers of these trends. The features demonstrate the regionally varying response of the land-atmosphere energy system to climatically important drivers including anthropogenic GHGs and aerosols, natural oscillations in the climate systems, and their interactions.

Future actions: GMD, with its international colleagues, will continue to track changes in the SRB, focusing on critical regional trends across the U.S. and globally. Processes influencing these patterns of change will be explored, and GMD will continue to evaluate the potential to expand networks to underrepresented regions that exhibit processes and responses that are critical to understanding climate and weather patterns.

Impact: The imbalance in Earth's radiation budget is an integral measure of the response of the climate system to forcing. Understanding the impacts and controls of the SRB on weather and climate leads to improved predictability of weather and climate patterns that allow for improved mitigation and planning strategies for human and economic health into the future.



Continuous monitoring of the net surface radiation budget and its components at the Surface Radiation (SURFRAD) network sites over the past two decades reveals strong but temporally varying trends. The envelope represents the standard deviation among the 7 continental U.S. sites and the white line the annual average of the net surface radiation anomaly. These data have been used to evaluate Dimming and Brightening trends and reveal that the increase is dominated by an increase in the downwelling solar component of the SRB due to an observed decrease in cloud cover over the same period. However, this trend has not been constant over the 20+ years of record; the trend for the first 15 years shows a 12.9 W m^{-2} increase in the net surface radiation anomaly and for the second 7 years constitutes a 0.1 W m^{-2} decrease (red trend lines).

Question 2: How do anthropogenic forcing and internal variability in the climate system work to redistribute clouds and their radiative properties through feedback mechanisms or aerosol-cloud-radiation interactions?

***Relevance*:** Clouds are the primary modulator of atmospheric and surface heating and cooling and are intricately connected to atmospheric circulation on a range of temporal and spatial scales. The ultimate response of the climate system to anthropogenic aerosol particles and GHGs depends in large part on the trends and variability in clouds and radiation at Earth's surface. Cloud feedbacks are highly complex and non-linear, differ across climate regimes, and remain the largest uncertainty in projections of future climate states.

Actions taken: Cloud radiative properties – e.g., fractional sky cover, transmission, optical depth in overcast conditions, and the cloud radiative effect – have been monitored and retrieved from surface radiation measurements at GMD sites across the U.S. and globally with records exceeding 20 to 40 years. Co-analysis of surface Dimming and Brightening tendencies with trends in cloud properties has provided an understanding of regional characteristics in cloud variability and their impacts on the surface radiation budget. Co-monitored aerosol optical depth has also been used to attribute some variability in the SRB to aerosol direct radiative effects and aerosol-cloud interactions.

What we've discovered: Clouds are the primary modulator of the SRB over the U.S. and are responsible for the appreciable trends in downwelling shortwave radiation; the impact is highly significant on decadal scales in comparison to GHG forcing alone. Aerosol direct radiative forcing has a smaller impact on the SRB in the U.S. However, regions that have experienced significant increases in aerosol emissions elsewhere show opposing trends to those in the U.S.

Future actions: GMD is expanding the suite of cloud properties monitored within the U.S. (SURFRAD) to include cloud base height and layering information, boundary or mixing layer height, cloud optical depth (all cloud types), and cloud drop effective radius. This added information will provide a basis for separating variability in cloud radiative effects due to large-scale circulation changes and local-to-regional scale dynamics and aerosol processes.

Impact: A mechanistic understanding of the controls on Earth's energy imbalance is required to develop proficiency in predictability from day-ahead to seasonal forecasts and to improve projections of future climate. Theoretical studies show that explicit representation of cloud-aerosol-circulation processes improves the fidelity of simulations of the current climate. GMD's national network of SRB measurements is unique in providing continuous, high-temporal resolution, high-accuracy measurements over various climate regimes. With expanded measurements, GMD will be able to contribute to a mechanistic understanding of controls on the SRB and the resulting impacts on weather and climate.

Question 3: How do the variability and trends of climatically important aerosol optical properties vary as a function of location, time, and atmospheric conditions?

Relevance: Aerosol radiative forcing is very likely opposite in sign of GHG forcing in the global average but may be similar in magnitude. Owing to short atmospheric residence times, aerosol distributions are highly variable. Gaining a better understanding of their weather and climate impacts requires better characterization of their properties and their distributions over space and time.

Actions taken: GMD manages a collaborative network of stations that measures surface aerosol scattering and absorption at 27 locations around the globe and column AOD at 13 locations, ranging from clean, remote sites, to sites with regionally representative aerosol types (e.g., anthropogenic emissions or dust).

Completing the new tower and sampling inlet construction at the Bondville Environmental and Atmospheric Research Site (Photo credit: Sybil Anderson)

What we've discovered: Recent analyses show decreases in tropospheric aerosol at many sites, however long-term measurements in Hawaii and shorter records at Asian sites indicate upward trends. The stratospheric component of the column aerosol extinction in the Northern Hemisphere has been found to track volcanic emissions exceptionally well and may be used to detect stratospheric aerosol changes from natural or human activities, such as attempts at geoengineering. Evaluation of satellite-based aerosol extinction using GMD in situ measurements suggest limitations in the satellite data for evaluating such trends, owing to a lack of sensitivity, drift of sensors, and cloud screening errors.

Future actions: GMD will continue to collaborate with others in the U.S. and internationally to improve spatial and temporal coverage of surface in situ measurements in different aerosol regimes, and is expanding aerosol optical depth measurement locations across the continental U.S. These measurements will continue to help evaluate how well climate models simulate aerosol spatial and temporal distribution. Spectral upgrades have been performed at existing sites for AOD measurement sites, allowing for improved retrievals of column aerosol size and absorption. In 2018, vertical aerosol profiling capabilities will be added to seven U.S. locations that will eventually provide better understanding of the impact of vertical structure on aerosol radiative forcing.

Impact: While GHGs operate on long time-scales, aerosol processes influence climate on long and short time-scales through feedback processes and instantaneous radiative forcing. Recent theoretical studies show opposing effects of GHGs and aerosol particles on cloud and precipitation distribution. Understanding the overall impact of these disparate processes on climate requires a more detailed characterization of their properties and variability across time and space.

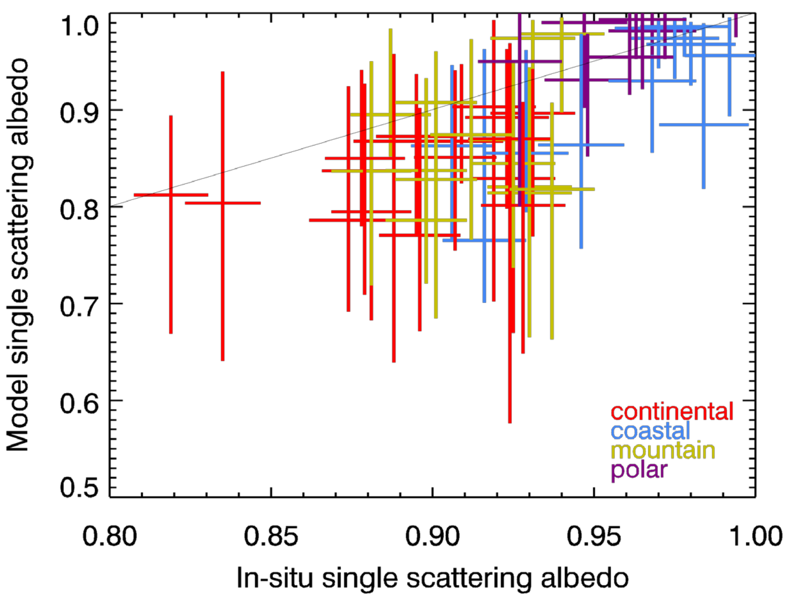
Question 4: How do changes in atmospheric black carbon and other light absorbing aerosol amounts influence lower atmospheric heating and cloud prevalence?

Relevance: Light absorbing aerosols can cause heating in the atmosphere and at the surface on local-to-regional scales, with potentially profound effects on cloud development and lifetimes, atmospheric dynamics, and circulation patterns. The radiative impact of absorbing aerosol particles is dictated by their vertical distribution as well as whether the particles are co-located with clouds, cloud type, the atmospheric dynamical regime and surface albedo.

Actions taken: GMD has monitored surface aerosol absorption and black carbon concentrations at many locations around the world, in some places for several decades, and has previously monitored the vertical distribution of absorbing aerosols using instrumented light aircraft.

What we've discovered: Absorbing aerosol particles are ubiquitous – they are measured at remote locations such as the South Pole – but the spatial and temporal variability recorded at many long-term monitoring sites cannot be reproduced by climate models. Additionally, our analyses suggest that there is a consistent discrepancy between airborne in situ measurements and remote sensing retrievals of column aerosol absorption, although determining where the errors lie requires further research.

Future actions: The instrument upgrades outlined above (Q3) allow for the retrieval of absorbing aerosol optical depth (AAOD) with greater sensitivity and temporal resolution than the existing, commonly used instruments and techniques. Current approaches will be comprehensively evaluated against the new, more sensitive methods to estimate the extent of biases in a range of aerosol regimes. Efforts to evaluate and improve model simulations of aerosol absorption with surface in situ measurements (Q3) will continue.



Comparison of annual median measured and modeled single scattering albedo at 550 nm at the surface, showing the large range in this climatically-important aerosol property for continental, coastal, mountain, and polar measurement regimes. Horizontal bars indicate uncertainty in the in situ measurements; vertical bars indicate range in model output for the 13 models participating in this AeroCom Phase III study. Bars cross at the model and in situ median values.

Impact: Currently, aerosol absorption cannot be determined from satellite-based measurements with the accuracy required. Integrating existing surface in situ observations into model studies will represent an appreciable step forward in placing constraints on models, adding value to the common practice of using only column integrated measurements. Our new remote sensing capabilities for retrieving column AAOD will place similar contraints on the existing observations.

Question 5: How do changing ozone, aerosol, cloud, and surface properties affect the distribution of ultraviolet radiation at Earth's surface and what are the implications for issues such as human health and marine ecosystems?

Relevance: Changing stratospheric ozone levels have caused levels of ultraviolet radiation (UVR) reaching Earth's surface to vary geographically and through time owing to emissions of ozone-depleting gases (ODS) and subsequent mitigation efforts (e.g., Montreal Protocol). Changes in UVR at the surface have a range of effects on marine and terrestrial ecosystems as well as human health. Levels of ozone in the atmosphere impact tropospheric chemistry, particularly production of the hydroxyl radical (OH), which is responsible for removal of atmospheric organics. However, factors other than ozone control UVR at the surface – most notably clouds, aerosols, and surface cover – thus measurements of spectral irradiance at the surface coincident with controlling influences are required to understand these impacts.

Actions taken: NOAA, with cooperation from EPA, established the NOAA Environmental Ultraviolet-ozone Brewer (NEUBrew) Network of Brewer Mark IV UV spectrometers in 2006 at six U.S. locations that produce absolute spectral UV irradiance. The network of Brewer instruments are currently focused on taking spectral UV irradiance (286-363 nm), instantaneous UV index, and daily erythemal dose. NOAA has also assumed operations of the former Antarctic National Science Foundation (NSF) UV Monitoring Network where multi-channel radiometers are deployed at McMurdo, Palmer, and South Pole stations. These measurements have been used extensively for satellite data product evaluation and a range of process studies.

What we've discovered: Variability in cloud cover and surface cover (e.g., the presence of snow) have a stronger correlation to UV surface radiation than ozone. While the UVB dose at the surface depends on changing ozone levels, better understanding of environmental controls on surface UVR is required for assessing these risks.

Future actions: GMD will seek to improve activities related to UV instrument calibration, characterization, and operation that allow for better accuracy in measuring UV irradiance and retrieving column profiles of ozone. Data products are being developed for spectral UV aerosol optical depth and actinic flux to aid in tracking processes that impact on UVR.

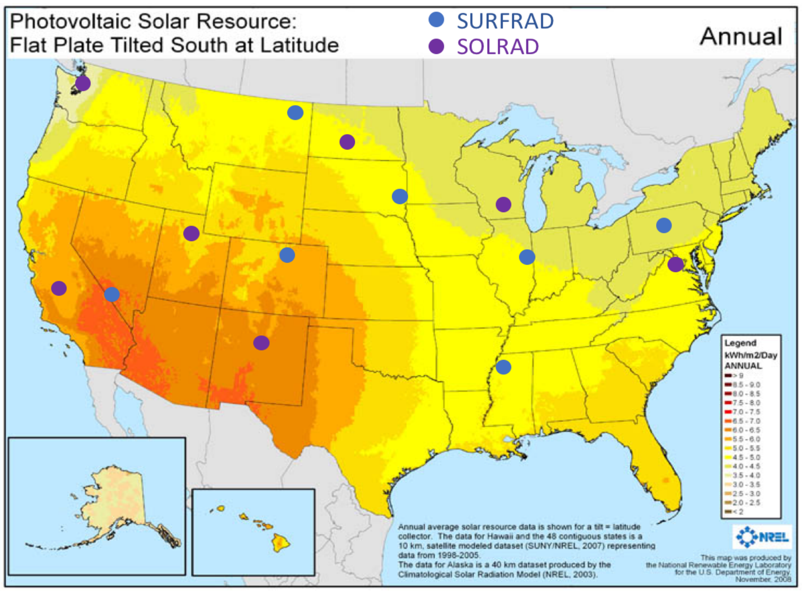
Impact: Spectral UVR measurements at Earth's surface are required for understanding variability due to changing ozone levels and response to variations in associated factors such as clouds, aerosols, and surface cover. A more complete characterization of these processes and evaluation of satellite-based retrievals is required for providing reliable UV Index forecasts relevant for humans and ecosystems. GMD's UV networks cover diverse geographical locations critical for validation and identification of areas that need improvement in the NOAA NWS UV Index forecasts.

Question 6: What are the impacts of current and future weather and climate states on solar and wind energy resource availability and efficiency?

Relevance: The availability of wind and solar driven energy is contingent upon weather, which is largely driven by energy at Earth's surface. Engaging atmospheric sciences to improve short-term weather forecasts specific to alternative energy resources is essential for advancing an efficient carbon-free energy system and concomitantly mitigating climate change.

Actions taken: GMD has participated in several projects supported by NOAA and DOE to improve Numerical Weather Prediction (NWP) model representations of land-atmosphere processes critical to effective and efficient exploitation of renewable wind and solar energy resources.

What we've discovered: Measurement-model comparisons have led to the identification of model biases resulting from inadequacies in cumulus cloud parameterizations, land surface model errors in energy exchange with the atmosphere, surface albedo characterizations, and aerosol properties. Addressing model errors with observations has resulted in a reduction of the surface solar radiation resource corresponding to a temperature bias reduction of ~70% at the 2 meter level over the U.S. Great Plains.

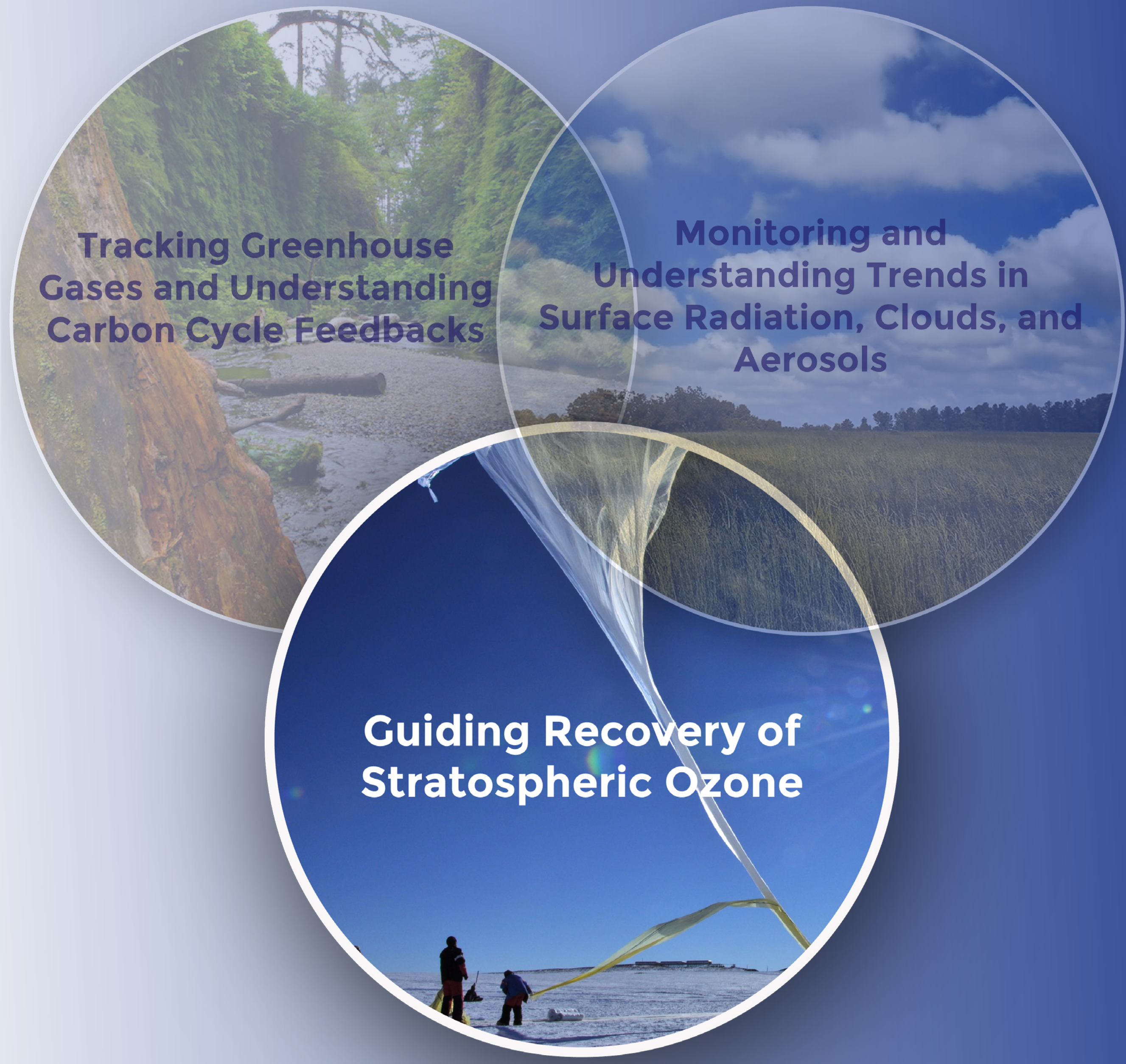


National Renewable Energy Laboratory (NREL) produces solar resource maps based on the National Solar Radiation Database (NSRDB) developed from empirical, semi-empirical, and more recently physical models. SURFRAD and SOLRAD network data are essential high-quality radiation sites for validation of the NSRDB solar products including Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI). The NSRDB is a publicly available resource to support and reduce costs for siting, financing, and deployment of solar renewable energy (NREL NSRDB, https://www.nrel.gov/gis/solar.html).

***Future actions*:** The NOAA Atmospheric Science for Renewable Energy (ASRE) program is embarking on a 5-year project to better understand boundary layer processes and how they relate to cloud formation distribution and attenuation of solar irradiance at the surface, to improve their representations in NWP, and to improve predictions of the solar power resource and variability (ramping) for the day-ahead (24 to 48 hour) forecast period. As part of this project, GMD will add cloud property monitoring capabilities to its SURFRAD sites across the U.S. and will work closely with NWP model developers to implement improvements in NOAA foundational research weather prediction models.

Impact: Clouds are the primary modulator of the amount and variability of solar irradiance at the surface and thus the availability of solar power. The SRB also controls the processes that to a large extent drive boundary layer winds. With expertise in cloud radiative effects and the surface radiation budget, GMD is well poised to provide robust evaluations of the potential of renewable energy modalities for reducing emissions as well as helping to develop the efficiency and effectiveness of strategies for implementation. Such progress is essential for the future environmental and economic security and health of the U.S. and its citizens. An additional benefit of this work will be improvements to operational NWP for general weather forecasts.

Research Theme 3: Guiding Recovery of Stratospheric Ozone



Research Theme 3: Guiding Recovery of Stratospheric Ozone

Depletion of stratospheric ozone can result in enhanced UV radiation levels that increase skin cancer rates and adversely affect organisms and ecosystems. Concern over these effects provided impetus for ratifying the 1987 Montreal Protocol, enacting the U.S. Clean Air Act of 1990, and initiating GMD's global-scale monitoring of stratospheric ozone and the gases responsible for its destruction.

GMD has developed a carefully designed network to monitor variations in ozone, ozone-depleting substances, stratospheric aerosols, and UV radiation. GMD research has been critical in determining long-term changes in concentrations of stratospheric ozone and chemicals causing ozone depletion. Our unique long-term observational records have led to an improved understanding of the production and fate of stratospheric ozone and the compounds and processes that influence ozone's abundance. These advances have furthered our understanding of the fundamental atmospheric processes affecting stratospheric ozone and provide usable information to policy makers for guiding the recovery of the ozone layer.

GMD conducts year round balloon-borne vertical structure and total column optical measurements of ozone over the South Pole. During the winter (preceding the early springtime Antarctic "ozone hole"), satellites are unable to measure polar ozone without sunlight. GMD monitors stratospheric ozone at lower latitudes and in the Arctic, measures the gases responsible for depletion of stratospheric ozone, and monitors changes in ultraviolet radiation that is controlled by the amount of ozone in the stratosphere. As such, understanding the production and fate of ozone and the ozone-depleting compounds is a focal point of GMD research.

Ground based measurements of total-column ozone have been made for over 50 years with the Dobson spectrophotometer; the 14-station GMD Cooperative Dobson Network is a significant portion of the global Dobson network as are the six GMD balloon-borne ozonesonde stations. These stratospheric ozone measurements are linked to the world calibration standards maintained by GMD as are a preponderance of the stations in other international global networks.

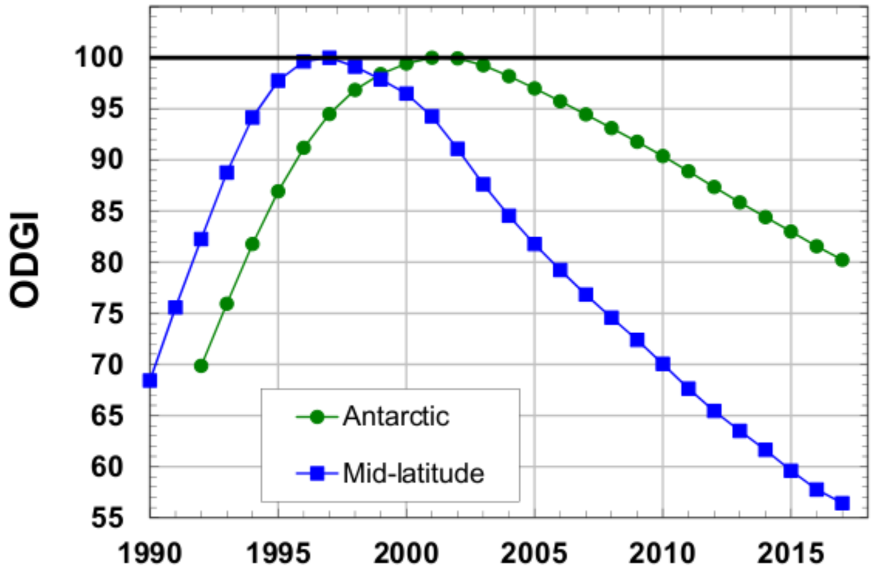
Three gases that make a significant contribution to stratospheric ozone depletion, CFC-11, CFC-12 and N_2O, have been monitored by GMD since the mid-1970s. Since then, numerous additional CFCs, HCFCs, and other halogenated gases have been incorporated into the measurement program as the number of monitoring sites increased. Most of the gases that are responsible for depleting stratospheric ozone are anthropogenic, but some, such as methyl bromide and methyl chloride, have natural contributions as well.

Question 1: Is the fully revised and amended Montreal Protocol successfully reducing the threat to stratospheric ozone posed by ozone-depleting substances?

Relevance: The intention of international and national controls on the production of ozone-depleting substances (ODSs) is to reduce atmospheric concentrations of these substances and allow for the stratospheric ozone layer to recover. This will bring UV radiation and, potentially, skin cancer rates back to their pre-ozone hole levels, and reduce the risk to agriculture and ecosystems.

Actions Taken: GMD continues to monitor the abundance and global distribution of ODSs at surface sites across the globe to ascertain if global production controls are having their desired effect. Changes in the summed atmospheric concentration of ODSs are tracked and updated annually with GMD's Ozone-Depleting Gas Index (ODGI). GMD also coordinates with other groups (e.g., the Advanced Global Atmospheric Gases Experiment (AGAGE)) to compare independent global measurements and calibration scales for ODSs.

What we've discovered: GMD results have demonstrated the ongoing success of the Montreal Protocol and U.S. Clean Air Act in reducing the concentrations of ODSs and, therefore, the threat they pose to the ozone layer. The summed concentration of ODSs has decreased steadily for over two decades, although increases in some short-lived chlorinated gases not controlled under the Protocol have been observed.



The Ozone-Depleting Gas Index (ODGI) vs. time calculated for the Antarctic and mid-latitude stratosphere. The ODGI is derived directly from the Equivalent Effective Stratospheric Chlorine (EESC) determined from GMD's atmospheric surface observations.

***Future Actions*:**
- Continue ongoing measurements of gases currently in the ODGI and others that pose a threat to the ozone layer.
- Inform policy-makers of the effectiveness of existing legislation and agreements for controlling atmospheric levels of ODSs through international scientific assessments, the extent to which "natural" processes and climate change affect atmospheric concentrations of ODSs, and the extent to which ODS substitutes are offsetting the climate benefits provided by the Montreal Protocol.
- Further guide ozone layer recovery by monitoring ozone trends and providing estimates of U.S. emissions of ODSs and their substitutes.

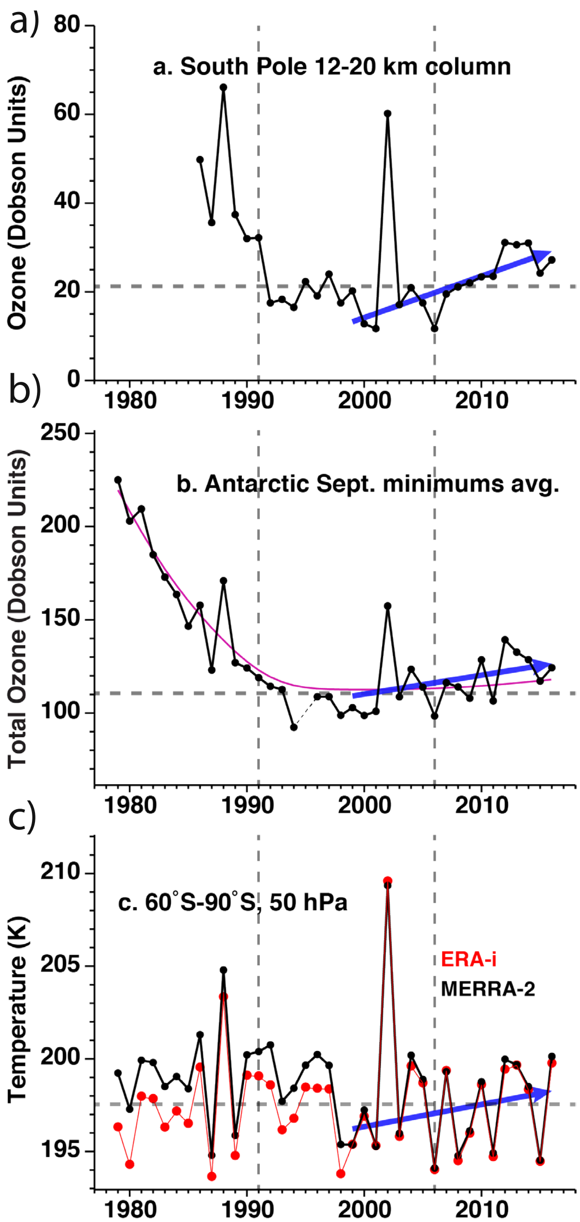
Impact: National and international policy makers will continue to have the best possible information to assess the effectiveness of existing policy on ozone-layer recovery, and understand the unanticipated consequences of increasing use of CFC replacements on climate change.

Question 2: Is stratospheric ozone recovering as expected?

Relevance: The implementation of the Montreal protocol and its amendments bans ozone-depleting substances from production. Levels of these harmful substances are decreasing (Q1), but still remain relatively high in the stratosphere. These reductions are expected to increase stratospheric ozone levels by the middle of this century and bring UV radiation and skin cancer rates back to their pre-ozone hole levels. However, changes in the atmospheric greenhouse gases are shown to impact on recovery of stratospheric ozone. The variability in future ODS and GHG levels in the atmosphere makes it difficult to predict ozone recovery and thus requires ozone levels to be continuously monitored.

Actions Taken: GMD's global, long-term monitoring of ozone is a core element of international ozone measurement networks. The results from GMD's program help distinguish between short and long-term processes, and enable the proper attribution of ozone changes to chemical and climate-related processes. GMD monitors decadal change in ozone at several research sites at strategic locations around the globe. Stratospheric and total column ozone trends are assessed from long-term, calibrated and quality assured records of ozonesonde balloon profiles, ground-based total column and vertical profile (Dobson Umkehr) ozone measurements. GMD provides the only year-round measurements at the South Pole to track ozone hole recovery.

What we've discovered: Historically, ozone decreased substantially as the concentrations of ODSs increased. After ODS concentrations peaked and began to decrease in the early 2000s, GMD-measured ozone levels in Antarctica stopped decreasing and have since shown the first signs of recovery. More recently, there is mounting evidence that ozone is recovering in the stratosphere. Moreover, at the South Pole station, GMD ozonesonde records collected during September show statistically significant ozone recovery since 2000. Nonetheless, large year-to-year variability in the stability of the Polar vortex due to climatically changing meteorological conditions and associated variability in ozone depletion levels requires continuous monitoring of stratospheric ozone.



Plots of GMD data showing the onset of ozone recovery and its impact on stratospheric temperature. (a) Column ozone measured within the primary depletion layer from 12 to 20 km by NOAA South Pole ozonesondes during the 21 September to 16 October period. (b) Satellite daily total ozone minimum values averaged over the 21 September to 16 October period. (c) 50-hPa September temperature averaged over 60–90˚S for Modern-Era Retrospective analysis for Research and Applications (MERRA-2 [black points]) and for European Reanalysis (ERA-Interim [red points]). The blue lines in each panel show the 1999–2016 trend, while the horizontal dashed lines show the 1991–2006 average values. The magenta curve in (b) is the quadratic fit of total ozone to EESC (BAMS State of the Climate Report, 98 (8), S170, August 2017).

Future Actions:
- Evaluate whether observed changes in ozone are consistent with those expected on the basis of GMDs measured changes in ODSs.
- Gauge the impact of other processes on stratospheric ozone trends such as volcanoes, increased methane, water vapor and nitrous oxide concentrations, and changes in stratospheric temperatures and circulation.

Impact: These continued efforts help policy makers and scientists around the world assess the effectiveness of international actions to allow the recovery of stratospheric ozone to pre-1980 levels, and help those communities to understand how policies have affected climate change. With full ozone-layer recovery anticipated by mid- to late-century, society will no longer face the impacts of increased UV radiation on human health and agriculture.

Question 3: How is the Brewer-Dobson circulation changing in response to increased greenhouse gas concentrations and how has this altered the global distribution of ozone and the atmospheric lifetimes of ozone-depleting and climate altering gases?

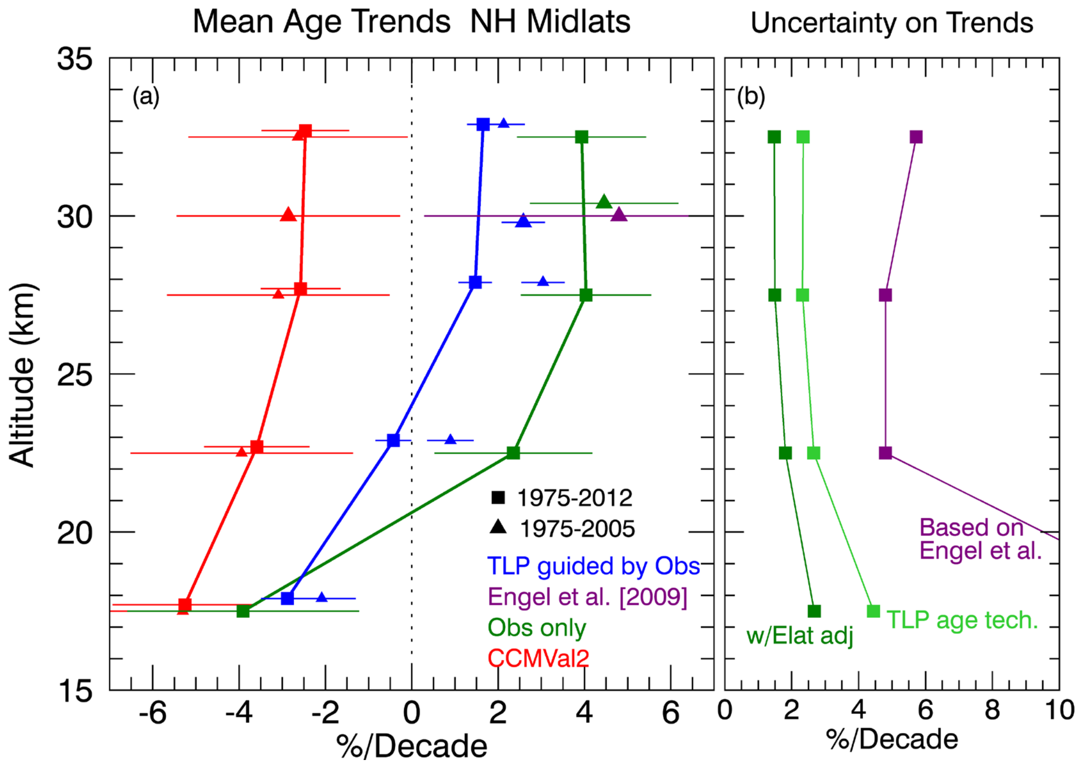
Relevance: Mean Brewer-Dobson circulation (BDC) affects ozone recovery in the stratosphere by modifying the lifetimes of the ozone-depleting species, by changing the local, highly nonlinear ozone chemistry, and by directly changing the distribution of ozone-depleting gases brought up from the troposphere. Tropical lower stratospheric water vapor is a sensitive indicator of changes in the strength of the BDC that alter cold point temperatures in the tropics. A larger impact of the change in BDC is that it affects circulation in the troposphere. The BDC appears to be increasing at altitudes below 25 km based on estimates of the mean age of stratospheric air. This result is expected from Global Climate Models as the lower tropospheric temperature increases from increased emissions of GHGs. In contrast, recovery of stratospheric ozone could weaken the BDC.

Actions Taken: GMD observations, along with others, have been used to infer changes in the mean-age of stratospheric air. However, stratospheric observations of trace gases that would help identify trends in BDC are not performed on a regular basis. GMD developed a plan to determine BDC changes using stratospheric age of air using AirCores and is currently working to support a three-year experimental campaign to measure numerous trace gases using AirCores and balloon-borne instruments at 4-5 locations around the world.

What we've discovered: Ozone depletion and climate models need to realistically take into account stratospheric circulation and its changes. At present, stratospheric circulation is poorly defined by stratospheric wind data assimilated into 3D models. The mean age of stratosphere air, derived from measurements of trace gases, shows that stratospheric circulation has been changing over the last 37 years. We have observed a decrease in the mean age of air at altitudes <25 km.

Future Actions:
We plan to continue monitoring changes in the mean age of air in the upper atmosphere through our efforts to measure atmospheric composition from NASA aircraft, deploy in situ instruments and launch AirCores on NOAA balloons, and fill flasks for analysis in Boulder. We will continue to monitor ozone, temperature, water vapor and other trace species in the stratosphere and troposphere to detect changes in atmospheric composition and to provide input to Global Climate Models.

Impact: Faster stratospheric circulation will alter the lifetimes of trace gases destroyed by photolysis in the stratosphere and impinge on circulation in the troposphere. Understanding these changes will improve climate and ozone analyses and ultimately predictions of Earth system behavior.



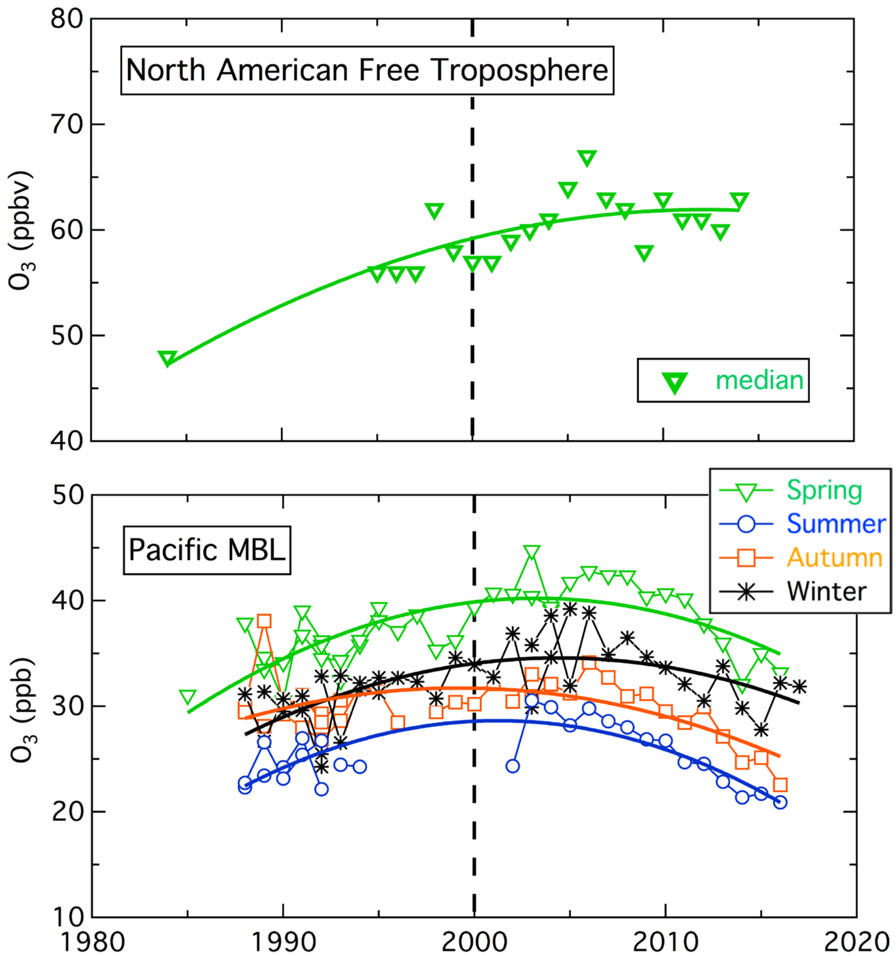
Trends in mean age of stratospheric air derived from measurements of SF_6 and CO_2 and by climate models as a function of altitude. The observations (dark green and violet) and a relatively simple model guided by observations (blue) show negative trends only in the lower stratosphere (below 20 km) (negative trend means faster BDC). In contrast, a composite of four climate models (red) shows negative trends at all altitudes (17-33 km). The right panel shows how observational uncertainties (Engel et al., Nature Geosci., 2, 28-31, 2009) can be reduced by augmenting the observations using a simple model (tropical leaky pipe (TLP) age tech.) (Ray et al., J. Geophys. Res., 121, 5356–5367, 2015) and by correcting for short-term variability in atmospheric transport (w/Elat adj).

Question 4: How sensitive is the oxidative capacity of the atmosphere and how is it changing over time?

Relevance: Atmospheric oxidation processes constantly cleanse the atmosphere of thousands of tons of reactive gases emitted by humans each year, including some that impact on stratospheric ozone. These human-derived pollutant emissions in turn affect the oxidative capacity of the atmosphere and its ability to cleanse itself of these pollutants.

Actions Taken: To track the oxidative capacity of the atmosphere, GMD has invested in long-term, high-quality measurements of short-lived halogenated gases (e.g., methyl chloroform), HCFCs, methane, surface ozone, and tropospheric and stratospheric ozone far away from the pollution sources and in locations with background conditions. The changes in atmospheric composition are regularly evaluated. The International Global Atmospheric Chemistry (IGAC) TOAR (Tropospheric Ozone Assessment Report, 2017) used GMD long-term records to evaluate changes in the global and regional tropospheric ozone burden.

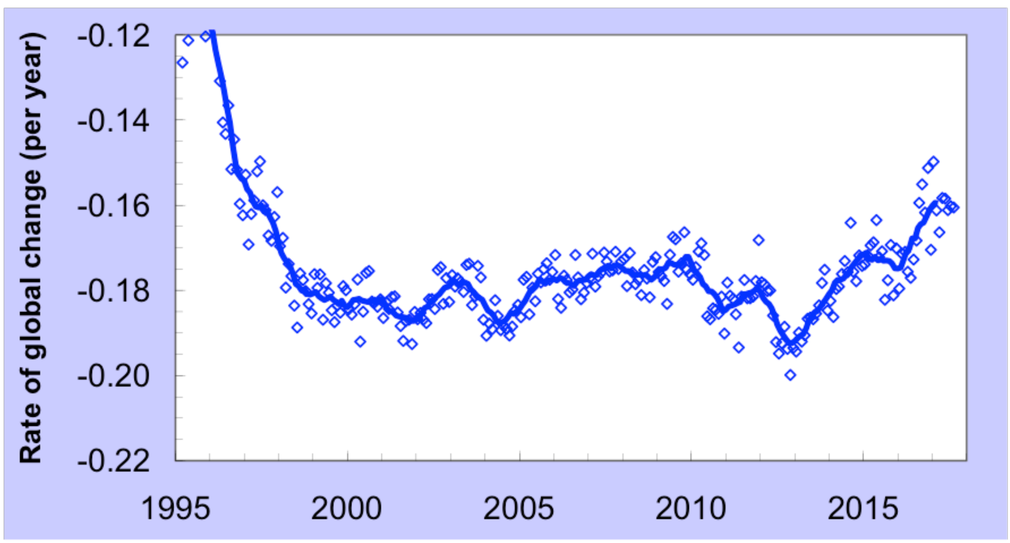
What we've discovered: Estimates based on global measurements of methyl chloroform have led to the conclusion that the oxidizing capacity of the atmosphere is well buffered against large interannual changes. Long-term changes, specifically of hydroxyl radical concentrations, are still possible. Ultimately, the stability of this oxidizing capacity will depend on the potential for significant increases in pollutant emissions and the resulting build up in background tropospheric ozone, as developing countries continue to industrialize. GMD records show that the tropospheric ozone burden is changing regionally and globally, while the location of the enhanced ozone precursors has recently moved to the tropics from mid-latitudes, where they have a larger impact on the global tropospheric ozone burden. Changes in the upper and lower troposphere have also been observed with satellites, but those records are not mature and differ from one another. GMD's long-term and globally distributed tropospheric ozone measurements provide critical information essential for improvement of climate chemistry and chemical transport models' prediction skill.



Long-term changes in tropospheric O_3 burden (North American Free Troposphere, top) and in the background ozone levels in the Pacific Marine Boundary Layer (Pacific MBL, bottom) observed at the Trinidad Head, CA measurement site (former GMD Atmospheric Baseline Observatory). GMD observations indicate the impact of the Asian pollution emissions reaching the North American coast and point to the recent leveling off in the transported pollution. The solid lines give the least squares regression fit to the data (modified from figure in Parrish et al., Geophysical Research Letters, 44,10, 675–10,681, 2017).

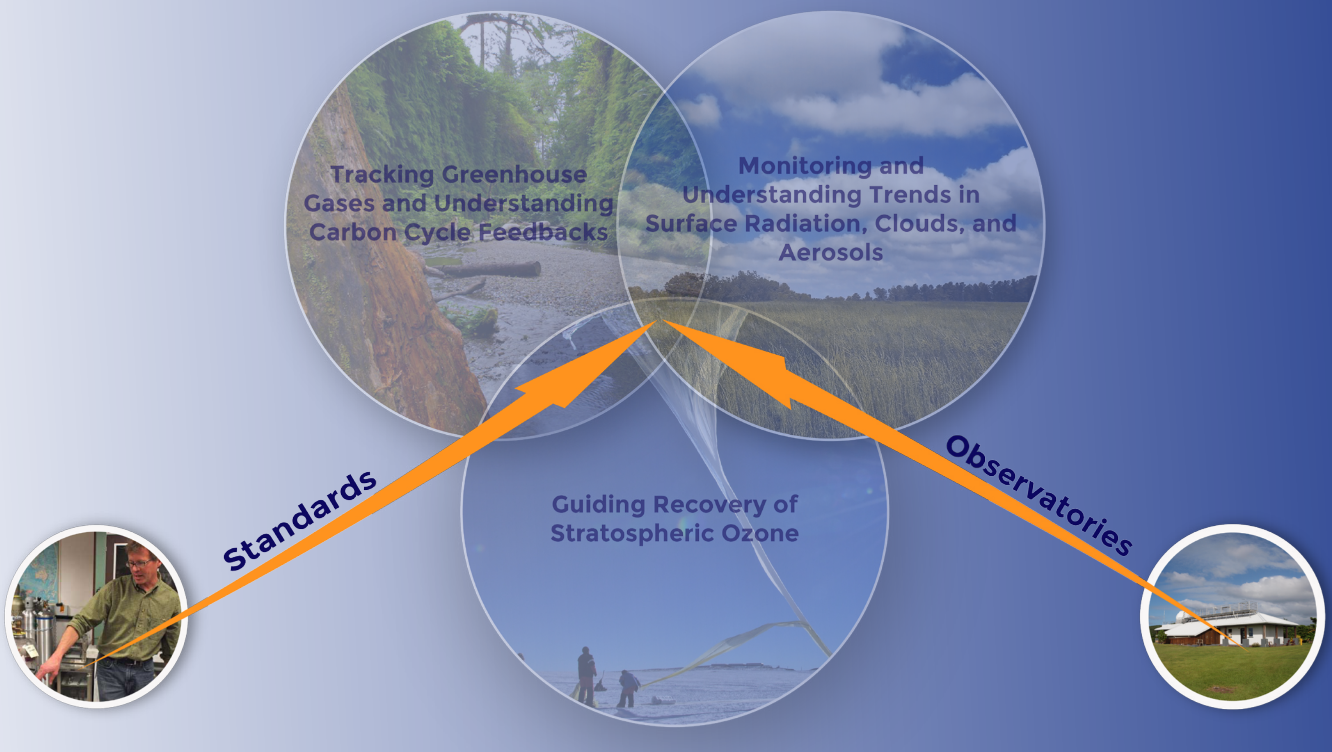
***Future Actions*:**
While methyl chloroform has provided the most accurate view of global OH changes in the past, its concentration has decreased to the point where it will soon not be useful for diagnosing changes in the global oxidizing capacity and hydroxyl radical concentrations. Future actions will

- develop other methods and continue to explore approaches for determining changes in oxidizing capacity in the absence of methyl chloroform. Initial work has identified a number of other gases that, along with unique analysis tools, could be used to diagnose oxidizing capacity on broad scales and we will continue this effort,
- quantify the effects of short-lived halogenated gases and degradation products on tropospheric ozone over broad atmospheric scales,
- continue to evaluate the contribution of stratosphere-troposphere exchange, climate-impacted changes in the long-range transport patterns on the concentrations of ozone, carbon monoxide, and other pollutants reaching the U.S. through measurements of surface, tropospheric and stratospheric ozone in the locations remote from the pollution sources, and
- relate changes in tropospheric OH to stratospheric ozone recovery through investigating the impact on lifetimes of HCFCs and HFCs.



The observed rate of change in global mean concentration of methyl chloroform over the past 20 years as measured in the NOAA/HATS group. This record implies that the methyl chloroform loss rate and, therefore, the global oxidizing capacity and mean global OH concentrations have not varied by more than a few percent from year-to-year over the past two decades (since 1998; pre-1998 rates were less negative because of continuing methyl chloroform emissions).

Impact: Understanding the oxidizing capacity is essential for understanding tropospheric chemistry, tropospheric ozone formation and loss, and the atmospheric lifetimes of methane, HCFCs, and other long-lived gases primarily removed from the atmosphere by oxidation by the hydroxyl radical. Understanding these processes will afford national and regional policy makers the opportunity to set realistic guidelines for emissions of chemicals affecting tropospheric composition and associated air quality.



The ability to answer GMD's research questions depends on high-quality, well-calibrated measurements made at our Atmospheric Baseline Observatories and global networks. The world relies on GMD's calibrations, standards, and infrastructure.

GMD's Supporting Infrastructure

GMD Standards and Calibrations

Accurate and reliable calibrations are an essential component of all high-quality measurement programs. Instrumental bias or drift can have a significant impact on our ability to accurately interpret physical spatial gradients and trends of interest. For data from multiple instruments or measurement networks to be interpreted together, they must be linked to common calibration scales and operating protocols.

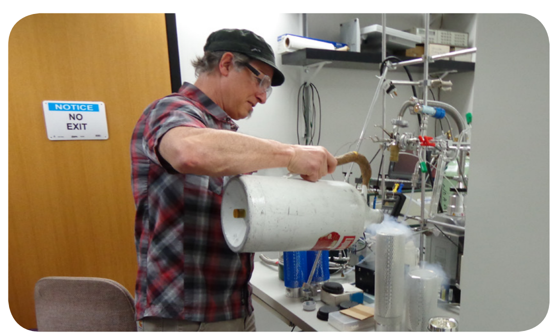
Performing a Dobson ozone measurement comparison.

GMD calibration activities support measurements of greenhouse gases, aerosols, ozone-depleting gases, column ozone, and shortwave and longwave radiation. GMD serves as the World Meteorological Organization / Global Atmosphere Watch (WMO/GAW) Central Calibration Laboratory for five gases (CO_2, CH_4, N_2O, SF_6, CO) and the World Calibration Center for the WMO standard Dobson. For WMO Region 4, GMD is the Regional Calibration Center for the Dobson ozone network (total column ozone), and the Regional Radiation Center for broadband radiation calibrations. Participation in these activities minimizes bias within the WMO/GAW measurement network, of which NOAA GMD is a major contributor. GMD offers trace gas reference materials and calibration services to WMO/GAW and other partners, calibrates Dobson Regional standard instruments to transfer the World ozone standard to the global network, calibrates standard ultraviolet lamps to promote compatibility in spectral UV irradiance measurements, and transfers standard calibrations for shortwave and longwave broadband irradiance for regional measurement groups and others.

GMD collaborates with National Metrology Institutes (such as NIST) and others including the Bureau of International Weights and Measures (BIPM), the WMO Commission for Instruments and Methods of Observations (CIMO), and WMO/GAW central facilities, to improve traceability of all observations.

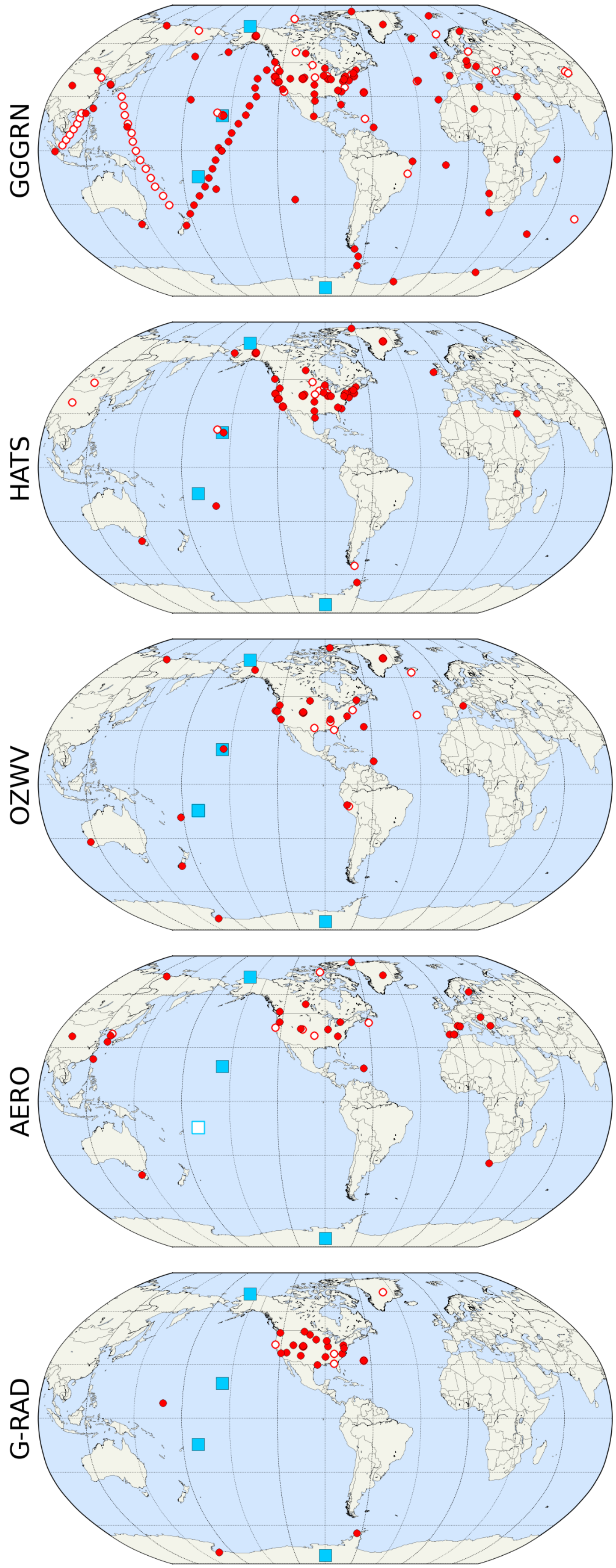
In this effort, GMD will continue to

- support WMO and related research communities,
- improve the accuracy of the CO_2 and other calibration scales,
- participate in the evaluation of a new standard for longwave irradiance,
- improve shortwave irradiance calibrations regarding infrared loss from sensors,
- expand common calibration services within the surface radiation measurement community,
- maintain accurate and stable calibrations for the World Dobson and Regional standards,
- train Dobson operators on common QA/QC practices, and
- prepare and circulate hundreds of trace gas standards each year.



Extracting CO_2 from air during manometric analysis

GMD Observing Networks



GMD's data originate from its monitoring sites, which are functionally divided into five research groups based on measurement capability to monitor different atmospheric properties. The Carbon Cycle Greenhouse Gases (CCGG) group manages the Global Greenhouse Gas Reference Network (GGGRN) that measures the atmospheric distribution and trends of CO_2, CH_4, N_2O, and CO at more than 50 sites. CCGG and the Halocarbon and other Atmospheric Trace Species (HATS) groups use GGGRN in situ measurements and discrete air sampling to characterize ~50 trace gas concentrations at very low levels. These measurements are made from a variety of platforms, e.g., surface sites using portable samplers, automated sensor suites at observatories and very tall (> 300 m) radio and TV towers, and aboard light aircraft, flying from the surface to as high as 8 km above sea level. The Ozone and Water Vapor (OZWV) group makes measurements regularly from surface-based, remote sensing instruments, balloon-based in situ sensors, and surface in situ instruments at a variety of locations worldwide. Measurements of in situ aerosol optical properties are made by the Aerosol (AERO) group at 27 regionally representative, long-term, surface sites around the globe. Downwelling solar global, direct, diffuse, and infrared radiation measurements are made by the Global Radiation (G-RAD) group with the aid of sun-tracking platforms at surface-based sites and nearby towers are the mounting point for corresponding upwelling solar and infrared measurements.

Blue squares show the four Atmospheric Baseline Observatories. Red circles indicate surface, balloon, tower or aircraft sites. Several surface and airborne sites have ceased operation recently and are shown as open red circles.

Atmospheric Baseline Observatories

The four Atmospheric Baseline Observatories provide a monitoring backbone of GMD's networks. Geographically distributed across the Pacific basin from north to south, the sites include Utqiaġvik (Barrow), Alaska; Mauna Loa, Hawaii; Cape Matatula, American Samoa; and South Pole, Antarctica. Each of the sites is located in the remote atmosphere, and samples extremely clean air, allowing them to accurately represent the background atmosphere at their respective locations. The observatories form the backbone of NOAA's and WMO's efforts to monitor climate, atmospheric composition, and ozone recovery.

The four Atmospheric Baseline Observatories also host cooperative research projects for other federal agencies, universities, and international partners. These cooperative projects assess the natural processes, distributions, and fluxes of greenhouse gases, ozone and ozone-depleting compounds, aerosols, the surface radiation budget, and various other environmental parameters. Together, up to 250 different data sets are produced at each observatory relating to climate, ozone, and atmospheric composition. These measurements are calibrated, maintained, and archived by a trained workforce at each observatory site and in Boulder, Colorado.

As the need for a better understanding of the climate system increases, the role of the NOAA Atmospheric Baseline Observatories and collaboration with global cooperative networks will become even more crucial to the study of atmospheric composition as it influences and responds to climate change. The long-term measurements made at these sites record Earth's changing atmosphere and provide current and future generations with unbiased data on the health of our background atmosphere.

In an effort to strengthen the contribution of the observatories to our scientific understanding and meet NOAA's mission, GMD will take the following actions:

Future Action: Improve infrastructure to facilitate and support research.

> **Impact**: Modernized infrastructure will allow an increase in research programs at the four baseline observatories. This will result in extending national and international networks and offering opportunities for GMD to advance its instrumentation and measurement techniques, keeping its measurements at the forefront of science and broadening their applicability.

Future Action: Increase green technologies at each site to reduce energy use.

> **Impact**: Reducing fossil fuel consumption at these remote, pristine observatories will save significant utility costs, thus improving GMD's ability to maintain these sites over time. This effort also helps NOAA to meet E.O. 13514 to increase renewable energy generation at Federal sites.

Future Action: Promote interdisciplinary research programs at the baseline observatories.

> **Impact**: Crosscutting "super-sites" that allow for multi-disciplinary and complementary science reduce overall logistical costs and better inform society about climate impacts on the planet. This will further enhance the linkages between the atmospheric climate system and oceanic, ecological, and social systems, as co-located measurements provide an element of synergy and improve on the ability to interpret the data streams.

Crossing the Transantarctic Mountains, the New York Air National Guard supports South Pole station from October to February each year, transporting supplies, food, fuel, and personnel in the LC-130 Hercules aircraft. Humans have not set foot on most of what is in this image, which is why the air at this remote site is considered pristine. (Photo credit: LT Joseph Phillips)

Barrow, Alaska (established 1973)

The Barrow Atmospheric Baseline Observatory (BRW) is located near sea level on the north coast of Alaska just to the east of Utqiaġvik (formerly known as the town of Barrow). As the northern most observatory hosting the longest records in the Arctic, BRW is essential for determining north-south gradients of many gases and other atmospheric properties. In addition, as the Arctic continues to warm, BRW will become an increasingly important site for monitoring atmospheric and Arctic change. Owing to its location, dedicated staff, and excellent power and communications infrastructure, the Barrow Observatory is host to numerous cooperative research projects from around the world. Within the past decade, the number of scientific programs has more than doubled. At present (2018), BRW has reached physical capacity and cannot support additional research programs without expansion of facilities.

The Barrow Atmospheric Baseline Observatory, Department of Energy Atmospheric Research Measurement, and United States Geological Survey Geomagnetic Observatory are co-located approximately 5 km outside of Utqiaġvik, Alaska. (Photo credit: Ross Burgener)

Mauna Loa Observatory viewed from upslope of the cooperative Climate Reference Network installation and precipitation gauge. (Photo credit: Matthew Martinsen)

Mauna Loa, Hawaii (established 1951)

The Mauna Loa Observatory (MLO), located at 3,397m elevation on the Mauna Loa volcano massif, is the premier, long-term, atmospheric observatory and research facility. MLO has been continuously monitoring and collecting data related to changes in atmospheric composition since the 1950s. The undisturbed air, remote location, and minimal influence of vegetation and human activity at MLO are ideal for monitoring constituents in Earth's background air that can cause climate change. MLO is also critically important for optical depth and ozone instrument calibration and comparison.

Cape Matatula, American Samoa (established 1973)

The American Samoa Observatory (SMO) is located in the middle of the South Pacific, on the northeastern tip of Tutuila Island, American Samoa. SMO is a key site in the GMD and WMO networks, because it is the only baseline observatory worldwide in the tropical Southern Hemisphere. It is important in defining north-south gradients of atmospheric composition and how they change with time. The prevailing easterly winds at 14° South make SMO a prime site for clean air sampling. It also hosts a long-standing comparison between measurements of the AGAGE and the GMD trace gas measurements.

The village of Tula (left) and the National Park of American Samoa (right) can be seen in the distance from the top of the observatory's tower. (Photo credit: LT Gavin Chensue)

The sun slowly sets on the Atmospheric Research Observatory, the National Science Foundation building housing NOAA's instruments at the South Pole. (Photo credit: LT Joseph Phillips)

South Pole, Antarctica (established 1957)

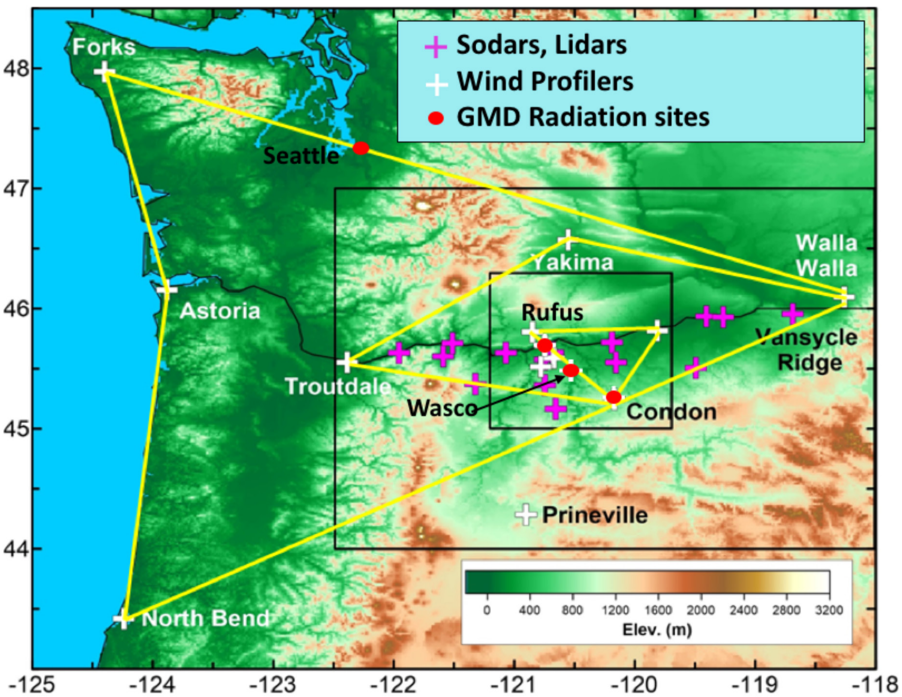
The South Pole Observatory (SPO), located at 2,837m elevation at the geographic South Pole, is high on the Antarctic plateau and 400m upwind of the NSF Amundsen-Scott South Pole Station. NSF provides infrastructure and logistics support for the GMD scientific operations at South Pole; GMD is responsible for managing the atmospheric science. The remoteness and negligible impact of life (animal or flora) at SPO provides pristine air samples. SPO is the only inland site on the Antarctic continent launching ozonesondes to measure the vertical distribution of ozone and is the prime location for detecting changes in stratospheric ozone.

GMD Research Applications

Application: Solar and Wind Forecasting for the Energy Sector

GMD is using its expertise and resources to provide atmospheric information that can improve accuracy and reliability of the electric grid. This will increase the penetration of renewable energy into the energy sector, a key to any climate change mitigation strategy. Integrating solar collecting and wind measurement systems into the nation's grid requires reliable weather and cloud forecasts, which in turn require high-quality observations as input for model improvement, verification, and data assimilation. The surface net radiation components measured by GMD's instrument systems represent the bulk of the available energy driving atmospheric dynamic processes. Improved forecasts of this available energy would enable power grid operators to schedule the optimal mix of power generation sources and avoid costly back-up reserves.

GMD works with other Divisions in the ESRL Atmospheric Science Renewable Energy (ASRE) program that focuses on the role of meteorology in wind and solar energy resource availability with an emphasis on serving the utility sector. GMD has participated in several projects including the DOE-NOAA Solar Forecasting Improvement Project I in 2014-2015 and the DOE-NOAA Wind Forecast Improvement Project in Complex Terrain (WFIP-2) 2016-2018, deploying a mobile SURFRAD station and two compact RadSys (radiation instrument systems) for 18 months at a cross-section of the study region. GMD's contribution to this study is to understand the diurnal and seasonal variability in radiation quantities across the region, how this variability correlates with planetary boundary layer (PBL) formation and wind characteristics at wind turbine hub-height, what its relationships to specific meteorological regimes (e.g., cold pools and mountain waves) are, and how well these processes are captured by NOAA'S Numerical Weather Prediction models.



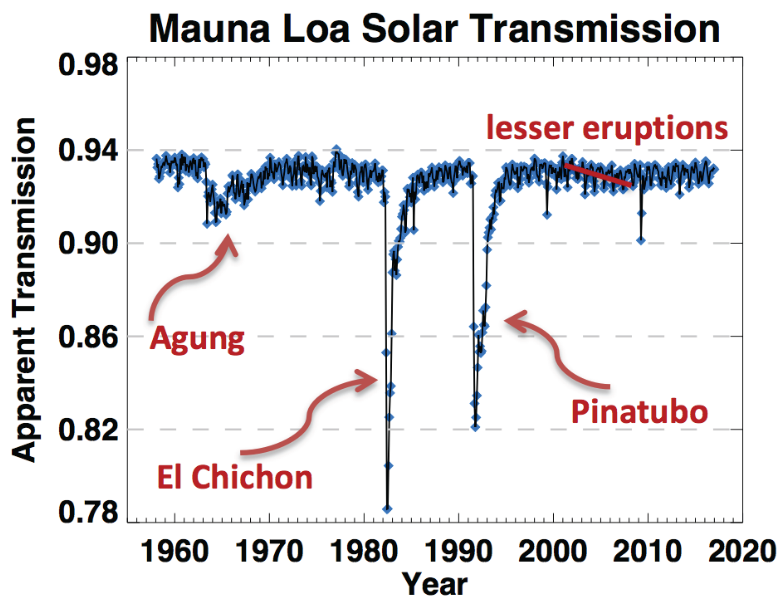
The WFIP-2 Project occurred in the Columbia River Basin, an area representing complex terrain. GMD deployed instrumentation at Rufus, Wasco, and Condon, OR. The long-term SOLRAD site at Seattle, WA was also °within the WFIP-2 domain. The yellow lines define multi-scale study regions within the project.

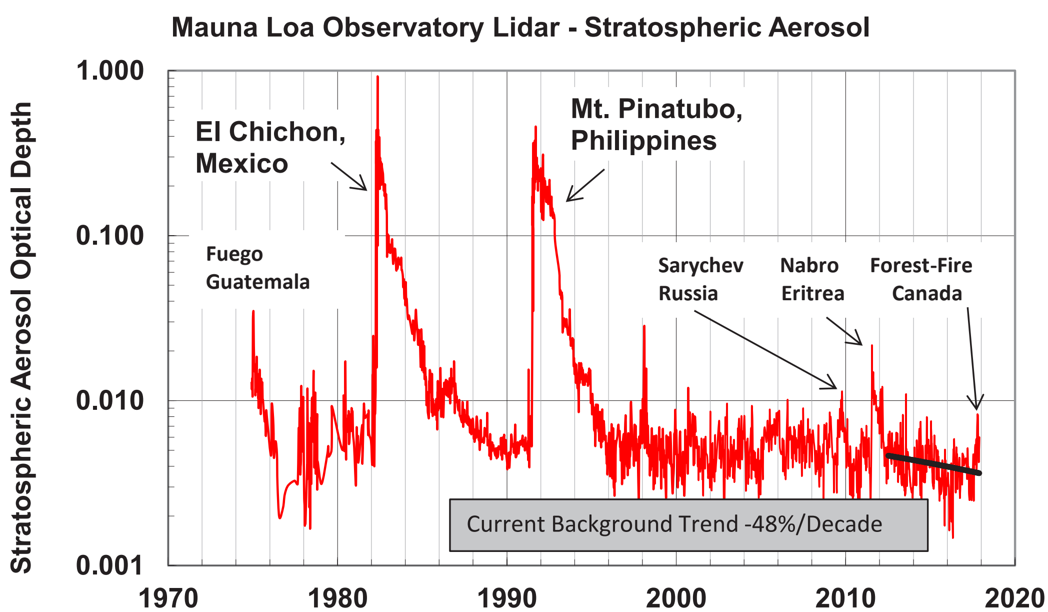
One of the greatest challenges in solar resource forecasting is predicting the temporal and spatial variability of clouds and conveying the uncertainties in these forecasts. In future research studies with the ASRE team, GMD's radiation, cloud, and aerosol measurements at long-term sites will be used to evaluate and improve the representation of sub-grid scale clouds in NWP. As a component to this project, new CL-51 ceilometers are being deployed at all SURFRAD sites, adding critical cloud and PBL information to our radiation measurements.

Application: Understanding Climate and Climate Intervention

Climate intervention has been suggested as a path to mitigating the warming of Earth's atmosphere by greenhouse gases by intentionally increasing the stratospheric aerosol layer. Because volcanic eruptions are natural phenomena that increase aerosol loading in the stratosphere and can decrease the global temperature considerably, understanding the climate impacts of volcanic eruptions can provide some insight into the benefits or risks of climate intervention.

GMD maintains the longest-running record of surface solar energy at Mauna Loa Observatory. These data are used to provide an apparent transmission of solar radiation through the atmosphere, revealing variability in the stratospheric aerosol layer. Large and small volcanic eruptions evident in this series have been shown to temporarily modify Earth's climate. The long-term series also demonstrates that the residence time of aerosols delivered to the lower stratosphere is on the order of 3-5 years, a time-scale that must be taken into account in climate intervention considerations.



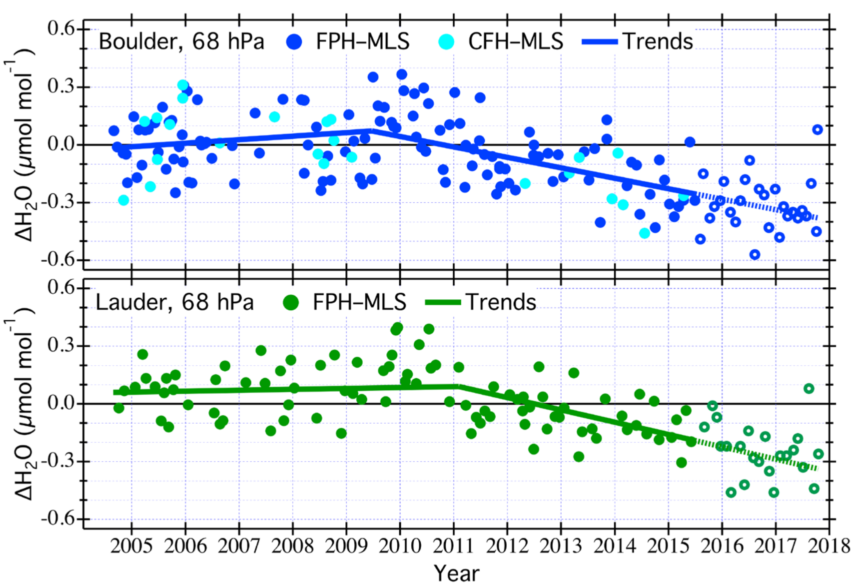


The MLO stratospheric/tropospheric aerosol lidar has operated continuously since the early 1970s. It complements the transmission record by providing a profile of aerosols with altitude, so changes in transmission can be attributed to certain altitudes. Individual volcanic eruptions and large forest fires inject layers of aerosol which can be followed over time as the aerosols evolve and dissipate.

Application: Using GMD Data to Evaluate Satellite Retrievals

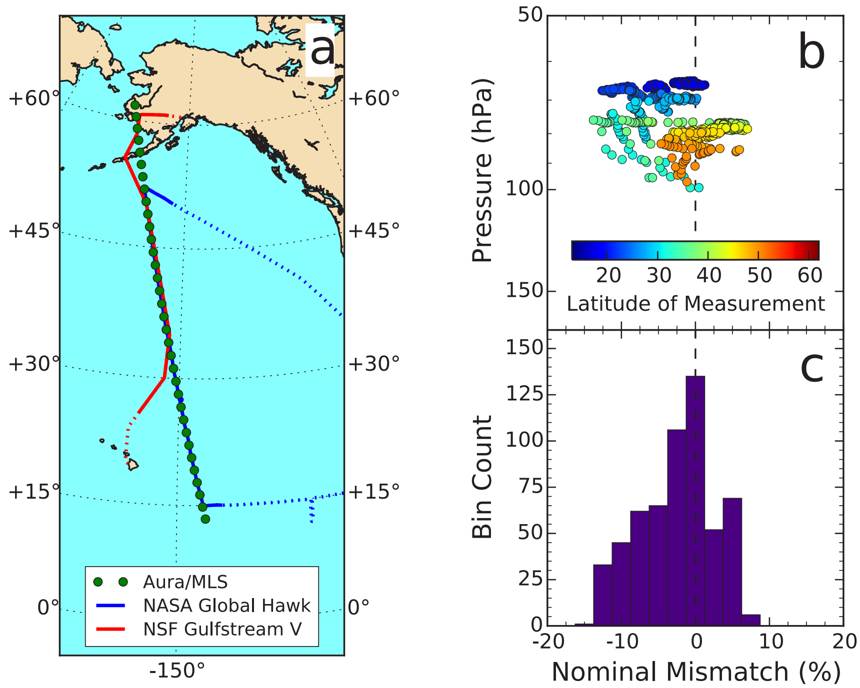
Ground-based observations are essential for development and reliable evaluation of satellite products. Satellite atmospheric composition products are often challenged by retrieval assumptions, low sensitivity to the near-surface concentrations of trace gases and aerosols, and low temporal sampling frequency. GMD provides high-quality long-term measurements of trace gases, radiation, and aerosols across the globe, and shorter-term regional measurements to provide specific validation and verification efforts. Below are a few of GMD's recent and continuing satellite-related activities.

- GMD's 40+ year record of balloon-based ozone and water vapor profiles provides an essential reference for merged, global satellite ozone records (SAGE, SBUV2, Aura, S-NPP). In addition, near-real-time measurements from GMD ground-based ozone sites continue to help bring new JPSS and ISS-SAGE III ozone and water vapor products to maturity (figure below).
- SURFRAD data, the most reliable and complete long-term data set across the U.S., are used for validation of operational downwelling shortwave radiation, radiation budget, land surface temperature and emissivity, surface albedo, photosynthetically active radiation, and Normalized Difference Vegetation Index (NDVI) satellite products for NOAA GOES and NASA EOS satellite sensors. GMD's mobile SURFRAD participated in a post launch field campaign for validation of the GOES-R satellite in Red Lake, AZ (next page, upper photos).
- New multi-filter rotating shadow-band radiometers (MFRSR) were deployed at each SURFRAD site for measuring upwelling and downwelling spectral solar irradiance for validation of the newest generation satellite products (GOES-R, JPSS Series). The extended spectral range out to the near-IR will provide new and improved products: spectral surface albedo, NDVI, green fraction, aerosol optical depth, fine and coarse aerosol mode, and cloud properties.
- Unmanned and manned aircraft measurements have been successfully used during the HIPPO and GloPac airborne missions for validation of Aura satellite accuracy in measurements of ozone, methane, and ODS across a range of latitudes and altitude (next page, lower figure).
- Data from GMD aircraft, surface sites, and tall towers in GMD's GGGRN have been used to evaluate satellite measurements of CO_2 (OCO-2, GOSAT, AIRS, TES), CH_4 (SCIAMACHY, AIRS), and CO (MOPITT). Comparisons between ground-based and aircraft data have revealed large biases (e.g., SCIAMACHY CH_4 measurements too high over the Amazon and GOSAT CO_2 retrievals biased over the oceans).



Trends in the difference between stratospheric water vapor measurements by frost point hygrometers (FPH, CFH) and the Aura Microwave Limb Sounder (MLS) over Boulder, Colorado, and Lauder, New Zealand. Solid lines depict the trends in FPH-MLS difference through mid-2015 (Hurst et al., Atmos. Meas. Tech., 9, 4447–4457, 2016). Open circles show the FPH-MLS difference since then, and dotted lines are simple extrapolations of the post-breakpoint trends. The downward trends in FPH-MLS differences since 2009-2011 imply that drifts in the MLS retrievals have produced significant and persistent biases.

The next generation of geostationary satellites, GOES-16, was launched in November 2016. The ABI sensor on GOES-16 has five times the spectral resolution, four times the spatial resolution, and three times the temporal resolution of its predecessor. GMD's mobile SURFRAD unit was deployed for validation during a post-launch testing period at Red Lake, AZ for verification of GOES-16 products (Photo credit: Gary Hodges).



Comparison of N_2O measured by the Aura/MLS satellite and GMD in situ instruments aboard the NASA Global Hawk during GloPac, and the NSF Gulfstream-V (GV) during HIPPO-3. (left panel) Map of overlapping GV, Global Hawk, and MLS overpass flight tracks on April 13, 2010. (right panels) Percentage difference comparison of MLS and GMD in situ N_2O data, color-coded by latitude (upper), and in histogram form (lower). This work shows good agreement between satellite and in situ observations of N_2O in the mid-latitude lower stratosphere, with potentially larger discrepancies at lower latitudes (precision reported for MLS observation shown here ranges from 5.8 to 10.8%).

Application: Improving Predictability in the Weather-Climate Continuum with Long-Term Observations

Observations are the foundation for understanding the Earth System and improving our ability to predict changes, and forecasting at seasonal and longer scales. Long time series of environmental observations are important for developing and improving model parameterizations, and they are especially useful for hindcasting, wherein model predictions are tested against observed variability. Model predictions can only be trusted to the extent that the models are able to capture the observational record of the past.

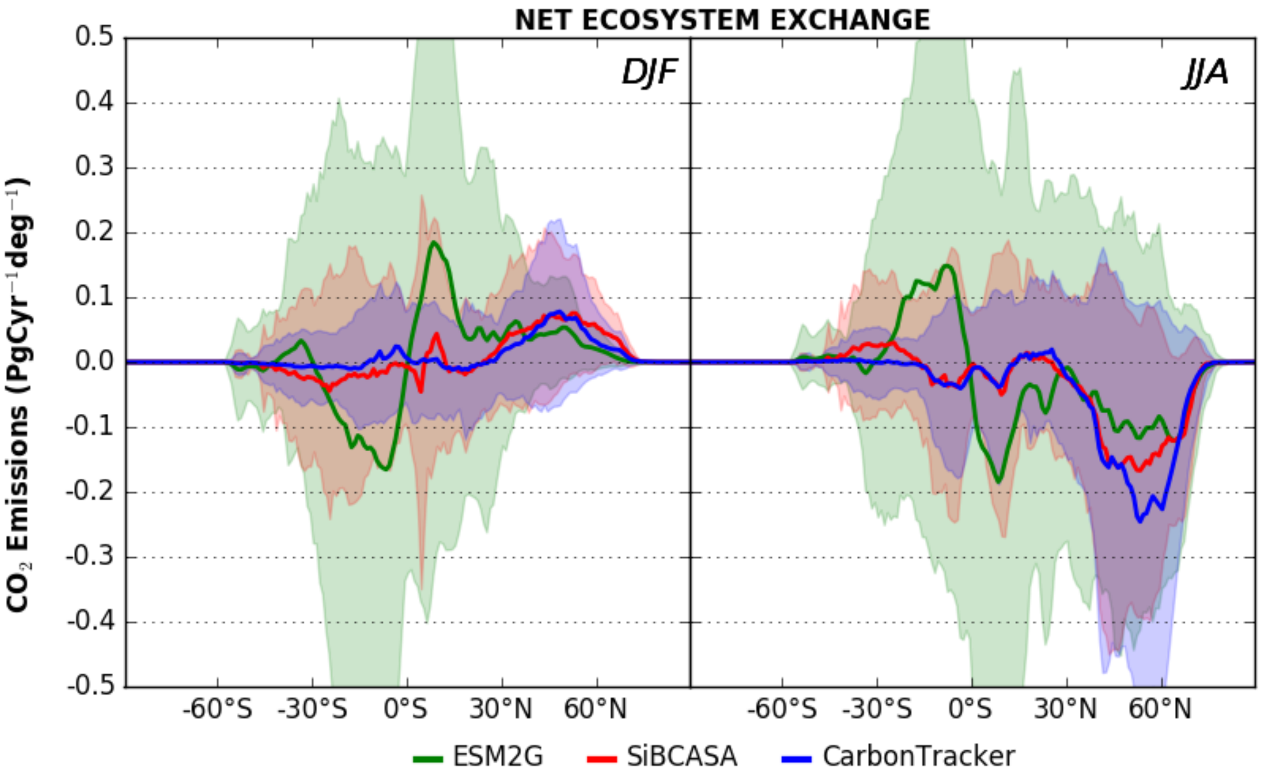
Although efforts over time to improve predictability have been effective (72-hour weather forecasts have better skill now than 36-hour forecasts 30 years ago), the current observed climate state can be reproduced by models only when anthropogenic impacts on the Earth's energy budget are included, namely greenhouse gas and aerosol concentrations. GMD's long observational records of the surface energy budget, aerosols, greenhouse gases, and other trace species that are radiatively active are being used today to improve environmental predictions.

GMD's aerosol and radiation measurements are useful in understanding changes in the surface radiation budget. Sustained observations of surface radiation over the continental U.S. have shown an increase in surface solar radiation over past decades, likely due to changes in cloud cover, which is currently not well represented in models. Likewise, the long atmospheric records of greenhouse gases can help not only to identify potential climate-carbon cycle feedbacks, but also to evaluate Earth System models that are being used to predict the future climate (see figure next page). Long-term observations of ozone are useful for evaluating models that predict air quality, which is important to human health and agricultural productivity.

GMD efforts that are planned and underway, and use existing data to improve predictability include

- improving representation of CO_2 and other atmospheric GHG gases for more accurately simulated radiative forcing and temperature fields,
- evaluating potential climate-carbon cycle feedbacks,
- improving representation of atmospheric transport and land-atmosphere exchanges of gases, moisture, and energy in models,
- improving 1-2 day forecasts of available solar energy,
- improving representation of boundary layer process in models using GMD's measurements of the surface radiation budget, cloud, and aerosol properties,
- analyzing and characterizing of how natural variability and anthropogenic atmospheric constituents interact to produce patterns of variability in weather, and disruptive events such as floods, wildfire, and drought, and
- evaluation of simulated aerosol optical properties in global climate models.

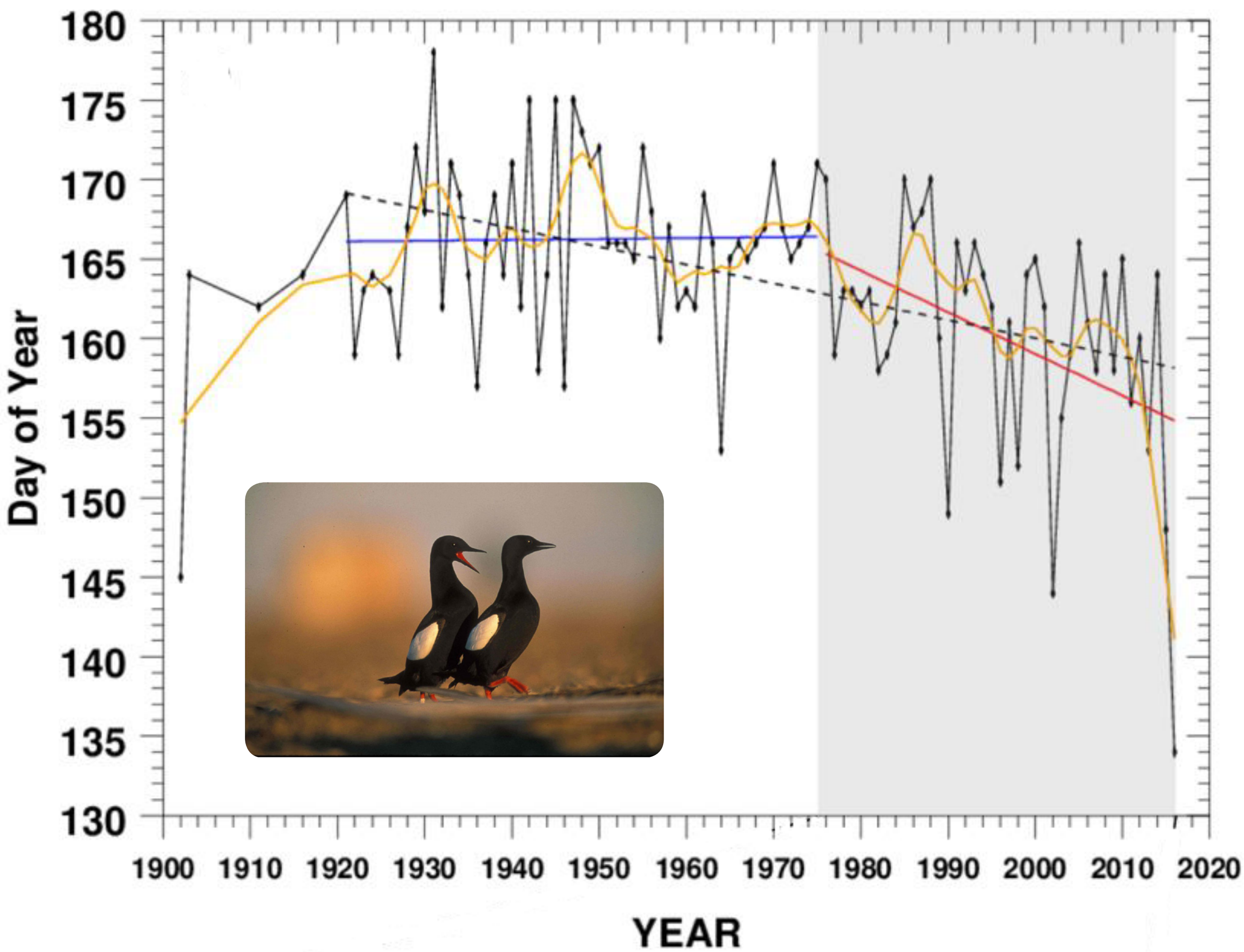
All of the observations that will be needed to address the predictability problem at scales from days to decades do not necessarily exist at this time. GMD has a role in designing new systems and expanding current networks in a way that addresses the problems most pressing for society. A small fraction of the costs of disruptive events invested in the next generation observing systems – a targeted, comprehensive, sustained observing system – could reduce those costs considerably into the future.



Meridional gradient of CO_2 net ecosystem exchange from the GMD's CarbonTracker atmospheric inversion (blue), a biogeochemistry model SiBCASA (red) based on NDVI, and a global climate-carbon model, the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) ESM2G (green). Positive PgC yr^{-1} deg^{-1} (degree latitude) values indicate a flux from land to the atmosphere. The left and right plots represent the sum of meteorological winter months (December-January-February) and summer months (June-July-August). CarbonTracker estimates are constrained by global observations from the NOAA GMD Greenhouse Gas Reference Network and data from collaborators. Shaded regions show the variability of each model (note the large variability of the GFDL model compared to the observationally-constrained models). Data-constrained models, such as CarbonTracker, are useful for evaluating Earth System model components, and can lead to improved prediction of future climate, including carbon cycle feedbacks.

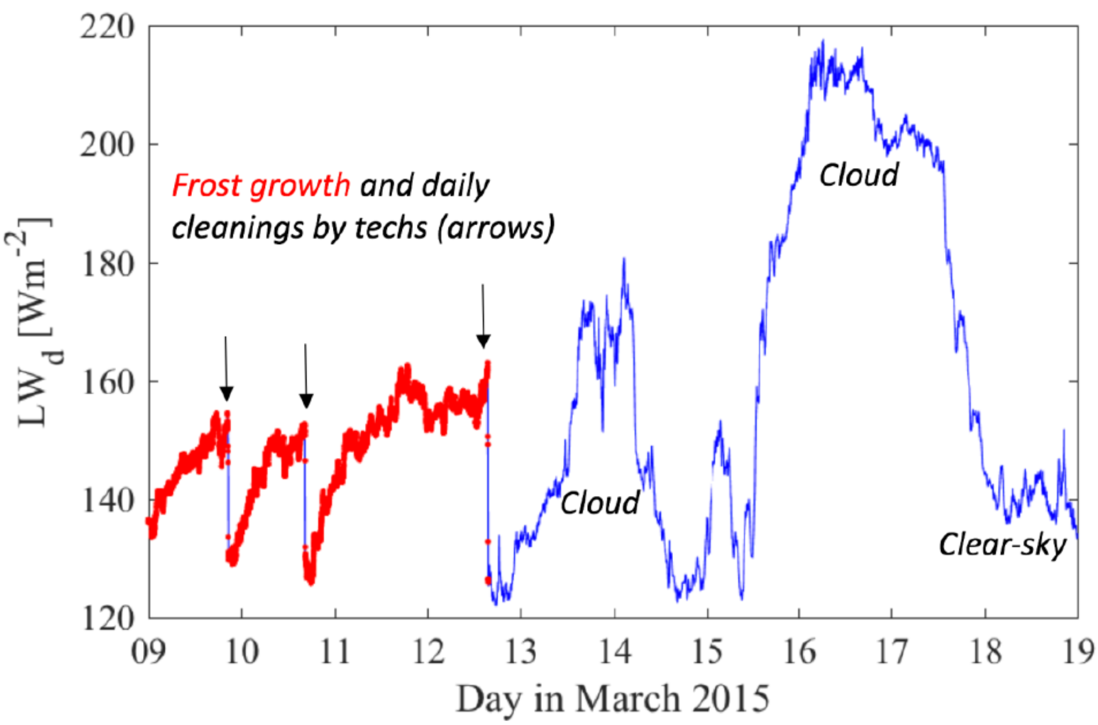
Application: Understanding Rapid Change in the Arctic

Global warming is manifest in the Arctic through sea ice loss, earlier spring snowmelt, thawing permafrost, retreating glaciers, and coastal erosion. Monitoring and analyzing trends in magnitudes and variability of the surface energy budget and feedbacks on Arctic climate is essential for improving our understanding of climate change and its impacts. The GMD Barrow Observatory is recognized internationally as one of the primary long-standing scientific Arctic sites and is a member site of the Baseline Surface Radiation Network (BSRN). Data have been used in studies relating the cloud radiative effects on springtime Barrow surface radiation to the later autumn sea ice extent, an indicator of the important role clouds and radiation play in the Arctic environment. Documentation of the recent but persistent earlier spring snowmelt and later onset of autumn snow accumulation demonstrates the lengthening snow-free period at Barrow, which in turn decreases surface albedo and accelerates change.



Time series of snowmelt dates at Barrow, Alaska; orange line is a ten-year running mean and linear fits are shown for 1920-1975 (blue), 1920-2016 (dashed) and 1975-2016 (red). The 1975-2016 linear trend is -2.86 days decade^{-1}, meaning that the snowmelt is occurring on average almost 3 days earlier each decade since 1975. The date that black guillemots (inset) lay their first egg on nearby Cooper Island is influenced by snowcover and highly correlated with the date of snowmelt at the nearby Barrow Observatory. (Photo credit: Joe McNally, Cooper Island Bird Observatory)

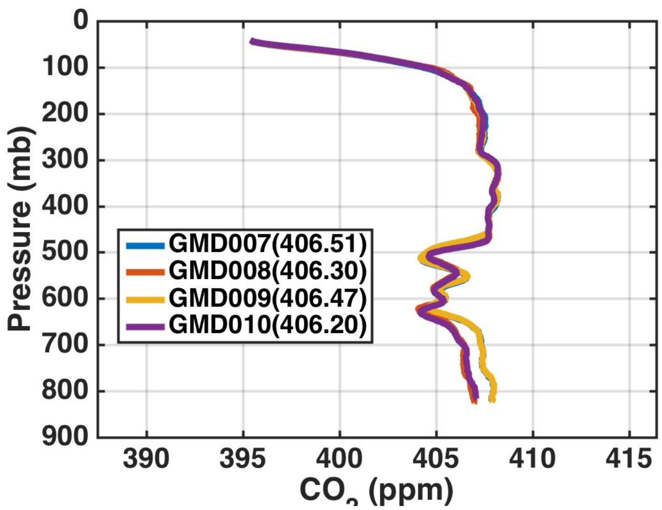
Harsh polar environments present significant challenges for making accurate, continuous surface radiation budget measurements as frequent episodes of frost, rime, and snow negatively impact the instruments. A De-Icing Comparison Experiment (D-ICE), a collaborative effort among NOAA Physical Sciences Division, the Department of Energy Atmospheric Radiation Measurement (ARM) Program, and GMD, is aimed at mitigation of frost contamination in order to reduce data loss.

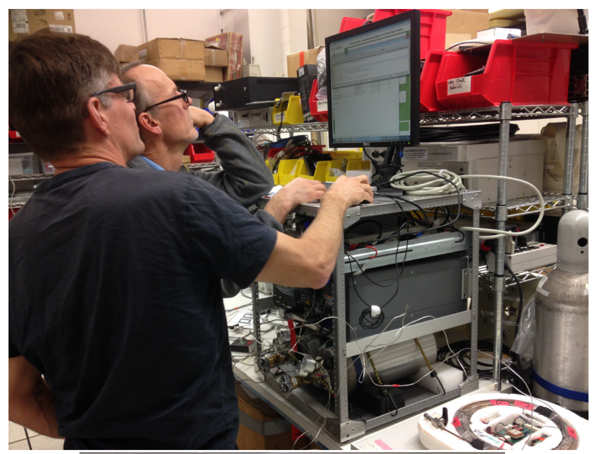


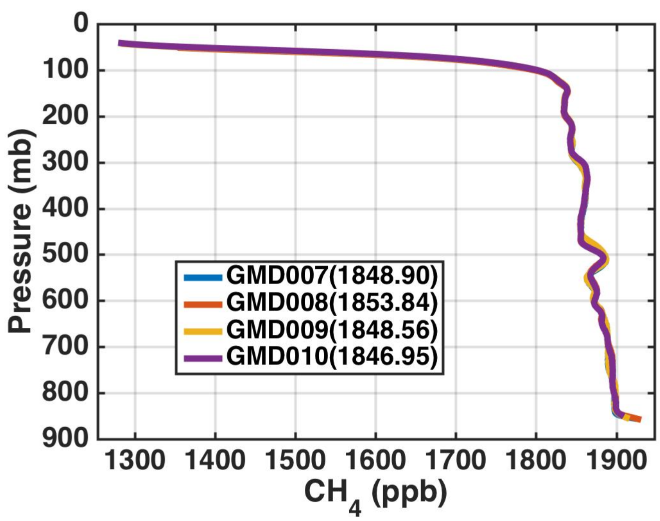
Frost on the radiometers during D-ICE show some designs do not mitigate radiometer dome contamination well (photo). Black arrows (in figure) denote the time that local operator technicians cleaned the frost off the domes, decreasing the longwave irradiance signal by 20 W m^{-2} or more. The frost contamination quickly built back up, however, producing a 4-day average bias error of greater than 15 W m^{-2} with this particular sensor.

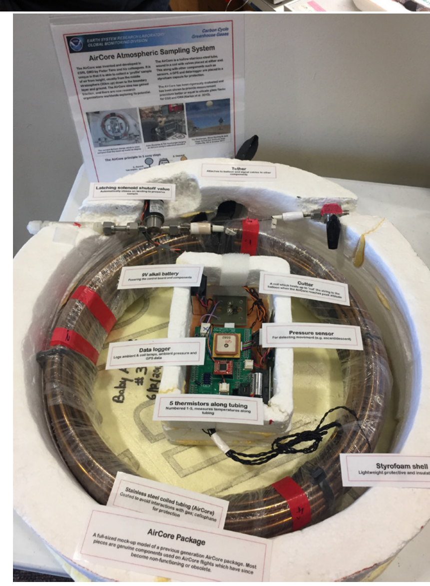
Application: AirCore: A Revolution in Sampling the Atmosphere

The AirCore sampling system, which obtains a continuous sample of air from above 30 km altitude (>98% of the atmospheric column) to the ground, was invented and developed by GMD scientists. It is a long tube, typically at least 60 m length, with a small diameter, 3-6 mm, hoisted by balloon to maximum altitude, and returned to the surface by parachute. During ascent one valve is open, allowing the initial fill air to flow out as the pressure decreases. During descent the increasing atmospheric pressure pushes a continuous sample of air into the tube. The new air coming in compresses the air that is already inside toward the back, with very little mixing. This system is passive; there is no pump. After landing, the content of the tube is analyzed sequentially by slowly pushing the sample air out of the tube through one or more analyzers, using pressurized standard air with known concentrations of the trace gases of interest. Until now we have only analyzed CO_2 and CH_4 which are ideal for validating satellite and TCCON retrievals, and for validating the mixing of air into the stratosphere by atmospheric transport models. GMD is currently developing a version for horizontal flight at low altitudes using a constant flow pump, with the AirCore acting as a "tape recorder" of the air encountered during flight. AirCore is currently being deployed experimentally by GMD partners and the world.







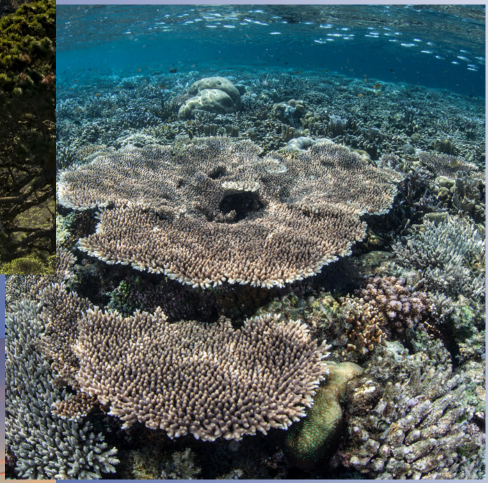


(left plots) Two flights on 14 July 2017 with two separate balloons launched about 15 minutes apart. One balloon carried AirCore 07 and 09, the other had 08 and 10. The very small differences of the AirCores flown in pairs, 0.04 and 0.10 ppm for the column integral of CO_2 and 0.34 and 6.89 ppb for CH_4, are an indication of the reproducibility. The larger differences between the two balloons for CO_2 reflect short-term variability in the troposphere. (right) Photos preparing an AirCore for launch. (Photo credit: Steve Rackley)

Applications Relevant to GMD Research

Renewable Energy

Climate Sensitivity



Ocean Acidification

Arctic Processes

Weather Forecasting

Climate Intervention

Air Quality

GMD Outreach

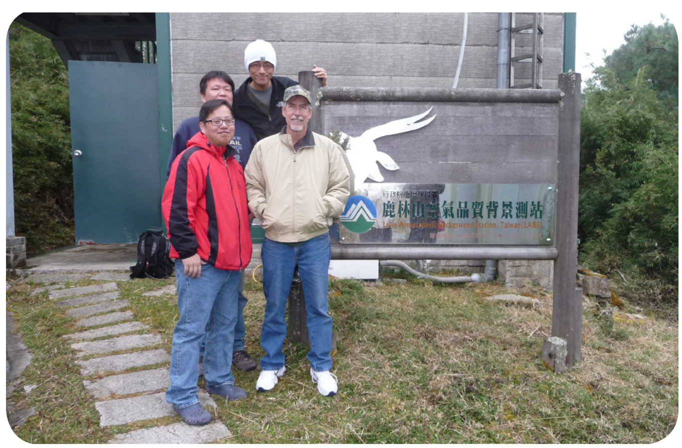
GMD researchers Allen Jordan, Dale Hurst and Emrys Hall worked with colleagues in Kunming, China, to launch instrumented balloons to study the effects of the Asian Monsoon on vertical distributions of water vapor and ozone in the upper troposphere and stratosphere.


AGU FALL MEETING
Academic Showcase
Rigaku
X-ray Diffract

Scientific Outreach – Helping Other Nations Develop Observing Systems

By sharing expertise, GMD scientists have helped institutions throughout the world develop and improve their observing systems. Many of GMD's global networks have expanded via collaboration among GMD scientists and scientists at various domestic and international agencies, institutions, and universities. The advantage of this cooperative approach is increased global coverage and collection of high-quality data which would not be possible by GMD alone. GMD's efforts in this respect are strongly endorsed by WMO in its efforts to build observing and research capacity. Some ways in which GMD has reached out to the wider scientific community include

- supporting foreign science organizations and the larger scientific community through its oversight and management of the NOAA Federated Aerosol Network; GMD's efforts provide the framework (i.e., protocols, procedures, tools, software, training) for making consistent and accurate aerosol measurements at 27 partner sites worldwide and simplifying data submission to the world data archives,
- continued support of China Meteorological Administration (CMA) scientists in making aerosol measurements at three stations in China by providing software, system designs and expertise for running complex aerosol systems,
- continued collaboration with Brazilian colleagues in Sao Paulo, Brazil, after establishing a replica of GMD's high-accuracy, high-precision, greenhouse gas analysis system there; support was provided for measuring GHG concentrations from background sites on the Brazilian Atlantic coast and at four aircraft sites in the Amazon, which represent some of the only regular GHG observations above the tropical terrestrial biosphere,
- continued assistance to Dobson ozone observing programs worldwide; GMD's care of the WMO GAW World standard (D083), with its absolute calibrations and other maintenance, enables international support for ~50 Dobson instruments in countries like Africa, Asia, South America and Indonesia,
- offering training during visits to the SHADOZ collaborating stations (e.g., Galapagos, Republic of Ecuador; Suva, Fiji) and ongoing support by sharing in-house built software and visual materials for ozonesondes and frost point hygrometer (FPH) launches,
- assisting South African and other groups with hardware, operational, and training needs at the International Pyrheliometer Comparison in Davos,
- expanding the Baseline Surface Radiation Network through assistance to several countries (e.g., Taiwan) in instrument location and configuration, software and data processing, and calibration guidance, and
- collaborating with Australia's CSIRO Oceans and Atmosphere Science Group over multiple decades. Collaboration includes staff exchange programs and active participation at yearly science meetings with GMD staff attending the Cape Grim Annual Science Meeting and CSIRO staff attending the GMD Global Monitoring Annual Conference (GMAC).



Patrick Sheridan (GMD) and Taiwanese colleagues during a maintenance and training visit to the Mt. Lulin Atmospheric Background Station in 2013

Public Outreach

GMD's educational outreach is two-tiered. The first tier is directed at K-12 education so that children are exposed to the environmental sciences. Familiarity with environmental sciences at an early age may pique an interest in a student who will then choose an environmental discipline as their secondary educational goal.

The second tier is management of the ESRL Student Program. This program is specifically directed toward advanced high school students, undergraduates, graduate students, and, in some cases, post-doctoral scientists. The purpose of the ESRL Student Program is to actively involve highly motivated students in the scientific research process. Several of the students are currently in Master's and Ph.D. programs. The Student Program began in 2007 and is coordinated within GMD.

Outreach is a significant part of the lives of GMD staff working at our four observatory sites. The remote locations provide a unique opportunity to educate and inform societies that otherwise may have limited access to this kind of information. For example, scientists and technicians at our baseline observatory in Barrow, Alaska were fundamental in implementing a summer science program for Inupiat high school students in the North Slope region of Alaska. Visits to our observatories aid in carrying our message to the general public.

- GMD scientists and outreach staff are active in supporting events such as science fairs and science open houses, giving talks to secondary school children both in the classroom and in the laboratories, and inviting domestic and international visitors to the laboratory for tours. GMD scientists have visited remote Alaska villages to introduce Yup'ik and Iñupiat students to careers in the sciences.
- The South Pole winter-over crew responds to email queries from classrooms throughout the world about life in Antarctica.
- Educational activities conducted at the Mauna Loa and Barrow Observatories directly involve students at local and distant schools. The American Samoa Observatory staff are involved with local communities and schools on the island, fostering a sense of community and promoting science education. Barrow staff hosted STEM summer science camps at the observatory for multiple years and conducted a live-feed video webinar with the San Francisco Exploratorium on carbon influences in Alaska.
- GMD collaborated with a retired K-12 teacher to develop over 100 lesson plans and classroom materials covering topics (e.g., chlorofluorocarbons, carbon footprint) relevant to GMD science. The lessons are posted on GMD's website.
- NOAA Boulder Outreach and Diversity Committees organized and conducted an open house for the American Indian Science and Engineering Society and the Tribal College Universities to inform and collaborate with them on environmental issues they face and introduce them to NOAA science careers.

The future success of scientific research conducted at GMD and elsewhere depends on educating the public and providing platforms such as Earth Day open houses, science speaker seminars, and science forums to bring scientists and the community together. As a broad range of decisions made by society around the world will increasingly require an understanding of science in general and Earth System Science in particular, the need to inform and educate the public becomes a growing responsibility for all.

GMD in the Future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Transformative Opportunities

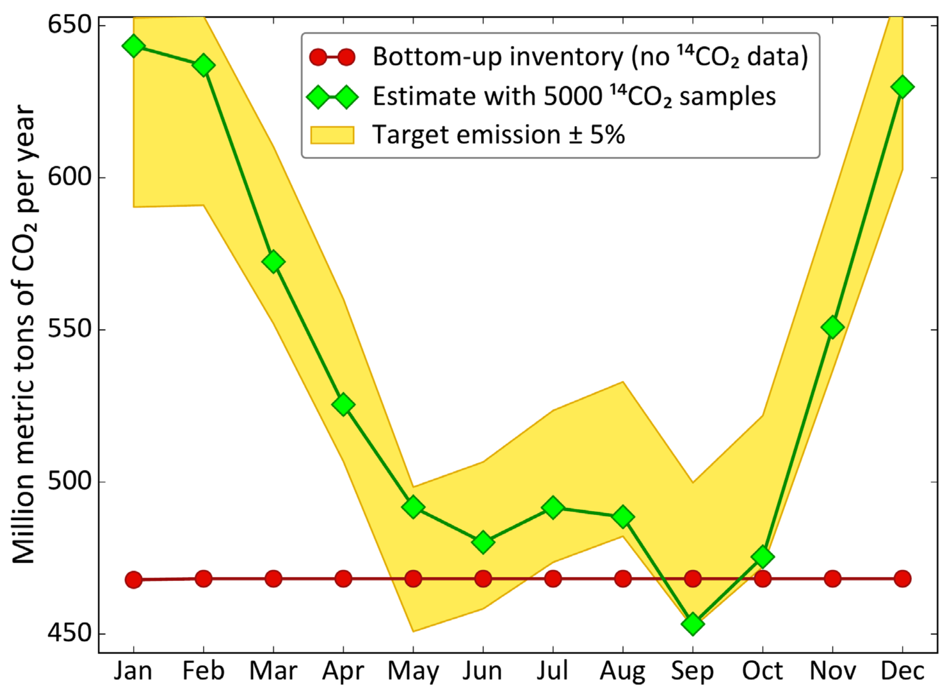
Should opportunities arise, GMD currently has the capability to transform existing observing systems, greatly enhancing the information needed for society to mitigate and adapt to climate change, and to make optimal decisions regarding ozone depletion and air quality. Today we see a near-term demand for increased information relative to greenhouse gas emissions, climate change feedbacks, renewable energy development, air quality, and ozone depletion. Some specific examples are listed below.

Commercial Aircraft Greenhouse Gas Observations

Instrumentation for the primary greenhouse gases (CO_2 and CH_4) that is sufficiently precise and stable to run unattended for a long time has recently become available. GMD is poised to initiate a program that deploys these instruments on a few dozen commercial aircraft. This would increase the number of vertical profile measurements by two orders of magnitude at very modest cost, transforming the use of inverse models for estimating sources and sinks of greenhouse gases. Hawaiian Airlines is the first U.S. commercial airline to carry observational instrumentation for GHGs and other atmospheric constituents.

Carbon-14 Measurements

It is feasible today to start an intensive systematic program for measuring ^{14}C in CO_2. Five thousand samples per year around North America, requiring one dedicated accelerator mass spectrometer, would cleanly separate the observation of CO_2 emitted by fossil fuel combustion from natural CO_2 sources and sinks. This would provide an independent verification of reported fossil fuel CO_2 emission inventories, especially needed in times where greenhouse gas emissions have an economic cost attached. Additionally, unbiased, observationally based estimates of fossil fuel CO_2 would strongly constrain estimates of natural sources and sinks in models like CarbonTracker and go a long way towards reducing bias in these estimates.



In a synthetic data experiment, 5000 $^{14}CO_2$ samples over North America are able to recover monthly fossil fuel emissions over the northeast U.S. to within 5% of the target emissions, even when starting from a biased inventory with no seasonality. Separating human from natural influences is essential for understanding carbon cycle feedbacks.

Global Greenhouse Gas Reference Network
GMD could significantly boost its calibration, data management and quality control activities to ensure coherent measurements among emerging independent networks. GMD serves as a greenhouse gas reference network for a diverse set of regional, national, and international networks. This substantially enhances the value and use of information from diverse networks.

Upper Atmospheric Research
GMD would be better able to detect changes in the meridional overturning (Brewer-Dobson) circulation of the stratosphere if balloon-borne in situ measurements of water vapor and ozone were combined with AirCore measurements of dynamical tracers. Understanding changes in the Brewer-Dobson circulation is vital because they influence both climate and stratospheric ozone depletion.

Expanded U.S. National Network for Clouds, Aerosols, and Surface Radiation
Currently, GMD's seven SURFRAD sites represent only a few of the ecological and climatic regions across the U.S. Improved predictability on time scales of weather and climate requires a better understanding of how different regions respond to global averaged increases in GHGs and temperature. Increasing the spatial density of this network, and addressing the full surface energy budget by adding sensible and latent heat instrumentation, could provide valuable data and services to the NOAA climate and weather forecast communities and the National Weather Service.

U.S. Tall Towers Network for Boundary Layer Composition Studies
A tall tower network of comprehensive measurements can improve understanding of the processes that entrain the long-range transported air masses with anthropogenic pollution and biomass burning signatures in the boundary layer. The location of measurements on the tall towers is dictated by the need for continuous measurements at several altitude levels within and above the boundary layer. Measurements of ozone, CO, CH_4, NO_x, VOC, $PM_{2.5}$, black carbon, actinic spectral flux, and meteorological observations are needed to understand the boundary layer diurnal and seasonal impact on variability of atmospheric composition at the surface, and to separate the contribution from local and remote pollution sources. These measurements can also help to improve weather and air quality forecast models. In the future, when geostationary satellites will collect air quality information over the U.S. with high temporal and spatial resolution, the network would provide verification for satellite products.

APPENDIX I. Milestones

Tracking Greenhouse Gases and Understanding Carbon Cycle Feedbacks

GMD MILESTONES (2018-2022)					
***Theme 1*: Tracking Greenhouse Gases and Carbon Cycle Feedbacks**	**2018**	**2019**	**2020**	**2021**	**2022**
Maintain and improve measurements of CO_2, CH_4, N_2O and other GHGs in NOAA's Global Greenhouse Gas Reference Network, with ~70 flask sampling sites, ~12 continuous measurement sites, and ~15 aircraft profiling sites	X	X	X	X	X
Maintain and improve the WMO calibration scales and provide calibrated standards to ~40 laboratories around the world in our role of Central Calibration Laboratory for CO_2, CH_4, CO, N_2O, SF_6	X	X	X	X	X
Maintain and improve our web pages presenting up-to-date data and derived products, such as trends, GlobalView, CarbonTracker, ObsPack, MBL, AGGI	X	X	X	X	X
Improve data assimilation scheme for CarbonTracker, ingest more CO_2 data, use multiple transport models, model additional gases including isotopic ratios	X	X	X	X	X
Provide objective quantification of U.S. GHG emissions using carbon-14 observations as well as CT-Lagrange for many gas species	X	X	X	X	X
Advance understanding of the carbon cycle and GHG sources and sinks with CarbonTracker updates	X	X	X	X	X
Evaluate satellite retrievals of column CO_2 and CH_4	X	X	X	X	X
Develop pumped version of AirCore for boundary layer sampling and operationalize vertical profiles to high altitude at a few sites		X	X		
Develop OSSEs to help improve GGGRN observing system		X	X		
Update CarbonTracker, the Global CO_2 Record, and the AGGI	X	X	X	X	X
Launch water vapor sondes with frost point hygrometers monthly at 3 stations (Boulder, Lauder, Hilo) and archive data at NOAA, NDACC, GRUAN	X	X	X	X	X

APPENDIX I. Milestones (continued)

Monitoring and Understanding Changes in Surface Radiation, Clouds, and Aerosol Distributions

GMD MILESTONES (2018-2022)					
***Theme 2*: Measuring Changes in Clouds, Aerosols, and Surface Radiation**	**2018**	**2019**	**2020**	**2021**	**2022**
Continue monitoring and reporting of broadband & spectral surface radiation at 29 sites and aerosol properties at 27 NOAA Federated Aerosol Network sites	X	X	X	X	X
Produce U.S. and global Dimming-Brightening index and update annually	X	X	X	X	X
Expand U.S. aerosol optical depth monitoring network	X	X	X		
Add ceilometers to SURFRAD sites	X	X			
Produce new cloud, surface, and aerosol property data products with improved latency for operational usability	X	X	X	X	X
Begin data assimilation of cloud location and aerosol optical depth into research numerical weather prediction models		X	X	X	
Produce actinic flux product for U.S.		X			
Begin operational calibration of radiation sensors for the Climate Reference Network (CRN)	X				
Co-deployment of surface radiation and boundary layer characterization instruments with NOAA Air Resource Laboratory for VORTEX-SE campaign		X			
Add four new aerosol monitoring sites	X	X	X	X	
Upgrade software at current aerosol sites	X				
Analyze co-located surface aerosol, surface radiation, and cloud property data at one or more U.S. sites to determine what, if any, relationships are present to improve parameterization in models			X	X	X
Use in situ aerosol measurements from NOAA network sites (and other DOE and GAW sites) to evaluate how well global climate models simulate surface aerosol optical properties (absorption and scattering)	X	X	X		

APPENDIX I. Milestones (continued)

Guiding Recovery of Stratospheric Ozone

GMD MILESTONES (2018-2022)					
***Theme 3*:** **Monitoring Recovery of Stratospheric Ozone**	**2018**	**2019**	**2020**	**2021**	**2022**
Continue to measure ozone-depleting substances on global and regional scales	X	X	X	X	X
Update the Ozone-Depleting Gas Index (ODGI)	X	X	X	X	X
Contribute to the WMO Scientific Assessment of Ozone Depletion	X				X
Publish 17-yr global datasets for $CHBR_3$, CH_2Br_2, and CH_3I			X		
Provide AirCore aircraft measurements of ODGs	X	X	X		
Complete the Atmospheric Tomography Mission (ATom)	X				
Improve measurements of CFCs, CCl_4, N_2O, and SF_6 in flasks	X	X			
Launch ozonesondes weekly at 5 stations (Boulder, Hilo, South Pole, American Samoa, Fiji) and archive data at NOAA, WOUDC, NDACC	X	X	X	X	X
Take daily measurements of total column ozone at 10 stations and archive data at NOAA, WOUDC, NDACC	X	X	X	X	X
Collect surface ozone measurements at 15 stations; analyze data and archive at NOAA and WDCRG	X	X	X	X	X
Produce near real-time data for satellite and model validation	X	X	X	X	X
Prepare for validation of geostationary satellites that aims at monitoring tropospheric composition and air quality					X
Calibrate World standard Dobson at MLO	X		X		X
Calibrate NOAA Dobson network and 5 Regional standards	X	X	X	X	X
Calibrate GMD surface ozone network, mobile and aircraft ozone analyses	X	X	X	X	X

Appendix II. List of Acronyms

Organizations and Networks

AERO – AEROsol, GMD group
AGAGE – Advanced Global Atmospheric Gases Experiment network
ARL – Air Resources Laboratory
ARM – Atmospheric Radiation Measurement
BIPM – Bureau of International Weights and Measures
BSRN – Baseline Surface Radiation Network
CCGG – Carbon Cycle and Greenhouse Gases, GMD group
CIMO – WMO Commission for Instruments and Methods of Observation
CIRA – Cooperative Institute for Research in the Atmosphere
CIRES – Cooperative Institute for Research in Environmental Sciences
CMA – Chinese Meteorological Administration
CRN – Climate Reference Network
CSD – Chemical Sciences Division
DOE – Department of Energy
ERA – European Reanalysis
ESRL – Earth System Research Laboratory
GAW – Global Atmosphere Watch
GCOS – Global Climate Observing System
GEOSS – Global Earth Observations System of Systems
GFDL – Geophysical Fluid Dynamics Laboratory
GGGRN – Global Greenhouse Gas Reference Network
GLoPac – NASA's Global Hawk Pacific
GMD – Global Monitoring Division
G-RAD – Global surface RADiation, GMD group
GRUAN – GCOS Reference Upper Air Network
GSD – Global Systems Division
HATS – HAlocarbons and other Trace Species, GMD group
HIPPO – HIAPER Pole-to-Pole Observations
IGAC – International Global Atmospheric Chemistry
INSTAAR – Institute of Arctic and Alpine Research, University of Colorado
IPCC – Intergovernmental Panel on Climate Change
MERRA – Modern-Era Retrospective analysis for Research and Applications
NASA – National Aeronautics and Space Administration
NCAR – National Center for Atmospheric Research
NEON – National Ecological Observatory Network
NEUBrew – NOAA Environmental Ultraviolet-ozone Brewer
NIST – National Institute for Standards and Technology
NOAA – National Oceanic and Atmospheric Administration
NREL – National Renewable Energy Laboratory
NSF – National Science Foundation
OAR – Office of Oceanic and Atmospheric Research
OZWV – Ozone and Water Vapor, GMD group
PNNL – Pacific Northwest National Laboratory
PSD – Physical Sciences Division
SURFRAD – Surface Radiation network
UNEP – United Nations Environment Programme
USGCRP – United States Global Change Research Program
WCRP – World Climate Research Programme
WMO – World Meteorological Organization

Chemical compounds

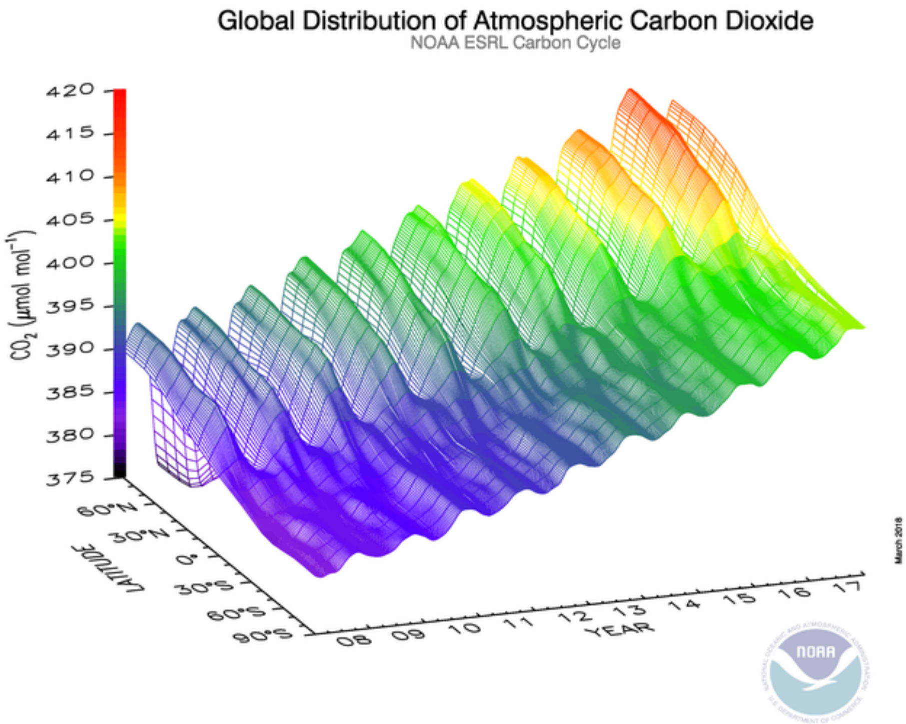
Br – Bromine
CCl_4 – Carbon tetrachloride
CFC – Chlorofluorocarbon
$CHBr_3$ – Bromoform
CH_2Br_2 – Dibromomethane
CH_3I – Methyl iodide
CH_4 – Methane
Cl – Chlorine
CO – Carbon monoxide
COS – Carbonyl sulfide
^{12}C – Carbon-12
^{13}C – Carbon-13
$\delta^{13}C$ – 'delta c thirteen'
^{14}C – Carbon-14, or radiocarbon
$^{14}CO_2$ – Carbon-14 CO2
CO_2 – Carbon dioxide
H_2 – Hydrogen
H_2O – Water
HCFC – Hydrochlorofluorocarbon
HFC – Hydrofluorocarbon
O_3 – Ozone
OH – Hydroxyl (radical)
N_2O – Nitrous oxide
$PM_{2.5}$ – Particulate Matter (≤ 2.5 microns width)
SF_6 – Sulfur hexafluoride
VOC – Volatile Organic Compound

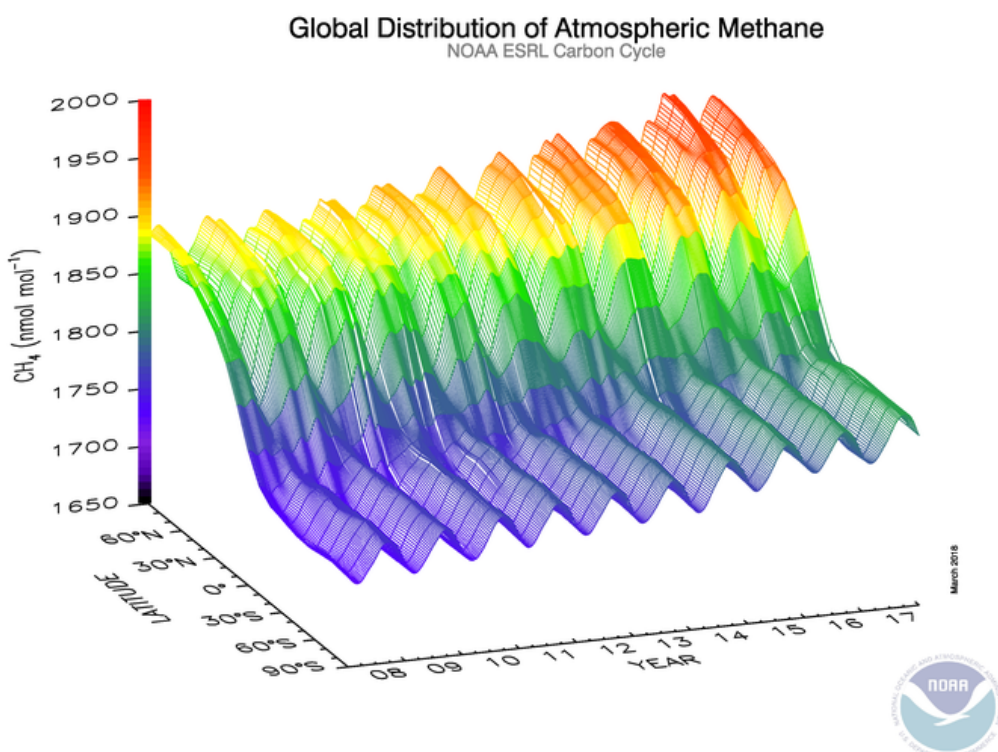
Satellites and Satellite Sensors

ABI – Advanced Baseline Imager
AIRS – Atmospheric InfraRed Sounder; satellite sensor
ASTER – Advanced Spaceborne Thermal Emission and Reflection Radiometer
CERES – Clouds and the Earth's Radiant Energy System satellite
EOS – Earth Observing System satellites
GOES, GOES-R, GOES-16 – Geostationary Operational Environmental Satellites
GOSAT – Greenhouse gases Observing SATellite
ISS – International Space Station
JPSS – Joint Polar Satellite System
MLS – Microwave Limb Sounder
MODIS – MODerate resolution Imaging Spectroradiometer satellite
MOPITT – Measurements Of Pollution In The Troposphere satellite
NDAAC – Network for the Detection of Atmospheric Composition Change
NDVI – Normalized Difference Vegetation Index
SAGE – Stratospheric Aerosol and Gas Experiment satellite
SBUV2 – Solar Backscatter Ultraviolet Radiometer satellite
SCIAMACHY – SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY
SNPP – Suomi National Polar-orbiting Partnership satellite
TES – Technology Experiment Satellite

Other Acronyms and Terms

AAOD – Aerosol Absorption Optical Depth
ABO – Atmospheric Baseline Observatory
AGGI – Annual Greenhouse Gas Index
AOD – Aerosol Optical Depth
ASRE – Atmospheric Science for Renewable Energy
AToM – Atmospheric Tomography Mission
BDC – Brewer-Dobson circulation
BRW – Barrow Atmospheric Baseline Observatory
CCL – Central Calibration Laboratory
CT – CarbonTracker
D-ICE – De-Icing Comparison Experiment
DNI – Direct Normal Irradiance
EESC – Equivalent Effective Stratospheric Chlorine
ENSO – El Niño Southern Oscillation
FPH – NOAA GMD Frost Point Hygrometer
GHG – Greenhouse gas
GHI – Global Horizontal Irradiance
GMAC – Global Monitoring Annual Conference
GV – Gulfstream-V
HRRR – High-Resolution Rapid Refresh
IR – Infrared
MBL – Marine Boundary Layer
MFRSR – Multi-Filter Rotating Shadow-band Radiometers
MLO – Mauna Loa Atmospheric Baseline Observatory
NSRDB – National Solar Radiation Database
NWP – Numerical Weather Prediction
ObsPack – Observation Package
OCO-2 – Orbiting Carbon Observatory-2
ODGI – Ozone-Depleting Gas Index
ODS – Ozone-depleting substance
OSSEs – Observing System Simulation Experiments
$PgCyr^{-1}$ – Petagrams of carbon per year, or Billion Tonnes of Carbon per year
PBL – Planetary Boundary Layer
PFP – Programmable Flask Package
ppb – parts per billion; ppm – parts per million
QBO – Quasi-Biennial Oscillation
RE – Renewable Energy
SMO – American Samoa Atmospheric Baseline Observatory
SPO – South Pole Atmospheric Baseline Observatory
SRB – Surface Radiation Budget
TLP – Tropical Leaky Pipe model
TOAR – Tropospheric Ozone Assessment Report
TTL – Tropical Tropopause Layer
UAS – Unmanned Aerial Systems
UCATS – UAS Chromatograph for Atmospheric Trace Species
UV – Ultraviolet; UVR – Ultraviolet Radiation
WDCRG – World Data Centre for Reactive Gases
WFIP – Wind Forecast Improvement Project
WLG – Mt Waliguan, China, Observatory
Wm^{-2} – Watts per meter squared, unit of radiative forcing
WOUDC – World Ozone and Ultraviolet Radiation Data Centre





Three-dimensional representation of the latitudinal distribution of atmospheric carbon dioxide (upper) and methane (lower) in the marine boundary layer. Carbon Cycle cooperative air sampling network date were used to produce these graphics. The surface represents data smoothed in time and latitude. Credit: Ed Dlugokencky, NOAA ESRL Global Monitoring Division

2017 Global Monitoring Annual Conference (GMAC) attendees, including GMD staff, OAR management, international and domestic partners, collaborators, and stakeholders

Notes

Notes

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