



# GLOBAL MONITORING DIVISION

2013-2017 Research Plan



## Acknowledgments

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# **Global Monitoring Division (GMD)**

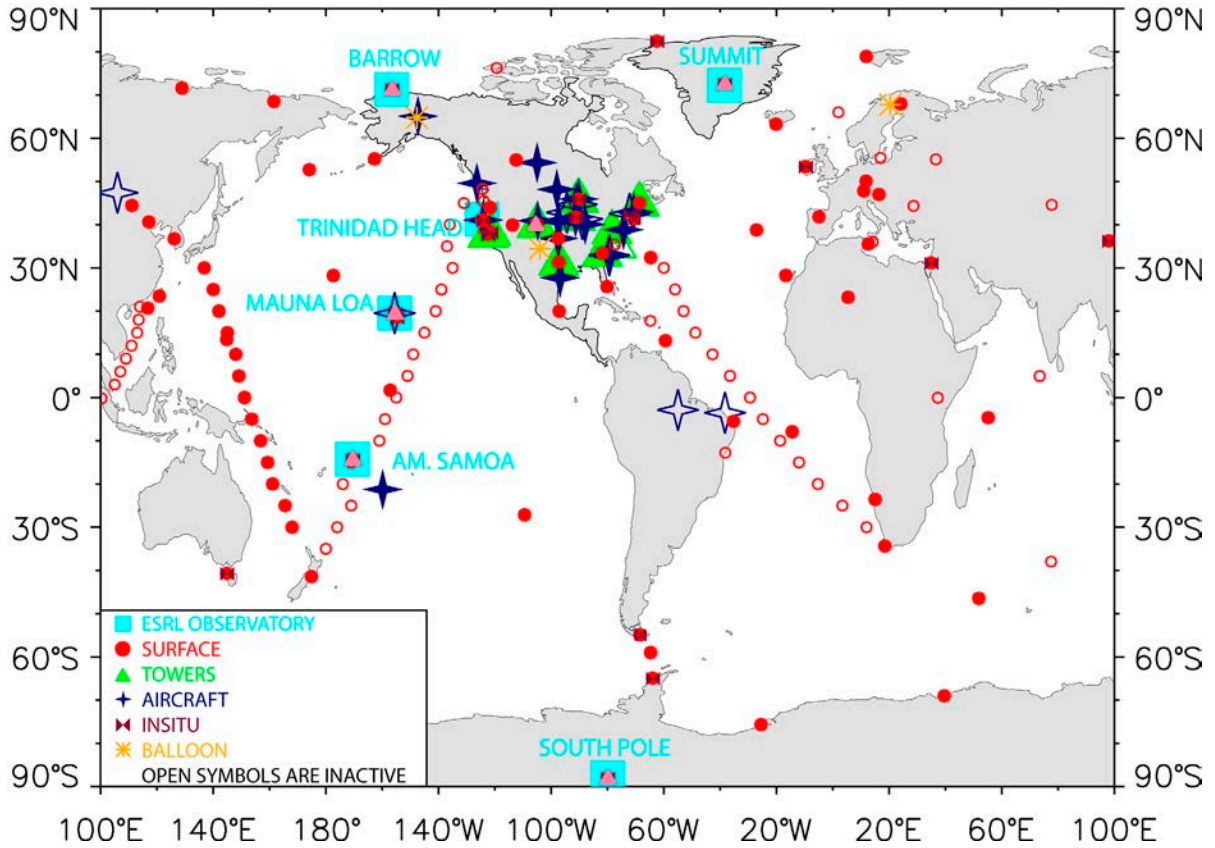
## **GMD Vision**

*A society that has access to and uses the best possible information on atmospheric constituents that drive climate change, stratospheric ozone depletion, and baseline air quality.*

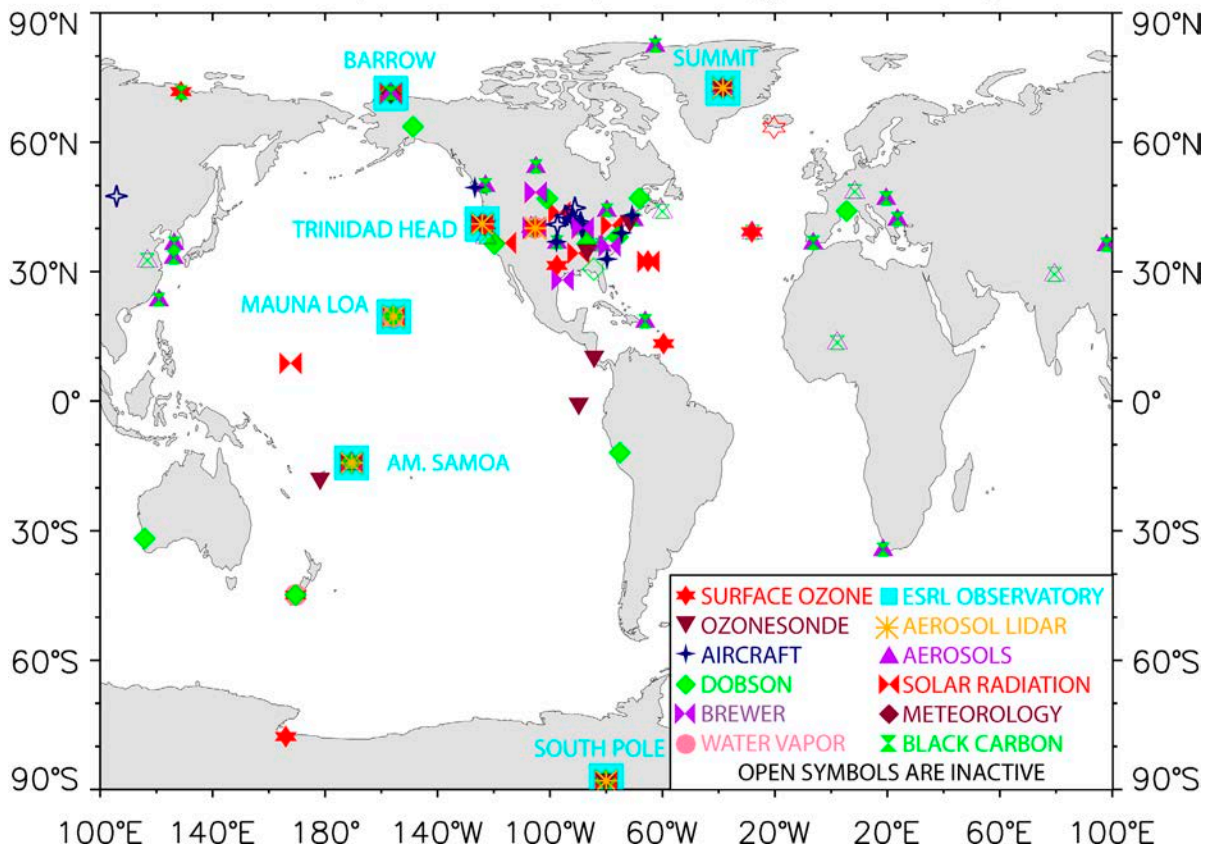
## **GMD Mission**

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

### NOAA ESRL Carbon Cycle and Halocarbon Gases



### NOAA ESRL Aerosols, Solar Radiation, Meteorology, Black Carbon, and Ozone



## Message from the Director




*I was recently asked in an interview what I thought GMD's greatest accomplishment to date was. I thought of the myriad significant publications, contributions to assessments, calibration and quality assurance activities, leadership roles, partnerships, and baseline observatories. But I ultimately had to say that the greatest success for GMD was having produced and maintained high-quality, long-term data records of atmospheric composition at over 100 sites around the world for up to five decades. That is not trivial and requires skilled scientists, technicians, and communicators to sustain it year in and year out. Collectively, GMD's is a unique contribution to understanding the changing composition of Earth's atmosphere and its influence on the Earth system as a whole. Though many partner with us, no organization in the world does what we do.*

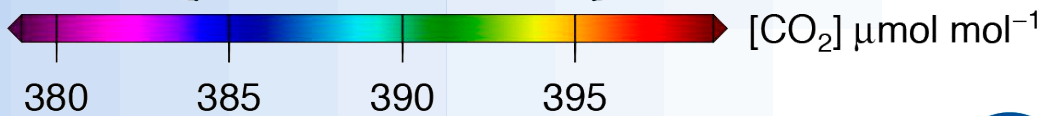
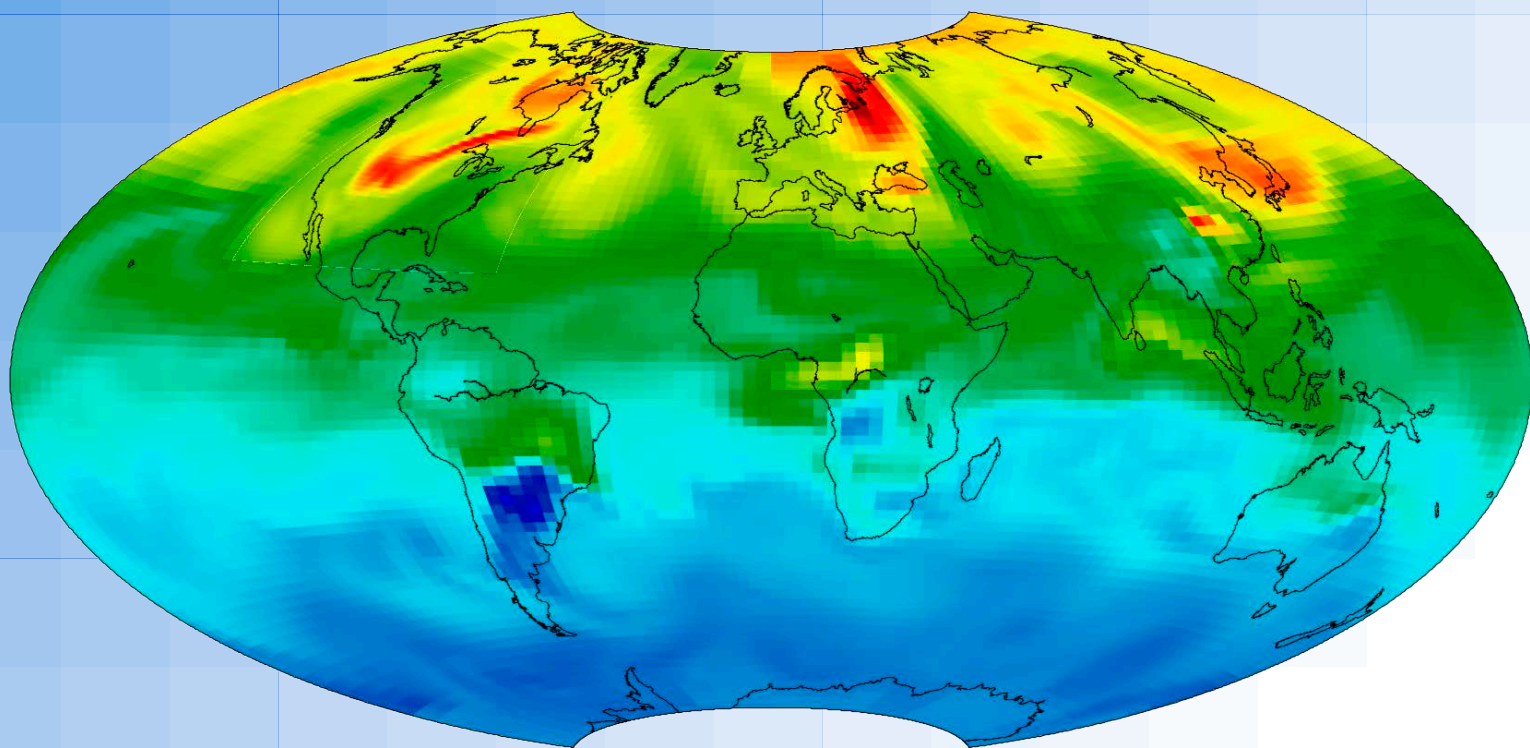
*I concluded the interview by noting that virtually all of our observations help to improve understanding of what is causing climate change. Many contribute to tracking the progress, causes, and consequences of stratospheric ozone depletion, and many also contribute to a better understanding of background air quality. These records, among the best in the world, are fundamental to the success of IPCC assessments, the quadrennial Scientific Assessments of Ozone Depletion, and numerous national and regional assessments and annual State of the Climate reports. Based entirely or in large part on data we produce, thousands of papers have been published in refereed literature, not only by our scientists, but by the global community as well, to whom we make all of our data available and with whom we work closely.*

*Over the decades, GMD's role has been fundamentally the same – its stated objective in its first annual report (1972), its raison d'être, was "to measure the necessary parameters for establishing trends of trace constituents important to climate change and of those elements that can assist in apportioning the source of changes to natural or anthropogenic sources, or both." Since its beginning, GMD's mission has not changed, and the critical data records continue.*

*This research plan underscores that role and provides a path forward for maintaining it over the next five years. But it also provides directions for research coming from these records that is relevant to today's scientific questions. This document guides us as we go forward and helps us stay on target, yet also conveys the important and unique role our mission and collective observations play in ensuring an adequate understanding of changes in the Earth System.*

  
James H. Butler  
Director

# free troposphere CO<sub>2</sub> 2010-Dec-31



NOAA Earth System Research Laboratory  
CarbonTracker CT2011 release



Carbon dioxide concentrations in the global atmosphere on December 31, 2010 as simulated by the CarbonTracker model. The Northern Hemisphere concentrations are higher at this time of the year (red colors) due to the absence of plant carbon uptake and the presence of fossil fuel emissions.

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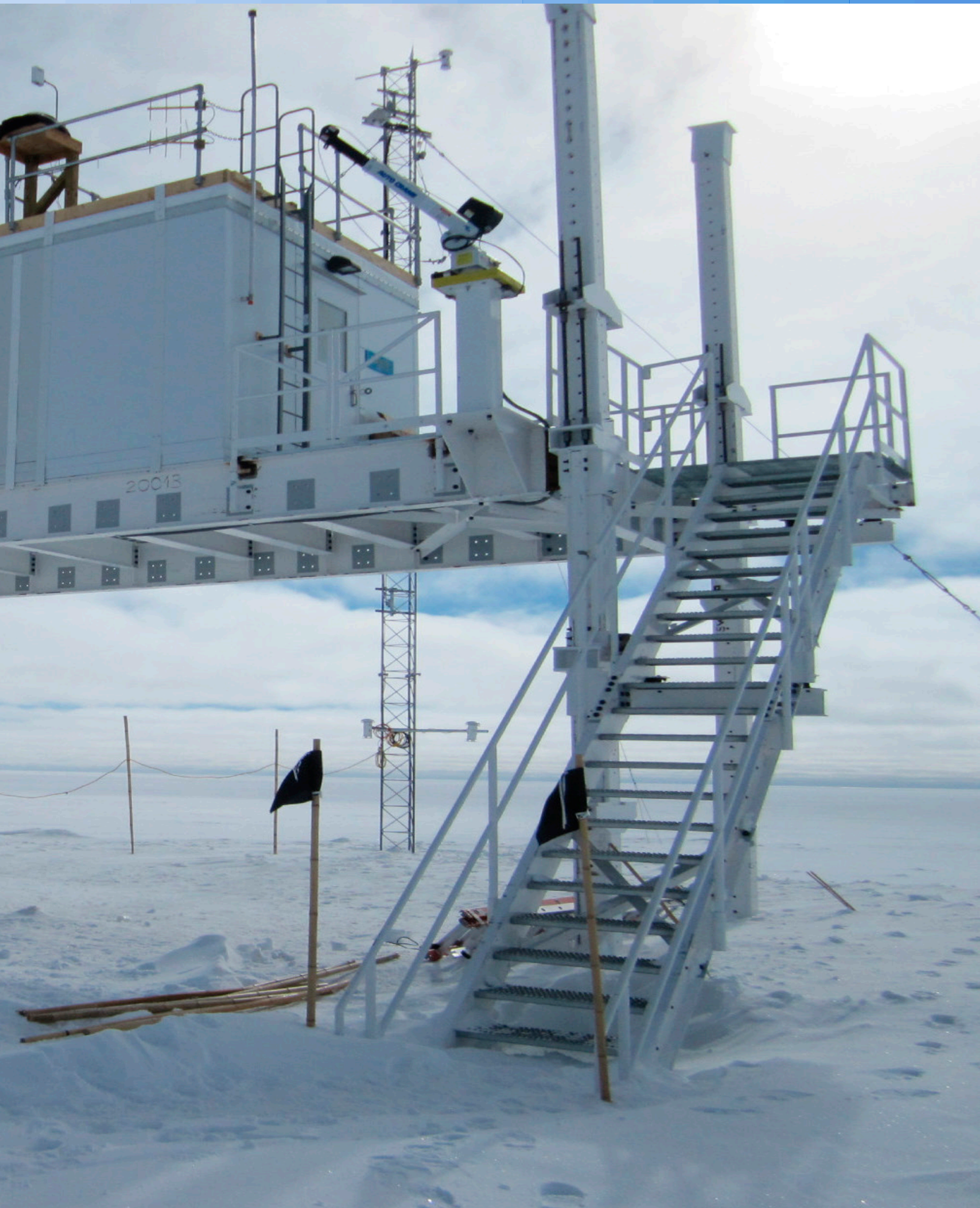
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# ABOUT THE GLOBAL MONITORING DIVISION







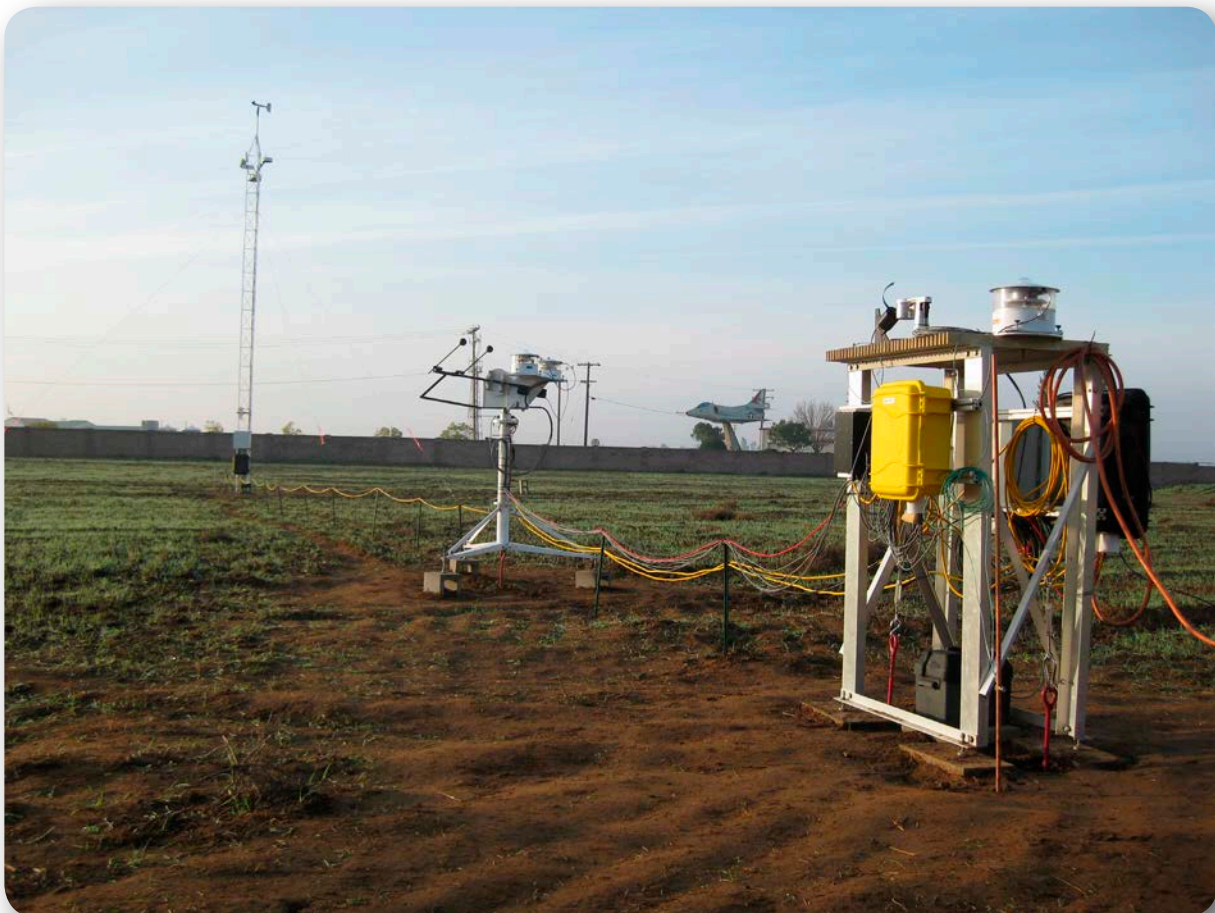
# Background for GMD Research

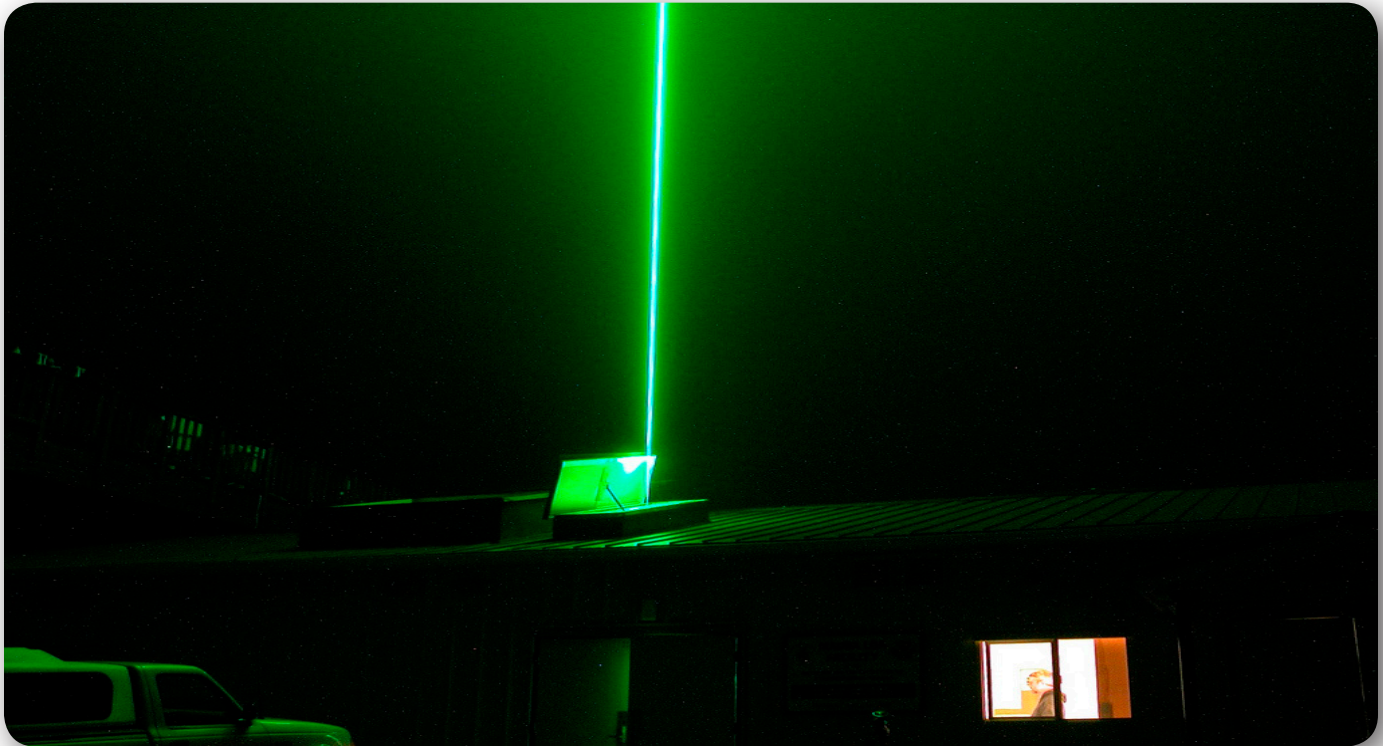
## Highlights of GMD Research

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**GMD scientists have unique and globally recognized expertise in making sustained atmospheric observations over extended periods, interpreting those observations, and communicating their findings to other researchers and the public. For example, we have:**

- documented the global atmospheric distribution and varying trends of carbon dioxide and methane for decades, including identifying the Northern Hemisphere terrestrial biosphere as a large sink for carbon dioxide;
- determined that the ocean and terrestrial biosphere continue to absorb half of all fossil fuel-CO<sub>2</sub> emissions, even as they increase over time;
- detected a 30+ year trend of increasing stratospheric water vapor that has a significant impact on climate.
- reported the turnaround and reduction of ozone-depleting chlorine and bromine in the atmosphere, and documented the stabilization of ozone depletion at the South Pole, the Arctic, Tropics, and Northern Hemisphere mid-latitudes.





- determined the amount of methane and pollutant emissions from oil and gas extraction at sites in the Western U.S.;
- consistently reported on the role of a multitude of long-lived gases other than CO<sub>2</sub> in forcing changes in climate;
- measured a surprisingly large 12 W/m<sup>2</sup> increase in net radiation over the continental United States in the last 15 years most likely resulting from decreasing clouds; and
- measured an increase of stratospheric aerosol since 2000 that may have reduced the expected warming of climate due to greenhouse gases over this period by 25%.

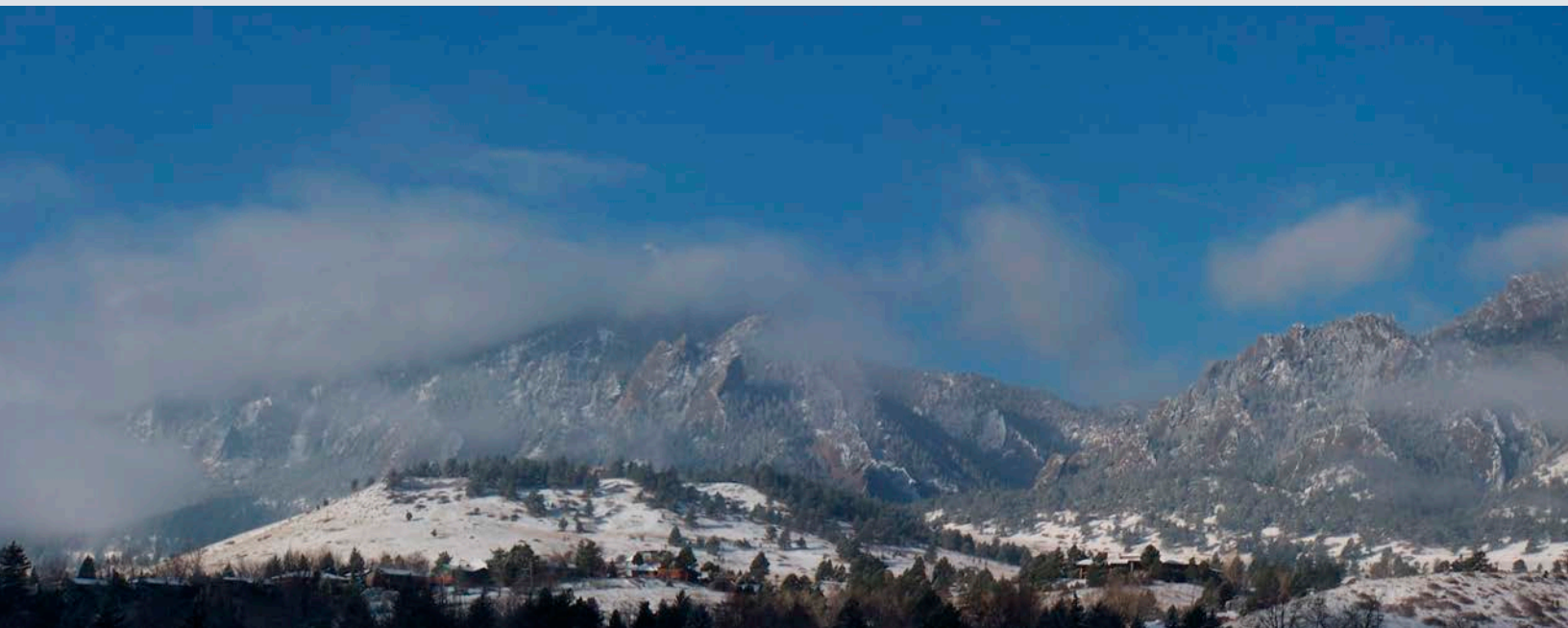
Above Photo: The NOAA/ESRL/GMD Mauna Loa Observatory laser radar (lidar). The lidar measures particle, water vapor, and temperature profiles in the troposphere and stratosphere.

**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;
- training researchers and institutions throughout the world to establish new monitoring programs, including private, educational, and domestic and international government agencies;
- creating, maintaining, and distributing globally recognized calibration scales, so that the goal of integrating diverse observing systems throughout the world can be achieved;
- providing data critical as inputs to and for evaluation of satellite retrievals and global and regional atmospheric models; and
- serving on national and international committees and commissions to ensure coherent observing systems, high-quality data, and relevant science.



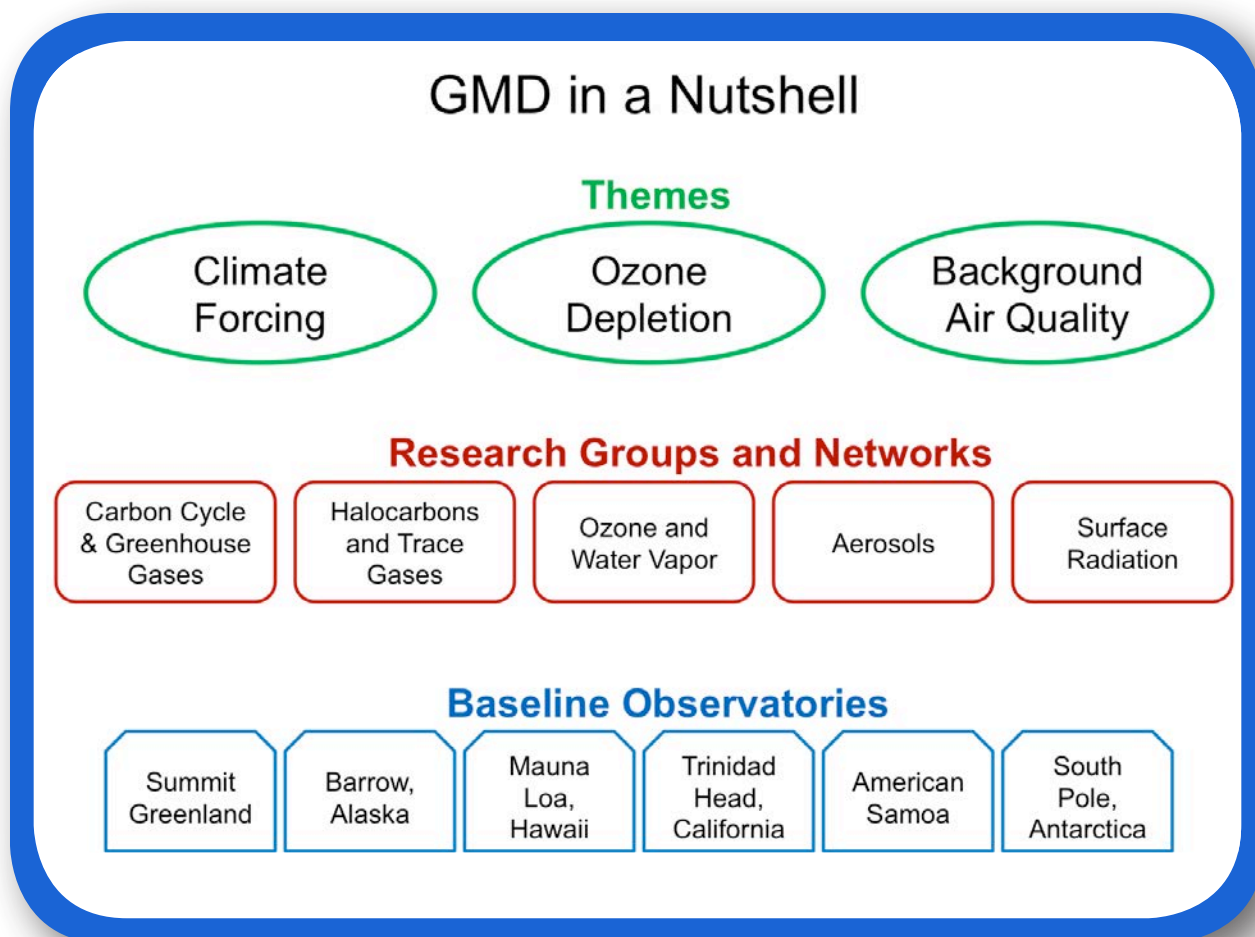
# GLOBAL MONITORING DIVISION RESEARCH STRUCTURE





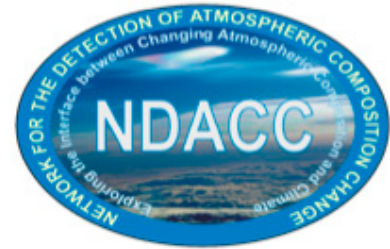
## Research Structure

Research emanating from GMD's networks addresses three major themes – **climate forcing**, **stratospheric ozone depletion**, and **background air quality**. To address these, GMD's five research groups are aligned according to the observations they make and, consequently, the skill-sets they require – Carbon Cycle and Greenhouse Gases (CCGG), Halocarbons and other Trace Species (HATS), Ozone and Water Vapor (OZVV), Aerosols (AERO), and Global Surface Radiation (GRAD). The unique observing systems operated by each research group join at GMD's baseline observatories, which serve as the backbone of the GMD observing system. GMD's research groups work together in both developing and maintaining their observing networks and especially in understanding, interpreting, and publishing results.





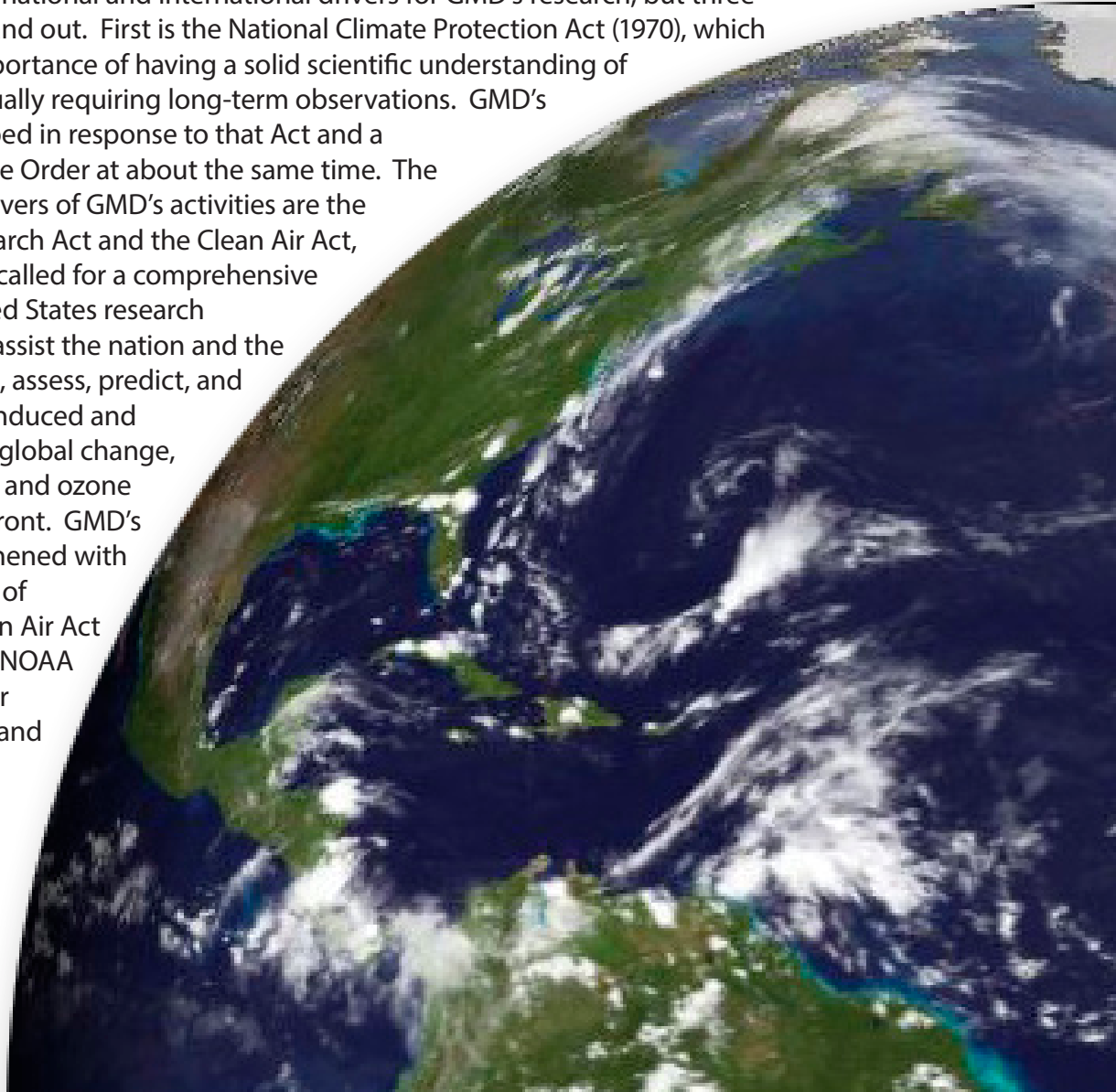
GMD's observations and research are critical to sustaining and preserving long-term observing records around the world. Because of GMD's observing systems' broad geographic coverage, consistent high quality, and relevance to on-going scientific endeavors, GMD's influence goes well beyond monitoring, research, and scientific publications. Ultimately, GMD provides numerous products and services; 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; and the basis for ensuring initialization and validation of satellite and modeling studies.



## GMD's National and International Linkages

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There are numerous national and international drivers for GMD's research, but three legislative drivers stand out. First is the National Climate Protection Act (1970), which underscored the importance of having a solid scientific understanding of climate change, virtually requiring long-term observations. GMD's mission was developed in response to that Act and a Presidential Executive Order at about the same time. The next two primary drivers of GMD's activities are the Global Change Research Act and the Clean Air Act, both in 1990, which 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, and brought climate and ozone research to the forefront. 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





A satellite view of Earth showing the Western Hemisphere, including North and South America, the Atlantic Ocean, and the Pacific Ocean. The image is positioned on the left side of the page, with the text overlaid on the right side.

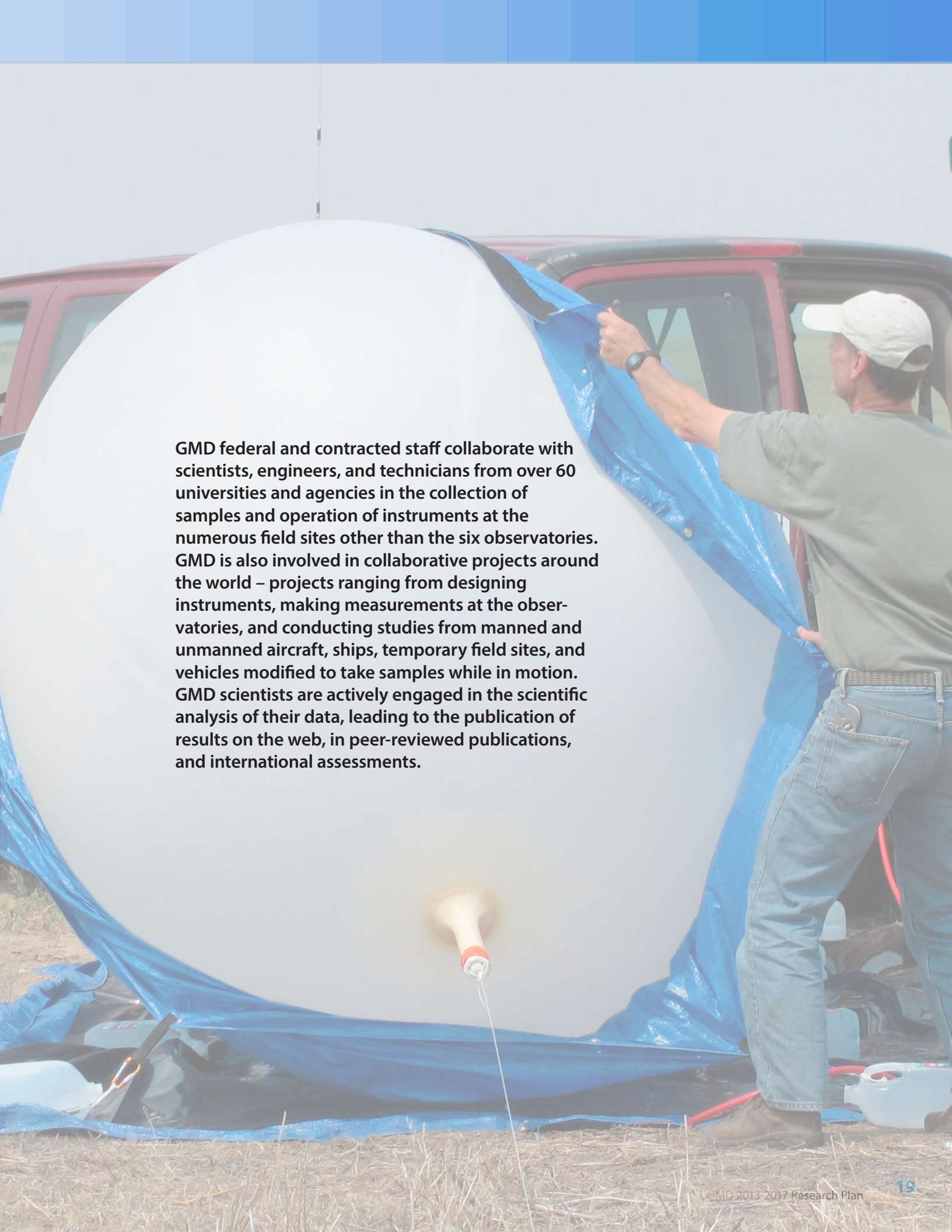
deplete it. GMD's mission, vision, and research support the broader objectives of the Department of Commerce, NOAA, and OAR strategic plans, and are consistent with the NOAA Research Plan. But GMD's reach goes far beyond its position within an agency structure. Owing to the high relevance of its measurements, calibrations, and quality control efforts, GMD's contributions are crucial to several aspects of the U.S Global Change Research Program. They are central and absolutely necessary to the World Meteorological Organization's (WMO) Global Atmospheric Watch Programme, they are a major component of atmospheric composition measurements in the Global Climate Observing System (GCOS), and are captured in the broader mission of the Global Earth Observing System of Systems (GEOSS). GMD provides leadership on a number of committees, commissions, and steering groups within these broader organizations to assist in achieving and sustaining relevant, high-quality observations in the service of science.

## **GMD's Workforce**

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The Global Monitoring Division maintains a federal workforce that works together with scientists from the University of Colorado's Cooperative Institute for Research in Environmental Sciences (CIRES) and Colorado State University's Cooperative Institute for Research in the Atmosphere (CIRA). CIRES and CIRA Research Scientists work side-by-side with NOAA federal scientists in GMD's laboratories and in the field, sharing in both the research efforts and the presentation of results at conferences and publications. The collaboration with CIRES and CIRA and other institutions such as the University of Colorado's Institute for Arctic and Alpine Research (INSTAAR) provides GMD access to a broader range of expertise in the academic community.





**GMD federal and contracted staff collaborate with scientists, engineers, and technicians from over 60 universities and agencies in the collection of samples and operation of instruments at the numerous field sites other than the six observatories. GMD is also involved in collaborative projects around the world – projects ranging from designing instruments, making measurements at the observatories, and conducting studies from manned and unmanned aircraft, ships, temporary field sites, and vehicles modified to take samples while in motion. 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.**



# RESEARCH QUESTIONS AND ACTIONS





# Research 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), ozone-depleting gases, aerosols, and atmospheric radiation to establish a basis for understanding the underlying causes for changes in climate, stratospheric ozone, and air quality—the three themes of our research. GMD's long data records add greatly to understanding the processes that impact the budgets of greenhouse gases, ozone, aerosols, and pollutants on timescales of days to centuries.

Although much of GMD's work is related to more than one of its themes, this document identifies the relevance, findings, and impacts of scientific questions according to the primary theme it supports. However, several actions stand out as supporting all three research themes.

## **Actions common to all GMD research questions:**

- Maintain existing global and U.S. observing networks (Observing System Section, pp. 41–45), including baseline observatories, remote sensing sites, and surface, tall tower, shipboard, aircraft, and balloon platforms. **These observing systems form the core of GMD's research and are essential to international networks. Ensuring their continuity and quality remains GMD's highest priority.** They will allow us to continue to make research-quality observations of gases, aerosols, and radiation.

- Sustain, update, and disseminate measurement standard scales to help ensure the quality of GMD's measurements and to assure the use of the accurate scales throughout the entire global scientific community. Global networks and the science that comes from them can only be as good as compatibility of their measurements and the continuity and accuracy of the calibrations that support them.
- 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 ensures their relevance and usefulness.
- Analyze and synthesize our data and disseminate these results via peer-reviewed publications and international syntheses like the WMO/UNEP Ozone Assessments and the IPCC Assessment Reports. Scientific publications are the essential building blocks of assessments and environmental policy.

## I. Climate Forcing

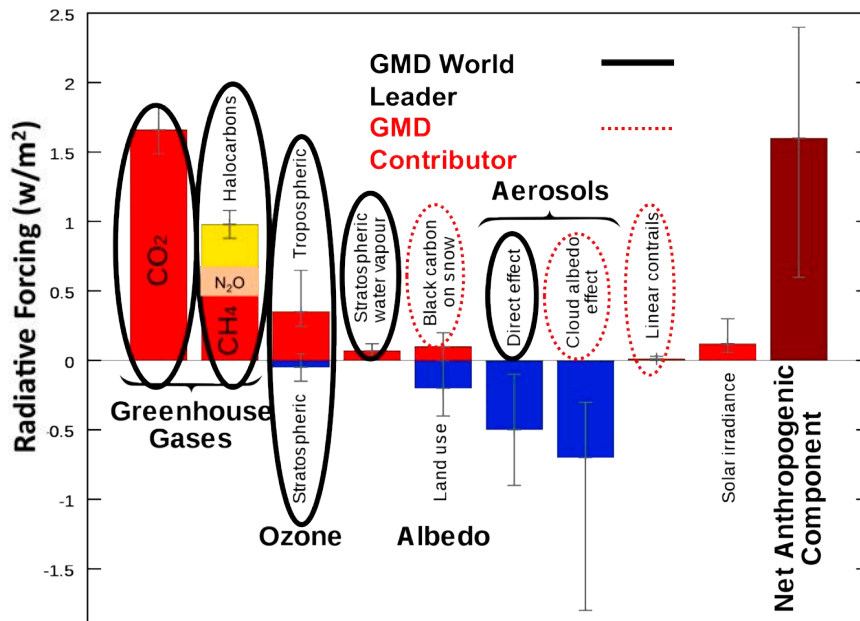


Fig. 2 IPCC AR4 components of radiative forcing with ovals highlighting GMD contributions.

*Understanding the mechanisms of Earth's changing climate is one of the grand challenges in Earth-system science and has significant implications for both ecosystems and society. Its importance only increases with time as society grapples with efforts to mitigate and adapt to climate change. GMD is at the forefront of understanding the primary driver of this change – the climate forcing that arises from increasing levels of greenhouse gases and aerosols at global, continental, and regional scales.*

**GMD is a world leader in producing the regional to global-scale, long-term measurement records that allow quantification of most of the factors affecting climate forcing today (Fig. 2).**

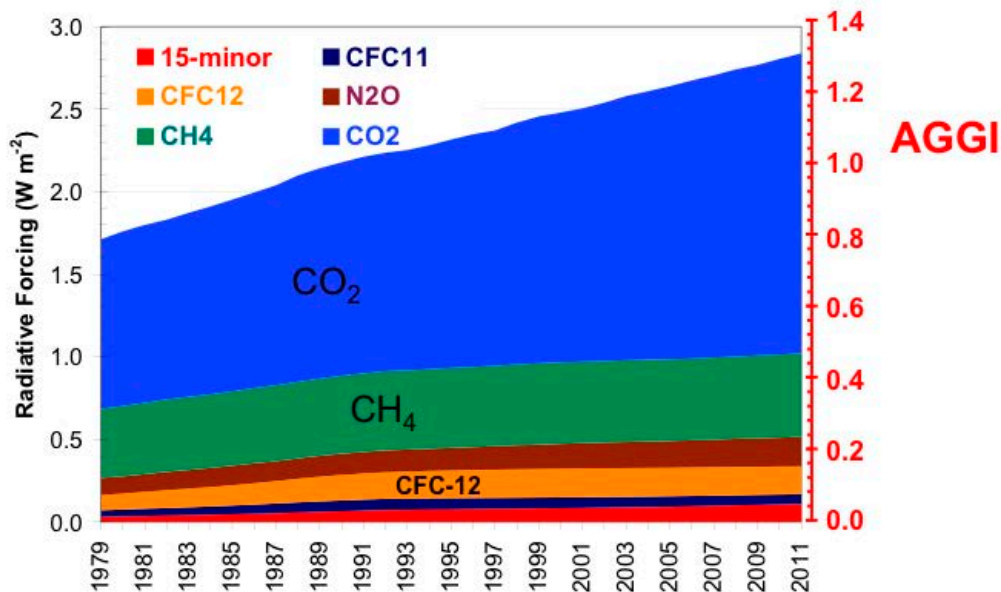
**Greenhouse Gases:** Global monitoring of atmospheric greenhouse gases, in particular carbon dioxide (CO<sub>2</sub>), has been part of NOAA's mission for over 40 years. GMD provides and interprets high-precision, high-accuracy measurements of the global abundance and spatial distribution of a suite of long-lived greenhouse gases that are the most significant contributors to climate forcing. Ozone and stratospheric water vapor, which also have significant climate impacts, have been monitored by GMD as well.

**Aerosols:** Aerosols (including black carbon) are the largest uncertainty in climate forcing calculations, and are highly variable in space, time, and composition. Their role in radiative

forcing is complex and can be either positive or negative, but they most often have a cooling effect. Aerosols affect climate directly via absorption and scattering and indirectly through influences on cloud properties. GMD focuses on the direct effects with measurements of aerosol optical properties that began in the 1970s, and underwent substantial improvement in the 1990s.

**Radiation:** Changes in the radiative balance at Earth's surface and at the top of the atmosphere result from forcing by greenhouse gases, aerosols, and other phenomena. Broadband measurements of incoming and outgoing solar and infrared radiation are made by GMD to quantify the surface radiation balance. GMD and its national and international partners have made substantial improvements in the accuracy of both solar and infrared measurements over the past 20 years, allowing detection of small changes in the radiation balance that have dramatic consequences for weather and climate.

## Question CF1: How are atmospheric levels of greenhouse gases changing and what are their impacts on radiative forcing?



NOAA/ESRL Global Monitoring Division  
Laboratory Review, April 3-5, 2013



**Fig. 3.** Greenhouse gas forcing from long-lived atmospheric gases has increased more than 30% since 1990.

**Relevance:** Long-lived GHGs like CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O and halogenated gases are the most important contributors to global radiative forcing (RF). RF is the primary cause of climate change.

**Actions Taken:** GMD has monitored greenhouse gases since 1967, and has created the Annual Greenhouse Gas Index (AGGI) based upon these high-quality data (Fig. 3) to track changes in RF.

**What we've discovered:** Although CO<sub>2</sub> accounts for the majority of RF, other gases also make substantial contributions; nevertheless, 80% of the increase in RF since 1990 is due to increases in global CO<sub>2</sub> concentrations.

**Future Actions:** GMD will continue to calculate the climate impact of long-lived GHGs, expand measurements to additional GHGs, and report results to the scientific community and public through the AGGI.

**Impact:** Beyond radiative forcing, the continued availability of on-going, robust, high-quality greenhouse gas measurements will improve model reanalyses and predictions and satellite retrievals.



## Question CF2: What are the anthropogenic and natural sources and sinks of long-lived greenhouse gases and how are they changing over time?

**Relevance:** Understanding variations in sources and sinks of greenhouse gases is fundamental to any attempt at emission management and future predictions.

**Actions Taken:** GMD has used its long-term atmospheric observations of GHGs to quantify their sources and sinks for more than 20 years. The most recent examples of this are the CarbonTracker data assimilation systems for CO<sub>2</sub> and CH<sub>4</sub> (See p. 26). Our source/sink calculations are limited in accuracy by number of data, and in the past ten years we have increased the density of measurements over the U.S. as part of the North American Carbon Program (NACP). We have also begun to measure more anthropogenic tracers over the U.S., including halocarbons and a limited set of <sup>14</sup>CO<sub>2</sub> observations for fossil fuel emission identification.

**What we've discovered:** Global CO<sub>2</sub> sinks have stayed roughly constant as a fraction of emissions over the past 50 years. U.S. sinks absorb one third of U.S. fossil fuel emissions, though with large variability (See p. 26). Global CH<sub>4</sub> emissions have increased since 2007 after having been steady for the previous decade.

**Future Actions:** GMD will:

a) Improve the CarbonTracker model by enhancing atmospheric transport with higher resolution and multiple wind field inputs, by developing methods for assimilating aircraft and remote-sensing data, and by extending the system to analyze multiple chemical species such as SF<sub>6</sub> and halocarbons.

b) Restore weekly airborne GHG measurements in the U.S. and collaborate with other groups (Earth Networks, NEON, etc.) to increase the number of tower-based GHG measurements, thereby improving the resolution and accuracy of emissions estimates over the U.S.

c) Take steps to initiate automated measurements of CO<sub>2</sub> and CH<sub>4</sub> on commercial airliners and expand the use of the AirCore vertical profiling system. These measurements will improve our ability to derive sources and sinks, understand transport of air in and out of the stratosphere, and help evaluate remote sensing measurements.

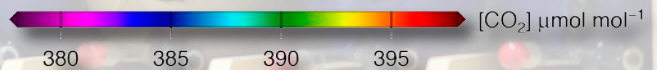
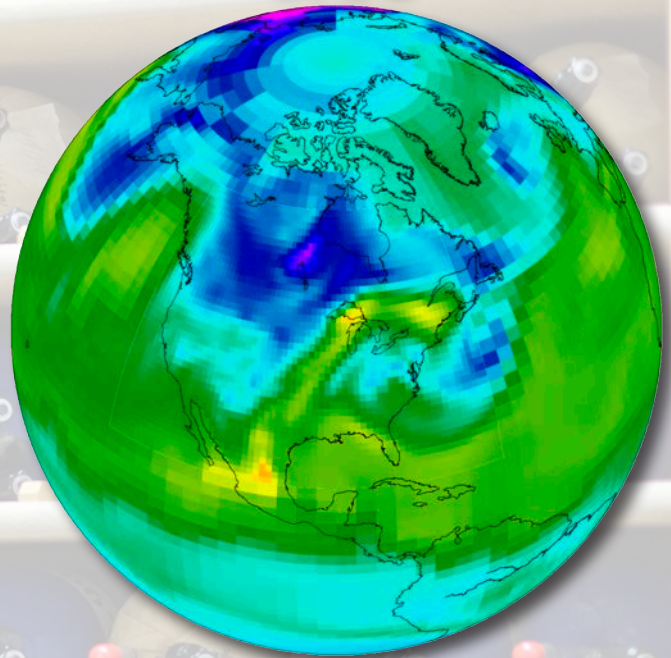
d) In collaboration with University of Colorado, INSTAAR, expand the limited set of <sup>14</sup>CO<sub>2</sub> observations over the U.S and East Asia to provide an independent quantification of fossil-fuel-CO<sub>2</sub> emissions and other greenhouse gases (e.g., halocarbons).

**Impact:** Expanding the number, location, and kinds of greenhouse gas measurements will improve calculation of North American and global emissions. Improved understanding of the North American and global carbon cycles (and budgets of other GHGs) will allow for better informed policy decisions, and enhance predictive capability of carbon cycle (and climate) models.

# CarbonTracker

free troposphere CO<sub>2</sub>  
2010-Jul-06

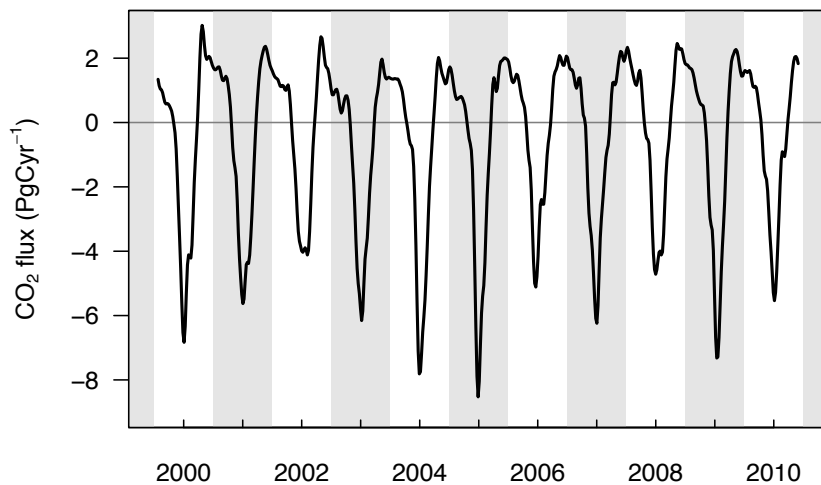
The CarbonTracker-CO<sub>2</sub> carbon data assimilation system is a global inverse model that focuses on North America, and allows us to estimate sources and sinks of CO<sub>2</sub>. Its North America focus relies on a higher data density in this region (See CCGG map on p. 41). In addition to sources and sinks of CO<sub>2</sub>, CarbonTracker also calculates atmospheric CO<sub>2</sub> concentrations that are increasingly being used in regional carbon flux studies. CarbonTracker has recently been extended to allow for calculation of methane (CH<sub>4</sub>) emissions.



NOAA Earth System Research Laboratory  
CarbonTracker CT2011 release



A snapshot of average CO<sub>2</sub> concentration in the free troposphere (~ 2 – 10 km asl) as calculated by CarbonTracker.



Biospheric carbon flux over temperate North America derived from atmospheric CO<sub>2</sub> data show inter-annual variability in carbon sources and sinks.

### Question CF3: How sensitive are the large reservoirs of arctic and tropical terrestrial carbon to rising temperatures?

**Relevance:** Carbon-climate feedbacks are a first-order uncertainty in predicting future climate. An enhanced understanding is critical for improving climate predictions and projections and for assessing the probability of potentially damaging climate feedbacks.

**Actions Taken:** GMD has measured CO<sub>2</sub> and CH<sub>4</sub> at multiple arctic sites over the past 40 years. In 2004 GMD helped establish a GHG measurement laboratory in Brazil that now measures CO<sub>2</sub>, CH<sub>4</sub>, and CO from an emerging Amazonian network (Outreach Section pp. 52–53).

**What we've discovered:** Despite high rates of warming, arctic-wide CH<sub>4</sub> emissions have been stable over the past decades.

Our measurements of the CH<sub>4</sub> global distribution indicate the recent increases in global CH<sub>4</sub> abundance originate mainly in the tropics.

**Future Actions:** GMD will:

- Continue inverse modeling of CO<sub>2</sub>, CH<sub>4</sub> and other gases at more than a dozen arctic and boreal sites to determine how sources and sinks vary.
- Add new arctic measurement sites via collaboration with other groups and continue to work with Brazilian partners on making and interpreting tropical measurements.

**Impact:** Understanding climate sensitivity of arctic and tropical carbon cycles will improve our ability to predict the probability and timing of potentially abrupt climate change.

### Question CF4: What are the historic, present, and future drivers of upper tropospheric, lower stratospheric water vapor abundances?

**Relevance:** Upper tropospheric, lower stratospheric (UTLS) water vapor has both strong sensitivity to and impact on Earth's climate. Satellite measurements of water vapor are broad-scale, but need continual evaluation.

**Actions Taken:** GMD has measured water vapor by balloon (from 2 – 30 km) since 1980 over Boulder, CO and now does so above Hilo, HI and Lauder, New Zealand. The number of sites is minimal but captures the basic global features.

**What we've discovered:** Measurements over Boulder (Fig. 4), the longest in existence, show a 27% net increase in stratospheric water vapor since 1980. These measurements have played a significant part in improving understanding of the influence of upper-atmospheric water vapor on climate.

**Future Actions:** GMD will:

- Continue to work with the satellite and modeling communities to ensure the continuity and accuracy of global satellite-based water vapor retrievals.
- Expand the number of water vapor vertical profiling sites to better understand drivers of trends.

**Impact:** An improved, ground-based observing network will put more confidence in estimates of water vapor feedbacks and impacts on climate change and ozone depletion.

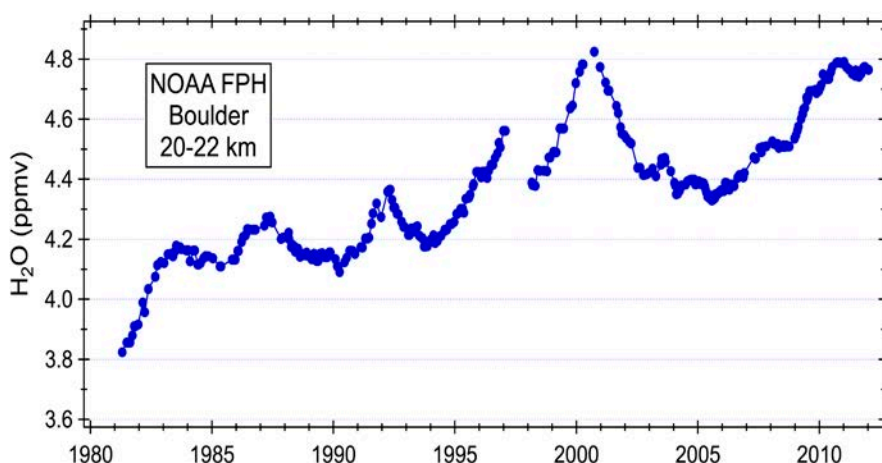


Fig. 4 Stratospheric water vapor trends above Boulder, as measured by the GMD Frost Point Hygrometer (FPH).

## Question CF5: How do the means, variability, and trends of climatically important aerosol optical properties vary as a function of location, time, and atmospheric conditions?

**Relevance:** The contribution of aerosol particles to direct radiative forcing remains one of the largest uncertainties in determining radiative forcing. It may be similar in magnitude (but opposite in sign) to that of GHGs.

**Actions Taken:** GMD measures aerosol scattering and absorption at 24 locations around the globe, ranging from clean, remote sites (e.g. Mauna Loa), to sites with regionally representative aerosol types from, e.g., dust and biomass burning.

**What we've discovered:** Recent analyses show decreases in tropospheric aerosol at most sites with >10 year measurements. Satellite evaluations of aerosol extinction using GMD in situ data have suggested limitations in the satellite measurements including sensitivity and cloud screening errors.

**Future Actions:** GMD will:

- a) Collaborate with other agencies to add additional sites to improve spatial and temporal coverage of different aerosol types.
- b) Augment current aerosol measurement systems with improved aerosol absorption, size distribution, and chemistry measurements to improve determination of climate relevant parameters.
- c) Continue to evaluate trends in aerosol properties (particularly absorbing aerosol, e.g. "black carbon").
- d) Assess surface measurements and restore some aerosol vertical profile measurements with the goal of evaluating chemical transport models and satellite retrievals as well as improving satellite algorithms based on aerosol type.

**Impact:** Addition observations will increase confidence in modeled calculations of aerosol impacts on climate change. This will decrease uncertainty in calculations of Earth's climate sensitivity.

## Question CF6: What changes in the worldwide radiation budget are we detecting at Earth's surface and what are the causes?

**Relevance:** Changes in Earth's radiation budget reflect the integrated influence of all direct and indirect climate forcing. Understanding these changes may be critical in efforts to plan solar energy development.

**Actions Taken:** Increasingly accurate broadband solar and infrared measurements have been made by GMD at 15 sites in the U.S. and around the world since the mid-1990s in cooperation with the global Baseline Surface Radiation Network.

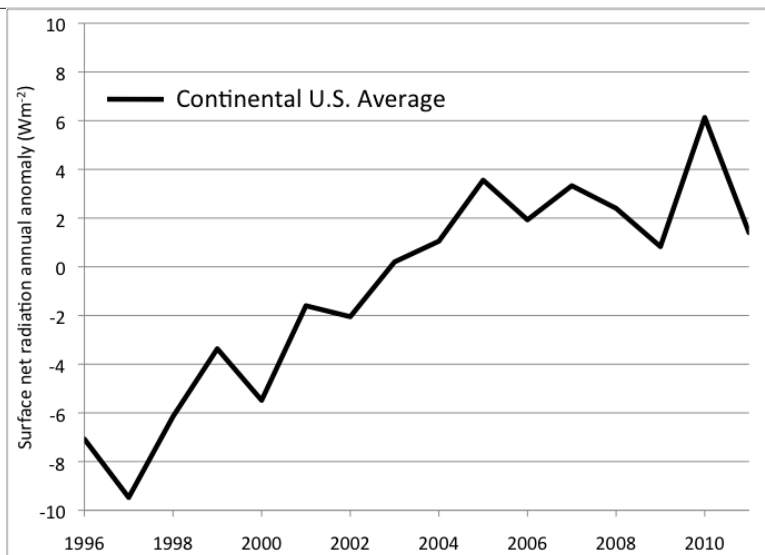


Fig. 5 The change in net radiation at the surface derived for continental U.S. over 15 years of SURFRAD measurements. This increase is mostly in the shortwave and is likely associated with reduced cloud cover.

**What we've discovered:** U.S. measurements show a  $12 \text{ Wm}^{-2}$  increase in net radiation since 1996, likely due to reduced cloud cover, much larger than expected from the direct influence of GHGs alone (Fig. 5).

**Future Actions: GMD will:**

- a) Collaborate with agency and university partners to expand measurements and include latent and sensible heat flux measurements to allow for full energy budget analysis.
- b) Upgrade a portion of equipment to allow for higher accuracy observations, which will allow for more rapid trend detection.

**Impact:** A ground-based measurement capability to calculate a full global energy budget will lead to a better understanding of the relative influences of increasing greenhouse gases and aerosols and of Earth-system feedbacks on climate change. It will also provide surface coverage to support and complement satellite retrievals.

## Question CF7: How will spectral surface albedo measurements improve our understanding of long-term changes in cloud and aerosol optical properties?

**Relevance:** Spectral surface albedo is essential to reconcile observed clear-sky radiation and the models used to predict it. It is also an important parameter for a broad spectrum of satellite retrievals.

**Actions Taken:** GMD has developed a mobile SURFRAD site with spectral capability.

**What we've discovered:** Initial findings show that spectral surface albedo is highly variable over space and time and not correctly represented by models, thus demonstrating the need for a larger, sustained, observing network.

**Future Actions: GMD will:**

- a) Augment current stationary SURFRAD sites with spectral surface albedo capabilities.
- b) Add an additional mobile site.

**Impact:** Besides providing essential spectral information for better satellite retrievals, the ability to measure and understand Earth's spectral surface albedo will allow retrievals of cloud optical depth and effective radius, retrievals of aerosol asymmetry parameter as a function of wavelength, and improved assessments of renewable energy potential.



Ells Dutton at the National Renewable Energy Laboratory in 2008 installing pyrheliometers for a year-long comparison of commercial instruments used for direct solar beam measurements.

# GMD Calibrations

Accurate, reliable calibrations are an essential component of all high-quality monitoring programs, and are required for proper interpretation of measurements of atmospheric gases, aerosols, and radiation. Long-term drift or bias among different instruments and components must be characterized or minimized if data are to be reliable. For data from multiple networks to be interpreted together, they must be linked to a common calibration scale. Global atmospheric measurement communities, be they surface-based, in situ, or remote, rely on GMD to provide that linkage.

GMD calibration activities include greenhouse and other trace gases, column ozone, and solar radiation. GMD serves as the WMO/GAW Central Calibration Laboratory for five greenhouse gases:  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{CO}$ ,  $\text{N}_2\text{O}$ , and  $\text{SF}_6$ . The GMD Solar Radiation Calibration Facility supports measurements at GMD baseline observatories and within the international Baseline Surface Radiation Network (BSRN). The Central Ultraviolet (UV) Calibration Facility provides calibration of UV monitoring instruments at GMD and at field sites using a portable calibrator.

Over the years, GMD has developed instruments and procedures specifically for the purpose of calibration and quality assurance in support of long-term measurement goals. We also conduct research to improve the quality of our calibrations and to understand any differences in application of GMD scales among laboratories around the world.

## To improve the quality of radiation, aerosol, and trace gas measurements worldwide, GMD will continue to:

- Maintain and improve GMD's calibration capabilities in support of being the WMO calibration laboratory for a number of greenhouse and ozone-depleting gases, solar radiation, and column ozone.
- Supply calibrated reference gases, calibration services, field and lab instrument comparisons, exchange of samples and reference gases to the domestic and international science communities.
- Provide end-to-end (instrument-to-data archive) support for collaborative aerosol and WMO World Dobson Ozone Networks.
- Provide surface, balloon, and aircraft data necessary to evaluate ground and space-based remote sensing measurements. (See p. 34)
- Create accurate and robust calibration scales for gases we will begin to measure (e.g. perfluorocarbons,  $\text{NF}_3$ , some hydrocarbons).



Natural-air gas standards are prepared in the Rocky Mountains, near Boulder. Over 500 compressed gas cylinders were filled, calibrated, and distributed world-wide in 2012.



## II. Ozone Depletion

*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 implemented 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 useable information to policy-makers for guiding the recovery of the ozone layer.

### OD1: Is the fully revised and amended Montreal Protocol successfully reducing the threat to stratospheric ozone posed by ozone-depleting substances?

**Relevance:** International and national controls on the production of ozone-depleting substances (ODSs) are intended to “heal” the ozone hole and bring UV radiation levels and skin cancer rates back to their pre-ozone hole levels.

**Actions taken:** GMD continues to monitor the abundance and global distribution of ozone-depleting substances at surface sites across the globe. Changes in the summed atmospheric concentration of ODSs are tracked and updated annually with GMD's Ozone-Depleting Gas Index (ODGI Fig. 6). GMD also coordinates with other groups (e.g. 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 threat to the ozone layer. The summed concentration of ozone depleting substances has decreased steadily for over a decade.

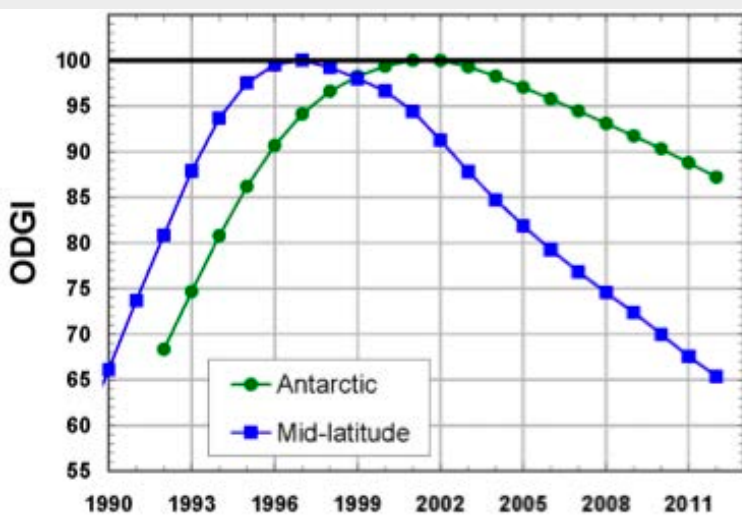


Fig. 6. NOAA Ozone-Depleting Gas Index (ODGI) derived from GMD's surface observations, showing a gradual return towards benchmark levels (ODGI=0 in 1980) in two regions of the stratosphere.

**Future actions: GMD will:**

- a) Continue ongoing measurements of gases currently in the ODGI, and add new gases that have high potential for ozone depletion.
- b) Inform policy-makers on the effectiveness of existing international legislation 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.
- c) Further guide ozone recovery by providing U.S. emissions estimates of ODSs and their substitutes.

**Impact:** National and international policy-makers will continue to have the best possible information for guiding recovery of the ozone layer and understanding unanticipated consequences of CFC replacements on climate change.

## **OD2: Given the atmospheric reductions in ozone-depleting substances, is stratospheric ozone recovering as expected?**

**Actions taken:** GMD’s global, long-term monitoring of ozone ( $O_3$ ), a core element of international networks, helps to distinguish between short and long-term processes, and guides science to properly attribute ozone depletion and recovery to chemical and climate processes. GMD measures the vertical and temporal extent of ozone depletion at sites across the globe from its long-term record of balloon profiles and ground-based total column and vertical profile (Umkehr)  $O_3$  measurements and provides the only year-round measurements at the South Pole.

**What we’ve discovered:** Historically, ozone has decreased substantially as the concentrations of ODSs increased. During the 2000s ODSs began to decrease, which is observed in stabilization of GMD-measured ozone levels in Antarctica (Fig. 7).

**Future actions: GMD will:**

- a) Evaluate whether observed changes in  $O_3$  are consistent with those expected on the basis of GMDs measured changes in ODSs.
- b) Gauge the impact of other processes on stratospheric ozone trends such as volcanoes, increased methane and nitrous oxide concentrations and changes in stratospheric temperatures and circulation.

**Impact:** These continued efforts help ensure that policies achieve the desired goal of pre-1980 levels of stratospheric ozone in a about a half-century, and help understand the influence of climate change decisions on ozone depletion. Society will no longer face the impacts of increased UV radiation on human health and agriculture.





## OD3: How does ozone variability affect UV radiation at Earth's surface?

**Relevance:** Although many processes affect UV radiation at Earth's surface, decreases in UV are expected in areas where significant ozone recovery is observed.

**Actions taken:** GMD has measured total horizontal UV spectral irradiance at two Northern Hemisphere sites since 1998. Since 2009, GMD has also operated six spectrometers in Antarctica (formerly operated by NSF). The Antarctic data record includes 24 years of continuous spectral UV measurements in a region that experiences the most dramatic column ozone changes on Earth.

**What we've discovered:** Total surface UV changes cannot be attributed simply to changes in column ozone, but that there are other atmospheric properties and processes influencing UV variability.

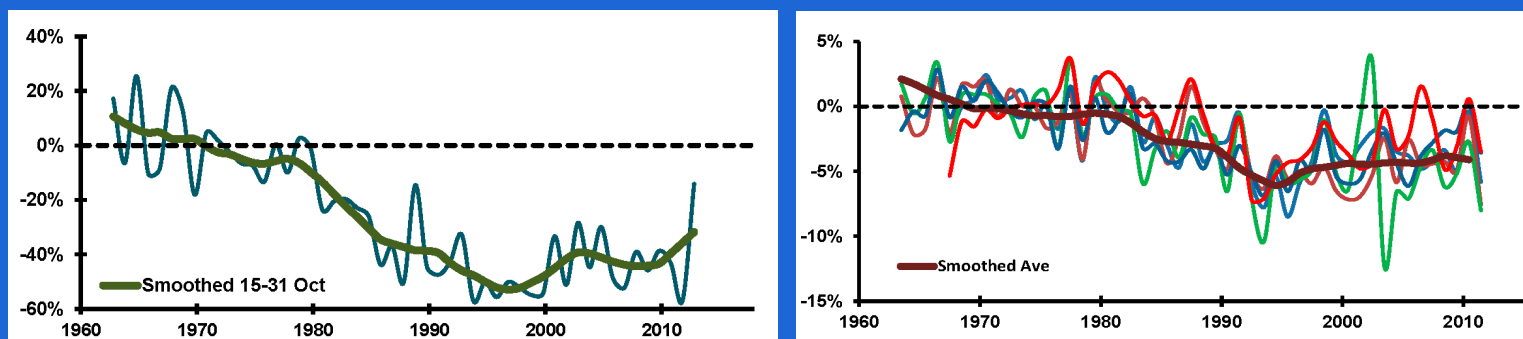


Figure 7: (Left) Total ozone time series capture the development of ozone hole over 50 years of GMD operations at South Pole. (Right) Long-term variability in the annual averages of total ozone record over Northern Middle latitudes as represented by data from five GMD sites.

**Future actions:** GMD will focus analyses on recent data streams that will allow partitioning of observed UV variability into those resulting from changes in cloud cover, aerosols, and ozone.

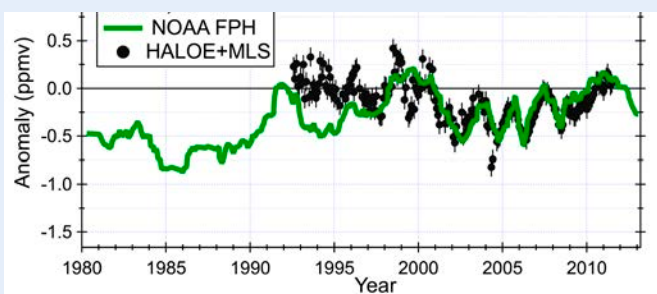
**Impact:** Further understanding the influences of various human-related activities on ultraviolet radiation will help alleviate or prevent increased damage to agriculture and incidences of cancer in humans.



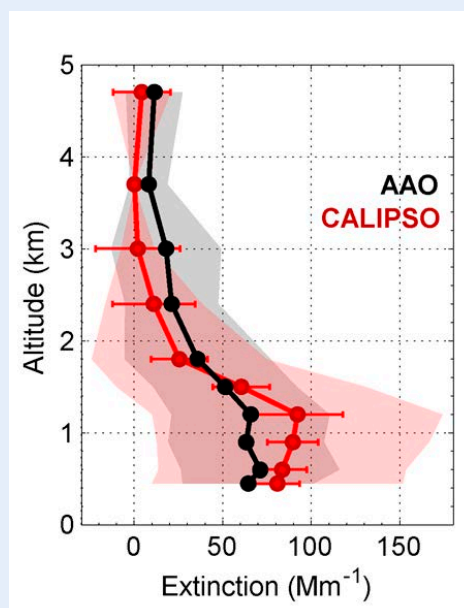
# Using GMD Data to Evaluate Satellite Measurements

GMD's high-quality trace gas, aerosol, and solar radiation data are essential for evaluation and homogenization of various satellite records. Satellite measurements can be limited by lack of sensitivity to the near-surface concentrations of trace gas species, low-temporal sampling frequency, and retrieval algorithm assumptions. Some of GMD's recent satellite-related activities include:

- GMD's 30+ year record of balloon-based ozone and water vapor profiles provides an essential reference for merged, global satellite ozone records (TOMS, UARS, SAGE, SBUV2, Aura). In addition, near-real-time measurements from GMD ground-based ozone sites have helped bring new SNPP ozone products to maturity.
- SURFRAD data have been used to develop surface albedo products for GOES-R and MODIS. It is used to validate operational GOES surface down-welling shortwave radiation, EOS CERES and MODIS photosynthetically active radiation products, as well as several GOES-8, ASTER, and MODIS land surface temperature and emissivity products. Other projects include validation of the CALIOP/CloudSat estimates of the up- and down-welling longwave radiation.
- GMD in situ aircraft profile measurements and CALIPSO retrievals of aerosol extinction are generally in good agreement. However, cloud screening issues and CALIOP lidar sensitivity may limit retrievals in some locations.
- Data from GMD aircraft, surface sites and tall towers have been used to evaluate satellite measurements of CO<sub>2</sub> (GOSAT, AIRS, TES), CH<sub>4</sub> (SCIAMACHY, AIRS), and CO (MOPITT). Comparison with ground-based and aircraft data has revealed large biases, e.g. SCIAMACHY CH<sub>4</sub> measurements were too high over the Amazon and GOSAT CO<sub>2</sub> retrievals are biased over the oceans (Also see pp. 46–47).
- Unmanned and manned aircraft measurements have been successfully used for validation of Aura satellite accuracy in measurements of ozone and ozone-depleting substances across a range of latitudes and altitude.



Comparison of GMD and satellite-based stratospheric water vapor measurements over Boulder, CO, showing how the long GMD time series helps to link the two shorter satellite series.



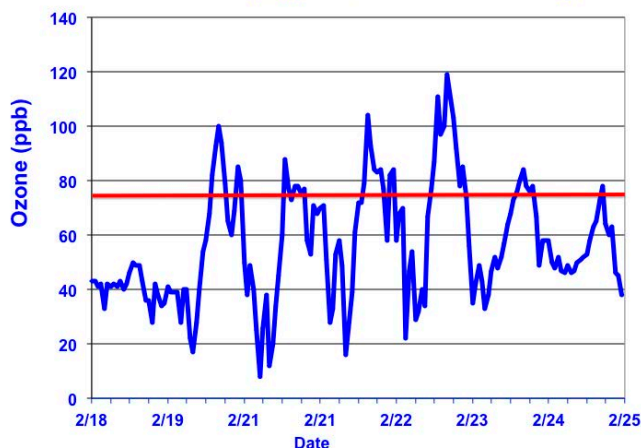
Comparison of mean aerosol extinction profiles from GMD's aircraft (AAO) and the CALIOP lidar on CALIPSO based on flights coincident with satellite overpasses. The shaded envelopes are standard deviations of the observations and the CALIPSO error bars are the propagated uncertainties of the satellite lidar measurement.

### III. Air Quality

Poor air quality, including high levels of hazardous pollutants, tropospheric ozone, and aerosols, has the ability to affect the health of millions of Americans. GMD strives to document and understand long-term trends and large-scale variations of these constituents across the United States and in the upwind atmosphere. This information is critical for defining appropriate mitigation strategies and assessing the efficacy of those strategies once they are implemented.

GMD has made significant contributions to understanding air quality by making measurements of ozone, aerosols, and carbon monoxide at remote sites upwind of the U.S. These results have allowed us to evaluate the effects of intercontinental transport of pollutants on background air quality. Long-term changes observed by GMD and associated networks allow us to assess impacts of air quality legislation. More recently, observations made at locations closer to pollutant emissions have been used to understand the distribution, sources, sinks, character, and chemical modification of atmospheric constituents (see p. 38), including several measurement campaigns to understand pollutant emissions associated with oil and gas extraction.

Wintertime Ozone, Upper Green River Basin, WY



#### AQ1. How is intercontinental transport of pollutants influencing air quality over the United States and adjacent oceans? How are these influences changing over time?

**Relevance:** Intercontinental transport of pollutant emissions from expanding Asian countries can adversely affect air quality and human health in the U.S. This influence can also restrict policy-makers' options for pollution mitigation.

**Actions Taken:** GMD monitors ozone and other pollutants at sites both upwind of the continental U.S., within the continent, and downwind.

**What we've discovered:** GMD's ozone data have played a major role in analyses showing that reductions in locally produced ozone are counteracted by increasing levels of episodic Asian ozone pollution. Long range transport has also been shown to deliver carcinogenic chemicals at one-in-a-million cancer benchmark concentrations.

**Future Actions:** GMD will:

- a) Continue to evaluate the contribution of long-range transport on the concentrations of ozone, carbon monoxide, and other pollutants reaching the U.S.
- b) Quantify the effects of short-lived halogenated gases and products on tropospheric ozone and mercury deposition over broad atmospheric scales.

**Impact:** Understanding these influences, which today are poorly quantified, will afford national and regional policy-makers the opportunity to place realistic guidelines for emissions affecting air quality.

## **AQ2: How does the cleansing capacity of the global atmosphere vary over time, and how sensitive is it to anthropogenic emissions?**

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**Relevance:** Naturally-occurring atmospheric oxidants remove pollutants from the atmosphere and limit their environmental impacts; they are also central to the formation of tropospheric ozone. Atmospheric concentrations of these oxidants may be sensitive to changes in human activities and natural processes.

**Actions Taken:** GMD has indirectly estimated the stability of the primary atmospheric oxidant (the hydroxyl radical, OH) by monitoring atmospheric concentrations of gases that react with this oxidant, such as methyl chloroform, methane, methyl halides, and chlorinated solvents.

**What we've discovered:** Measurements on a global scale demonstrated that concentrations of the OH, and therefore lifetimes of many trace gases, do not vary substantially from year to year.

**Future Actions:** GMD will:

Continue monitoring methyl chloroform concentrations and explore the usefulness of other trace gases for inferring longer-term changes in atmospheric oxidant concentrations.

**Impact:** Because of increasing global emissions of pollutants that are oxidized in the atmosphere, monitoring OH will be important for implementation of successful policies relating to emissions of a variety of gases.

## **AQ3: How does the production and extraction of fossil fuels affect air quality?**

---

**Relevance:** Natural gas extraction has dramatically increased over the past decade but its influence on air quality is not well-quantified.

**Actions Taken:** GMD has initiated and participated in measurement campaigns in areas of the western U.S. strongly impacted by natural gas production. GMD has brought a unique set of capabilities to these studies, drawing from the instrumentation and measurement strategies of our global networks.

**What we've discovered:** Elevated levels of ozone (particularly in winter) and a number of other air pollutants appear to be directly related to drill site activities (see p. 38). GMD's published records and analyses

have strongly suggested that accounting-based (i.e. “bottom-up”) calculations of emissions do not adequately explain observations.

**Future Actions:** GMD will:

**a)** Continue to develop airborne and mobile ground-based systems for measuring emissions associated with fossil-fuel extraction.

**b)** Continue to improve methodologies and participate in campaigns designed to characterize and quantify emissions associated with fossil fuel extraction.

**Impact:** In addition to assessing how fossil fuel extraction affects air quality, quantifying these emissions is essential for the assessment of the climate impact of natural gas. These findings will aid policy-makers in their efforts to ensure high air quality across the nation and to minimize impact of large scale, fossil fuel development on climate.

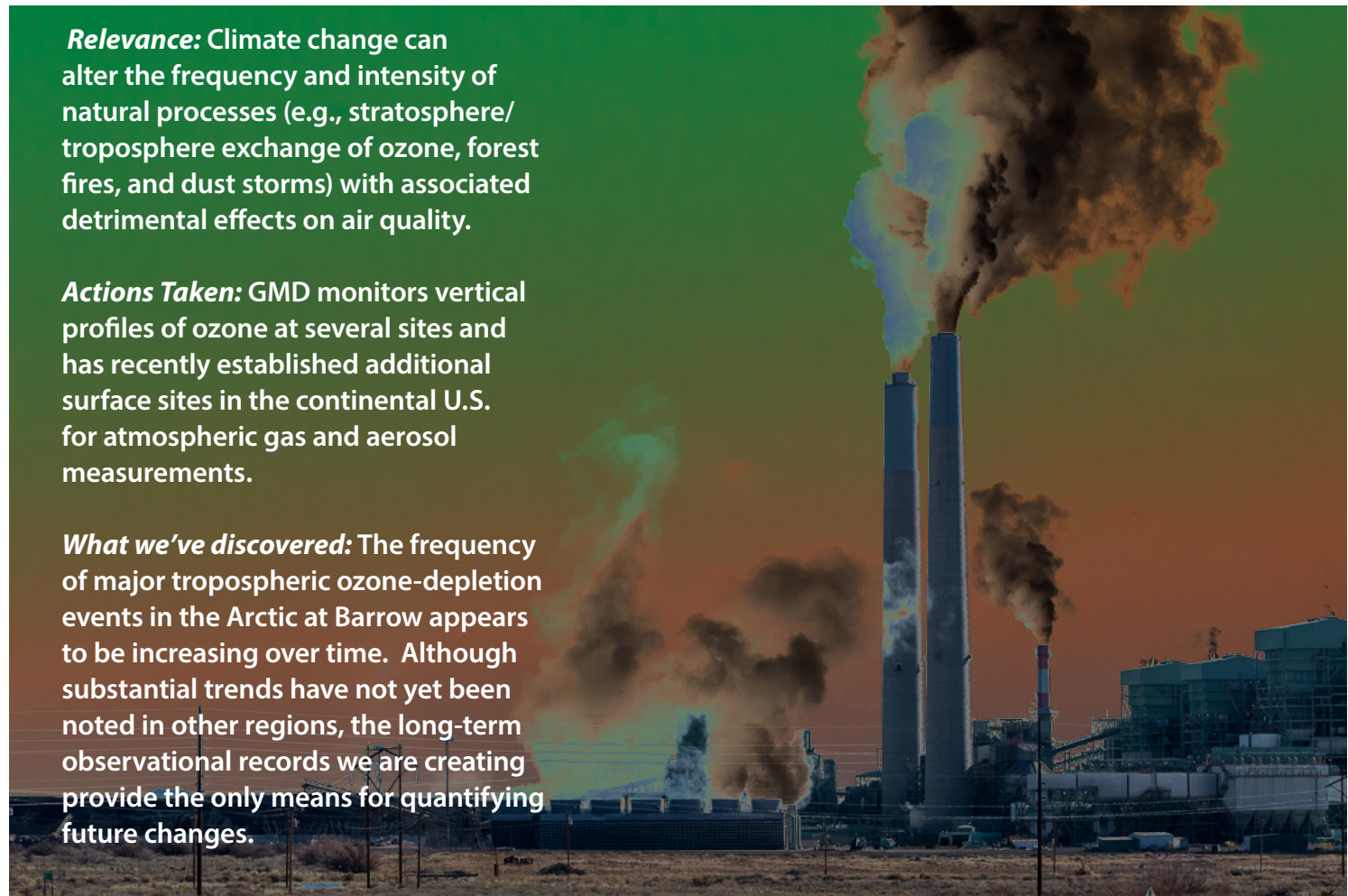
#### **AQ4: How are changes in climate affecting air quality?**

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**Relevance:** Climate change can alter the frequency and intensity of natural processes (e.g., stratosphere/troposphere exchange of ozone, forest fires, and dust storms) with associated detrimental effects on air quality.

**Actions Taken:** GMD monitors vertical profiles of ozone at several sites and has recently established additional surface sites in the continental U.S. for atmospheric gas and aerosol measurements.

**What we’ve discovered:** The frequency of major tropospheric ozone-depletion events in the Arctic at Barrow appears to be increasing over time. Although substantial trends have not yet been noted in other regions, the long-term observational records we are creating provide the only means for quantifying future changes.



**Future Actions :** GMD will:

**a)** Assess the role of climate change in long-term changes in U.S. pollutant levels.

**b)** Restore some capability for vertical profile measurements of aerosols and ozone.

**Impact:** Understanding the sensitivity of pollution to climate change is essential for design of effective pollution mitigation policies.

# Inter-disciplinary Research: Oil and Gas Extraction Impacts on Climate and Air Quality

Three GMD studies of oil and gas producing regions in the Rocky Mountain West (Fig. A), have shown enhanced amounts of pollutants like ozone and benzene in addition to leakage of the potent greenhouse gas methane. In 2005, a study in Wyoming's Green River Basin showed potentially hazardous levels of surface ozone resulting from emissions of NO<sub>x</sub> and volatile organic carbon (VOC) effluents associated with the production of natural gas in the area. In 2007, GMD began routinely monitoring the atmosphere's composition at a tower in northeastern Colorado. Instruments on the tower immediately detected plumes of air rich with chemical pollutants including the potent greenhouse gas methane. Custom air sampling devices, including a mobile

laboratory were developed and deployed in the region downwind of possible sources to collect chemical "fingerprints" that would help identify the possible sources. This study showed that oil and gas extraction leaked or vented an estimated 4 percent of all natural gas produced to the atmosphere. The study further found that emissions of benzene, a known carcinogen tracked and regulated by the EPA, also had been underestimated, and that oil- and gas-related emissions of volatile organic compounds, which contribute to lung-damaging ozone pollution, had been underestimated. Most recently, a field study in Utah used airborne and surface measurement platforms to observe large amounts of methane being released due to oil and gas production.

## Pollution linked to drilling

High levels of ozone were found in Wyoming's Green River Basin and Utah's Uintah Basin, raising concerns about air quality in Colorado oil fields including the Piceance Basin. Methane and propane were found in high levels close to the Denver-Julesburg Basin in Colorado.



Sources: U.S. Geological Survey and National Oceanic and Atmospheric Administration

The Denver Post



Photo above: Mobile sampling lab. Photo (Top Right): Gaby Petron tells U.S. Rep. Jared Polis how she uses the mobile lab to monitor conditions in local oil and gas fields i.e. in Utah (Bottom Right).

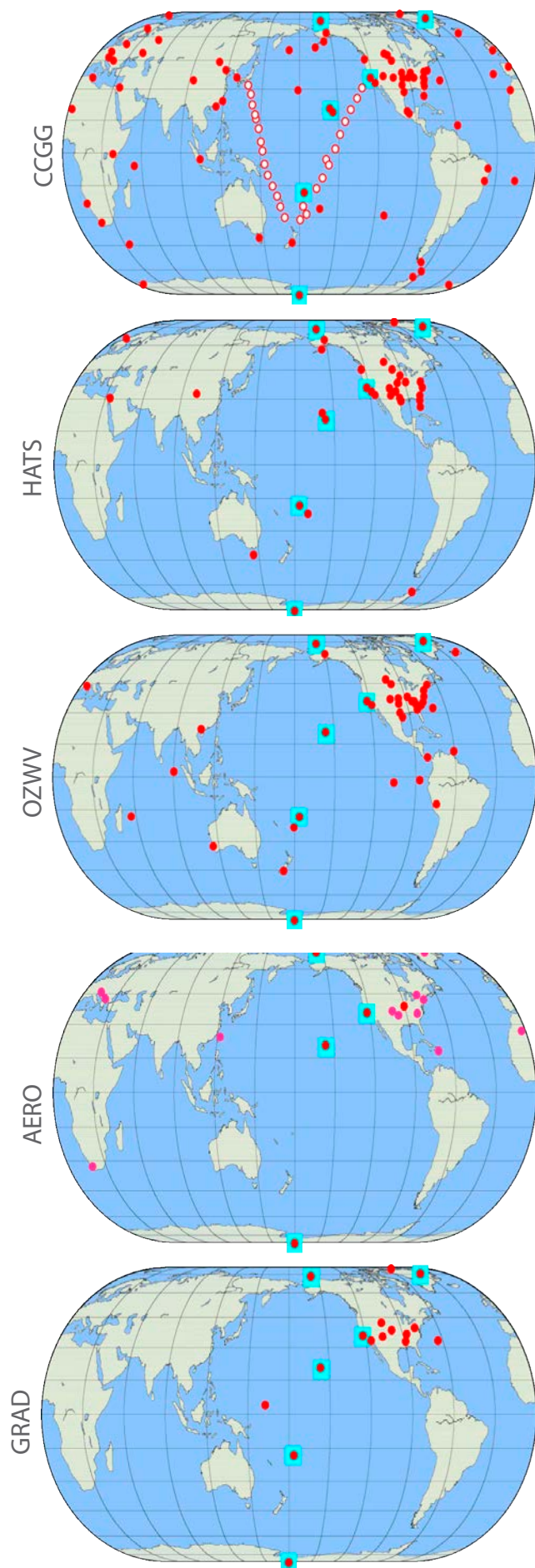
Fig. A





# GMD OBSERVING SYSTEMS





GMD's data originate from its monitoring sites, which are functionally divided into five separate networks that use distinct technologies to measure different atmospheric properties. Carbon cycle (CCGG) and halocarbon (HATS) groups use in situ measurements and discrete air sampling to characterize trace gas concentrations. 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. Ozone and water vapor measurements (OZWV), on the other hand, are made 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 (AERO) are made at 24 regionally representative, long-term, surface sites around the globe. (Measurements of aerosol aircraft vertical profiles were shut down in 2007 and 2009, but plans remain to restore them.) Downwelling solar and infrared radiation measurements (GRAD) are made on sun-tracking platforms at surface-based sites. A nearby 10-m tower is the mounting point for matching upwelling solar and infrared measurements.

**Figure 8.** Red circles indicate surface, balloon, tower or aircraft sites (See left). Several surface and airborne sites have ceased operation recently and are shown by unfilled red circles. Blue squares show the baseline observatories.

## Atmospheric Baseline Observatories

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At the core of GMD's measurement networks are the baseline observatories located at Mauna Loa, Hawaii; South Pole, Antarctica; Barrow, Alaska; Cape Matatula, American Samoa; Trinidad Head, California; and Summit, Greenland. The sites were established in order to provide sampling of very clean air, away from sources of pollution, so that the background atmosphere could be monitored, resulting in, for example, the iconic Mauna Loa CO<sub>2</sub> time series. These observatories form the backbone of NOAA's and the WMO's efforts to monitor climate forcing, background air quality, ozone depletion and related phenomena.

The Baseline Observatories host monitoring projects from other federal agencies, universities, and international partners in order to assess the distributions and fluxes of measured greenhouse gases, ozone and ozone depleting compounds, aerosols, and solar radiation in the remote atmosphere. The observatories conduct about 250 different measurements related to climate, ozone depletion, and atmospheric composition. These measurements are calibrated and maintained by a highly trained and stable workforce. As the need for an understanding of the climate system increases, the role of the atmospheric baseline observatories and the global cooperative networks will become even more crucial to the study of atmospheric composition as it influences climate change, ozone depletion, and air quality.



South Pole Observatory



Trinidad Head, California Observatory,  
Copyright (C) 2002-2013 Kenneth & Gabrielle Adelman, California Coastal Records Project, [www.Californiaoastline.org](http://www.Californiaoastline.org)



Barrow, Alaska Observatory



American Samoa Observatory



Mauna Loa, Hawaii Observatory

**Future Actions and Impacts:** In an effort to strengthen the contribution of the observatories to our scientific understanding GMD will do the following:

**Action:** Improve infrastructure to facilitate and support research.

**Impact:** Increased research programs and partnership networks collocated at the six baseline observatories will extend national and international networks. Better understanding of the climate, ozone, and air quality is possible with increased co-located data sets.

**Action:** Promote inter-disciplinary 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 with how climate impacts affect the planet. This will further enhance the linkages between the atmospheric climate system and oceanic, ecological, and social systems.

## Baseline Observatory Activities

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### **Mauna Loa, Hawaii (Established 1957)**


The Mauna Loa Observatory (MLO), located at 3397 m elevation on the Mauna Loa volcano massif, is the premier, long-term, atmospheric observations and research facility that has been continuously monitoring and collecting data related to changes in atmospheric composition since the 1950s. The undisturbed air, remote location, and minimal influences 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 calibrations and comparisons.

### **South Pole, Antarctica (Established 1957)**

The South Pole Observatory (SPO) is located at the geographic South Pole on the Antarctic plateau at an elevation of 2837 m. The National Science Foundation provides the infrastructure for the GMD scientific operations. SPO was recently remodeled with construction completed in 2010. A Clean Air Sector (CAS) isolates the unique atmospheric and terrestrial conditions from South Pole station influences. Like MLO, the remoteness and minimal impact of life (animal or vegetable) provides pristine air samples. SPO is the prime location for detecting changes in stratospheric ozone.

### **Barrow, Alaska (Established 1973)**

The Barrow Observatory (BRW) is located near sea level on the north coast of Alaska. As the northernmost observatory, BRW is critical for defining the north-south gradients of many gases and other atmospheric properties. As the Arctic continues to warm, BRW will become an increasingly important site for monitoring atmospheric change. Due to its unique 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 doubled, but at present BRW has reached physical capacity and cannot support additional research programs without expansion of facilities.



### **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 networks, because it is the only baseline observatory in the tropical Southern Hemisphere. It is important in defining north-south gradients of atmospheric composition and how they change with time. It also hosts a long-standing comparison between measurements of the Advanced Global Atmospheric Gases Experiment (AGAGE) and the GMD trace gas measurements.

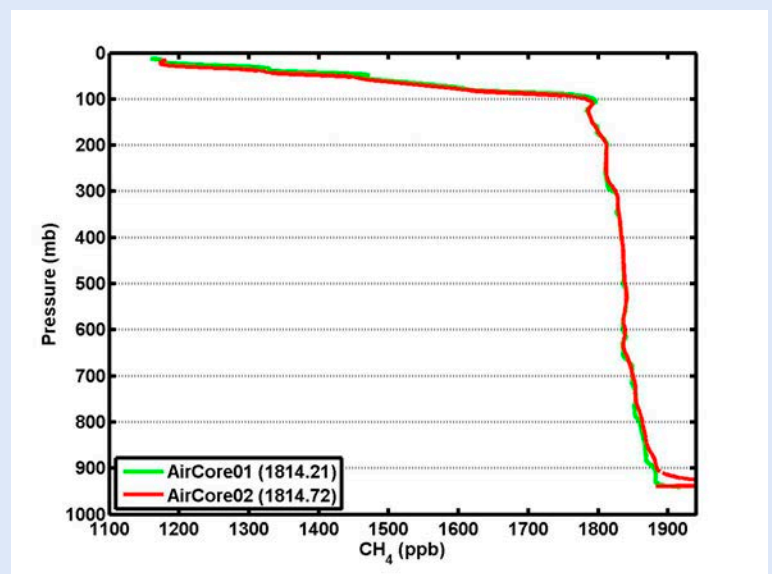
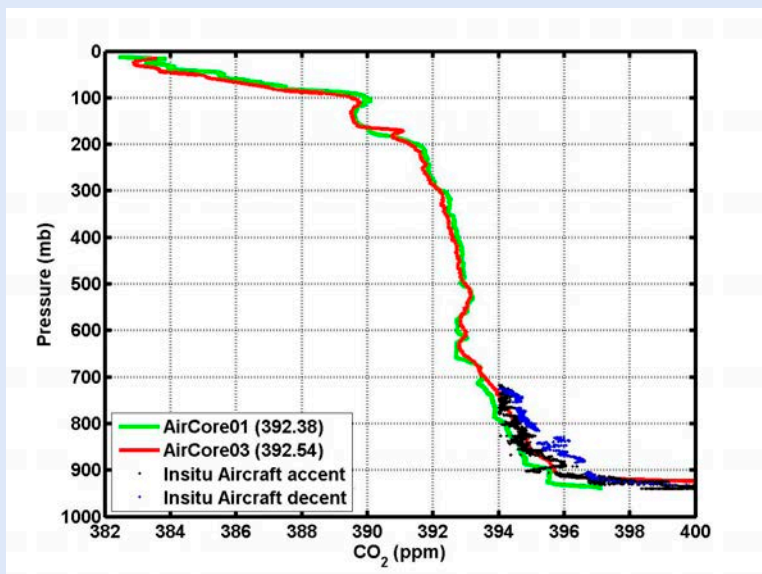
### **Trinidad Head, California (Established 2002)**

Trinidad Head Observatory (THD) is located on a point jutting into the ocean along the remote northern coast of California approximately 40 km north of Eureka, the main regional population center (pop. 27,000). To the immediate west of Trinidad Head is the unobstructed Pacific Ocean and to the east are redwood-dominated forested lands. Trinidad Head Observatory provides an opportunity to observe and monitor both regional and global influences because of the relatively remote coastal location.

### **Summit, Greenland (Established 2005)**

The Greenland Environmental Observatory (SUM), on the summit of the Greenland Ice Sheet at 3200 m elevation, was established by the U.S. National Science Foundations and the Government of Greenland to provide opportunities for arctic research in the 1990s. With NOAA's engagement in 2003, it became a year-round, long-term monitoring site for atmospheric composition and investigations of the arctic environment. Summit is a unique, high-altitude, arctic site that offers access to the free troposphere and is free of local influences that could corrupt climatic records. Summit is situated ideally for studies aimed at identifying and understanding long-range, intercontinental transport and its influences on air and snow chemistry and surface albedo. For radiation measurements, it is the only arctic site with a year-round dry snow and ice background.

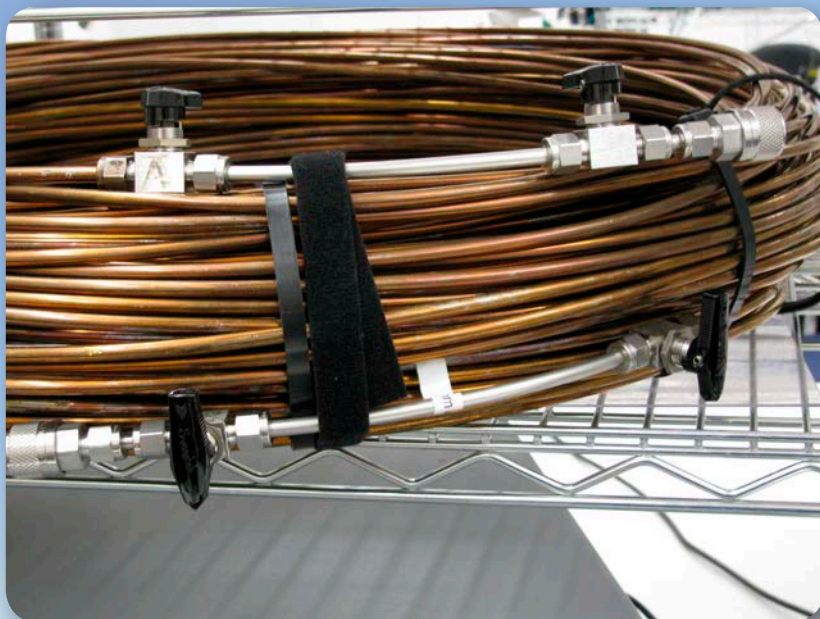
# New Technologies for Air Column Sampling: AirCore and Global Hawk



The AirCore air sampler was developed by GMD scientists and is carried by a weather balloon to altitudes above 30 km (> 98% of the atmospheric column). AirCore captures a vertically resolved sample of the air column in a long, small-diameter tube (below). After landing, its contents are analyzed to retrieve profiles of CO<sub>2</sub> and CH<sub>4</sub> that are ideal for evaluating satellite measurements and may prove useful for validating atmospheric transport models commonly used in weather and climate analyses.

The NASA Global Hawk Unmanned Aircraft Systems (UAS) can fly continuously for 26+ hours and reach altitudes of 20 km. GMD measurements on the Global Hawk include greenhouse gases, ozone, and water vapor, which give us a unique view of transport in the upper troposphere and lower stratosphere.

(Right) AirCore Launch – AirCore coil is suspended below balloon. (Right) AirCore coil removed from flight package. (Left) Example profiles for CO<sub>2</sub> and CH<sub>4</sub> from AirCore from surface to the top of the atmosphere (red and green lines are separate profiles from the same day) (Lower Left) The NASA Global Hawk UAS in flight over California, where NOAA is an equal partner by providing pilots, crew, and research scientists. Current and near-term future research involves tropical transport and chemistry trace gases, ozone, and water vapor.

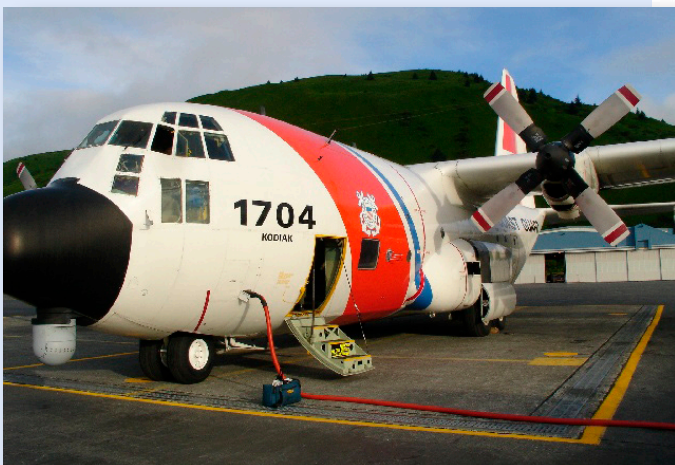
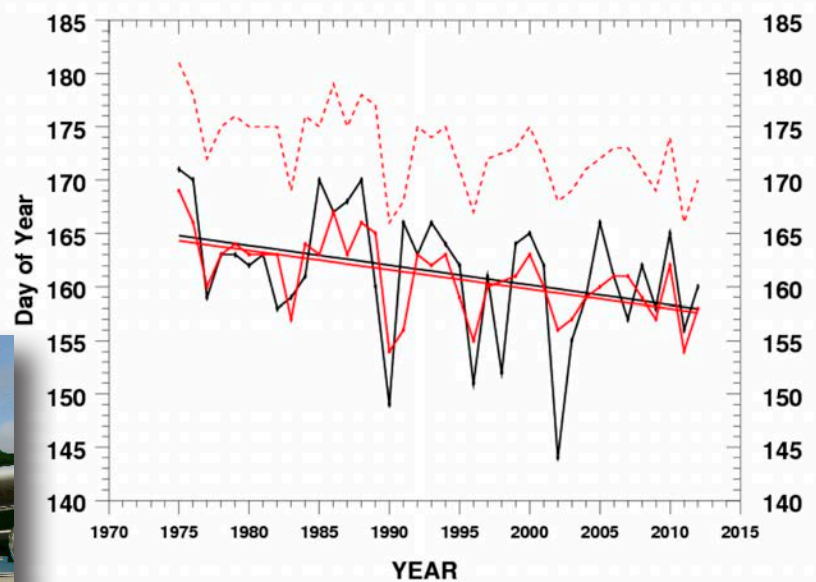


# Arctic Research

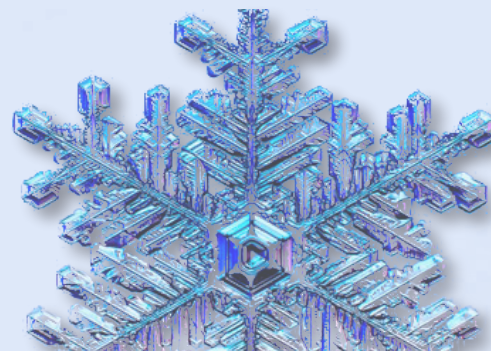
The Arctic is warming nearly twice as fast as the global average. In addition to affecting natural, economic, and cultural resources, arctic climate change may also be a driver of global climate via changes in surface albedo and warming-induced emissions of greenhouse gases from permafrost and ocean sediments. GMD has been making measurements at the Barrow observatory in northern Alaska since the 1970s, added another observatory at Summit, Greenland, in 2005, and has collaborated with international partnering observatories throughout the Arctic. Over the past decade GMD has worked with national and international institutions to initiate additional long-term surface and aircraft measurements at sites in Alaska, Canada, and Siberia. GMD has also participated in several short-term arctic campaigns using surface and mobile platforms to address various science questions related to climate forcing, ozone depletion, and air quality. Some recent findings from GMD's expanded arctic measurement portfolio include:

- A 38-year record of surface ozone ties the increased frequency of ozone depletion events to the multi-year decline in sea ice,
- Earlier egg laying by the black guillemot is strongly correlated with surface albedo and earlier snowmelt dates,
- Identification of the importance of Asian biomass burning on trace gases and aerosols in the Arctic,
- Determination that decreasing trends in Arctic aerosol are dominated by changes in emissions from Eurasia rather than changes in atmospheric circulation.

(Right) The highly correlated time series of the annual disappearance of snow at Barrow (black line: using measured surface albedo) and the date of the appearance of the 'first egg' laid by black guillemots (red line) that migrate to Cooper Island (about 40 km away). Time for 'actual first egg' (dashed line) are offset from melt data by about 13 days due to time required for gestation.



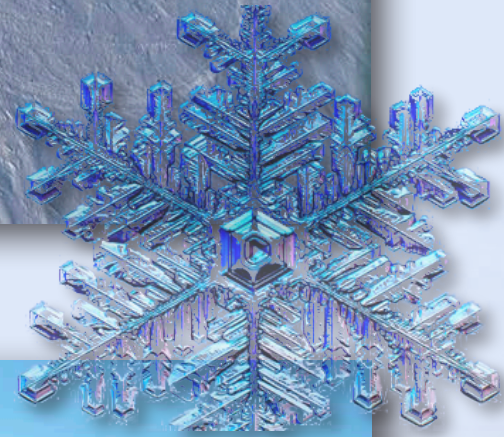
U.S. Coast Guard C130 used by GMD for regular greenhouse gas sampling throughout Alaska.







GMD Baseline Observatory in Barrow, Alaska.



Greenland ice edge.



# GMD OUTREACH





鹿林山

環保署陳重信署

環保署邱文  
車員會勘兩非  
對背景站之

行政院 Environ

## 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 between 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 otherwise 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:

- In 1994, GMD scientists helped the Chinese Meteorological Agency (CMA) establish an air sampling and in situ CO<sub>2</sub> measurement capability at the Mt. Waliguan Observatory (WLG) in Qinghai Province, China.
- In 2005, GMD helped deploy a full aerosol system at WLG. WLG continues to operate today and is a background WMO Global Atmosphere Watch (GAW) site and the anchor for an emerging greenhouse gas monitoring network.
- In 2010, a delegation of 15 CMA scientists spent ten days in Boulder and two at Mauna Loa to learn about everything from measurement approaches to site logistics to CarbonTracker.
- Starting in 2003, GMD established a replica of our high-accuracy, high-precision, greenhouse gas analysis system in Sao Paulo, Brazil. Since 2004, this system has measured greenhouse gas concentrations from background sites on the Brazilian Atlantic coast and at four aircraft sites in the Brazilian Amazon, which represent some of the only regular greenhouse gas observations above the tropical terrestrial biosphere.
- GMD was instrumental in expanding the Baseline Surface Radiation Network (BSRN), establishing radiation monitoring sites for numerous countries.
- GMD scientists continue to assist with Peru's Dobson ozone observing program and with regional ozone calibration centers in South America and Africa.



Delegation of Chinese scientists during 2010 visit to GMD.



Dr. Luciana Gatti with greenhouse gas analysis system in Sao Paulo, Brazil.

## 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 go on to study in this important research area.

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. This program began in 2008 and is housed within GMD.

Outreach is a significant part of the lives of GMD staff working at our six 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 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.
- The South Pole winter-over crew responds to e-mail queries from classrooms throughout the world about life in Antarctica.
- Educational activities conducted at Mauna Loa and Barrow directly involve students at local schools. The Samoa Observatory staff has been involved with the tribal communities of the island, fostering a sense of community and promoting science education.



Patricia Lang teaches kids about air sampling during Earth Day demonstrations at NOAA.

*The future success of scientific research conducted at GMD and elsewhere depends on educating the public and providing 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 of all.*

# GMD IN THE FUTURE

## Transformative Opportunities

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*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 ( $\text{CO}_2$  and  $\text{CH}_4$ ) 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 them 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.

### **Carbon-14 Measurements**

It is feasible today to start an intensive systematic program for measuring  $^{14}\text{C}$  in  $\text{CO}_2$ . Five thousand samples per year around North America, requiring one dedicated accelerator mass spectrometer, would cleanly separate the observation of  $\text{CO}_2$  emitted by fossil fuel combustion from natural  $\text{CO}_2$  sources and sinks. This would provide an independent verification of reported fossil fuel  $\text{CO}_2$  emission inventories, especially needed in times where greenhouse gas emissions have an economic cost attached. Additionally, unbiased, observationally-based estimates of fossil fuel  $\text{CO}_2$  would minimize bias in estimates of natural sources and sinks in models like CarbonTracker.

### **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 would serve as a *greenhouse gas reference network* for a diverse set of regional, national, and international networks. This would substantially enhance the value and use of information from diverse networks.

### **Upper Atmospheric Research**

Intensify measurements of water vapor in the upper troposphere and lower stratosphere. With increasing climate change, water vapor amounts are now rising in the upper atmosphere, producing both ozone-depletion impacts and climate change feedbacks. We can combine the balloon-borne water vapor measurements with AirCore, so that we would not only track  $\text{H}_2\text{O}$  vapor, but also provide a diagnosis of ongoing changes of stratospheric circulation.

## **Renewable Energy**

GMD has the potential to help transform the nation's electric power system from one that depends mostly on coal and gas for generation to one that increasingly depends on renewable sources. Integrating solar collecting systems into the nation's grid requires reliable forecasts, which in turn depend upon high-quality observations to support them. GMD has the expertise to provide the required ground-based measurements of solar irradiance for data assimilation, model improvement, and verification. Accurate forecasts will enable power grid operators to schedule the optimal mix of power generation sources and avoid excessive back-up reserves. This would be a key step in any successful climate-change mitigation strategy.

## **Arctic Observations**

The Arctic has been warming more rapidly than any other large region on Earth, and part of this warming has been attributed to absorption of sunlight by black carbon aerosols in the air, snow, and ice. An enhanced black carbon measurement network in the Arctic, including improved instrumentation at new and existing stations, as well as instrumented aircraft monitoring black carbon aerosols above clouds, would transform our understanding of the role of black carbon in driving Arctic climate change and greatly improve arctic forecast models.

## **Can natural gas be a “bridge” fuel toward renewable energy sources?**

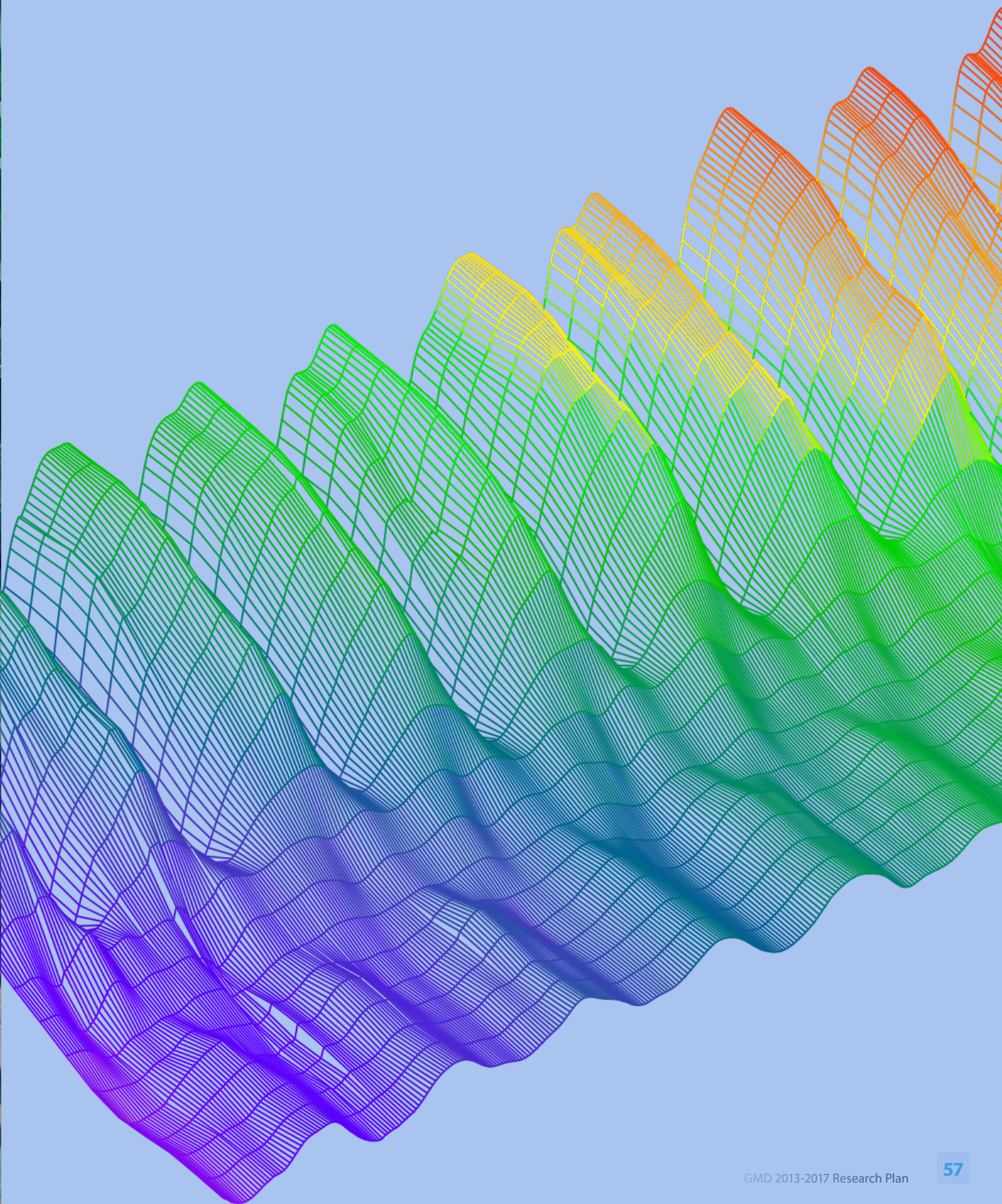
GMD measurements are showing that the current emissions inventories of leaks associated with the full “life cycle” of natural gas are inadequate, potentially misleading policy choices. A carefully designed, transparent, and objective atmospheric observing system can provide useful, accurate information for industry and policy-makers that is necessary for achieving the potential of natural gas as a low-carbon energy source.



# APPENDICES







# Milestones

## A) Climate Forcing (CF)

Action	Milestone	2013	2014	2015	2016	2017
CF1:	Update the AGGI	X	X	X	X	X
CF2a:	Update standard CarbonTracker (CT)	X	X	X	X	X
CF2b:	Implement multiple transport models for CT		X		X	
CF2c:	Use aircraft in situ, and ground- and satellite-remote sensing data in CT		X	X		
CF2d:	Enhance measurement capacity and capability for non-CO <sub>2</sub> GHG measurements			X		
CF2e:	Provide N. American non-CO <sub>2</sub> GHG emission from CT and data-centric approaches.			X		
CF2f:	Incorporate <sup>14</sup> CO <sub>2</sub> (Fossil Fuel) into CT		X			
CF2g:	Add four new <sup>14</sup> CO <sub>2</sub> sites	X		X		
CF2h:	Add four regular AirCore sites		X		X	
CF2i:	Begin commercial aircraft CO <sub>2</sub> and CH <sub>4</sub>			X		
CF3a:	Develop Arctic Regional Inverse model			X		
CF3b:	Develop S. American Regional Inverse model		X			
CF4:	Add one new water vapor profile site		X		X	
CF5a:	Add one new aerosol site		X		X	
CF5b:	Upgrade instrumentation at current aerosol sites	X		X		X
CF6a:	Add latent and sensible heat measurements to sites			X		
CF6b:	Upgrade accuracy of current equipment at radiation sites		X			X
CF7a:	Add spectral albedo to SURFRAD sites		X	X	X	X
CF7b:	Add one mobile SURFRAD site		X			

## B) Ozone depletion (OD)

Action	Milestone	2013	2014	2015	2016	2017
OD1a:	Update the ODGI	X	X	X	X	X
OD1b:	Publish 17-yr global datasets for CHBr <sub>3</sub> , CH <sub>2</sub> Br <sub>2</sub> , and CH <sub>3</sub> I		X			
OD1c:	Provide N. American emissions of ODSs derived from modeling and data-centric (using CO and <sup>14</sup> CO <sub>2</sub> ) techniques			X	X	X
OD1d:	Provide Aircore stratospheric measurements of ODSs			X	X	X
OD2:	Contribute to WMO/UNEP Ozone Assessment		X			X
OD3:	Add two additional UV sites		X		X	
OD4:	Reprocess all GMD ozone-sonde historical records for homogenization of long-term time series		X			
OD5:	Reprocess all GMD Dobson ozone data with the new ozone absorption cross sections, and automate using new software		X	X		
OD6:	Publish cross-platform comparisons of ozone profiles at MLO		X			
OD7:	Calibrate World standard Dobson at MLO		X		X	
OD8:	Calibrate JMA and BoM Dobson Regional Standards in Boulder	X				
OD9:	Calibrate NOAA network Dobson instruments against World Standard			X		X

## C) Air Quality (AQ)

Action	Milestone	2013	2014	2015	2016	2017
AQ1a:	Use North American data to assess formation mechanisms of ozone over the U.S.			X		
AQ1b:	Use North American data to assess cancer risks from Hazardous Air Pollutants entering the U.S.				X	
AQ1c:	Use observations of brominated gases to assess the atmospheric mercury budget			X		
AQ2:	Optimize OH in global inverse model using multiple gases			X		
AQ3a:	Add aerosol and ozone sensors to mobile lab		X		X	
AQ3b:	Measure oil and gas emissions in important basins	X	X			
AQ4:	Convert all surface ozone data collection to an automated data processing system	X	X	X		

# List of Acronyms

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## **Organizations and Networks**

AERO – AEROSols, GMD group  
AGAGE – Advanced Global Atmospheric Gases Experiment network  
BSRN – Baseline Surface Radiation Network  
CCGG – Carbon Cycle and Greenhouse Gases, GMD group  
CIRA – Cooperative Institute for Research in the Atmosphere  
CIRES – Cooperative Institute for Research in Environmental Sciences  
EPA – Environmental Protection Agency  
ESRL – NOAA's Earth System Research Laboratory  
GAW – WMO's Global Atmosphere Watch  
GCOS – Global Climate Observing System  
GEO – Group on Earth Observations  
GMD – Global Monitoring Division  
GRAD – Global surface RADIation, GMD group  
HATS – HALocarbons and other Trace Species, GMD group  
INSTAAR – Institute of Arctic and Alpine Research, University of Colorado  
IPCC – Intergovernmental Panel on Climate Change  
NACP – North American Carbon Program  
NASA – National Aeronautics and Space Administration  
NEON – National Ecological Observatory Network  
NOAA – National Oceanic and Atmospheric Administration  
NSF – National Science Foundation  
OAR – NOAA's office of Oceanic and Atmospheric Research  
OZWV – Ozone and Water Vapor, GMD group  
SURFRAD – Surface Radiation network  
UNEP – United Nations Environment Programme  
WCRP -- World Climate Research Programme  
WMO – World Meteorological Organization

## **Chemical compounds**

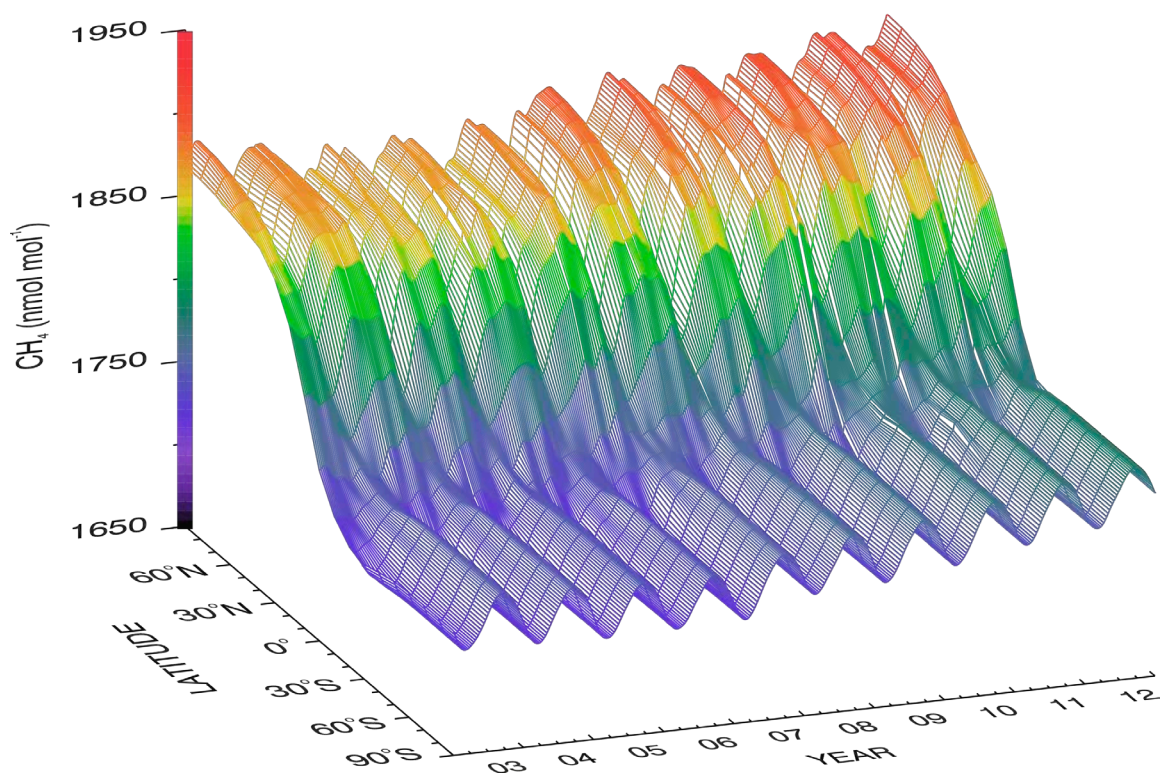
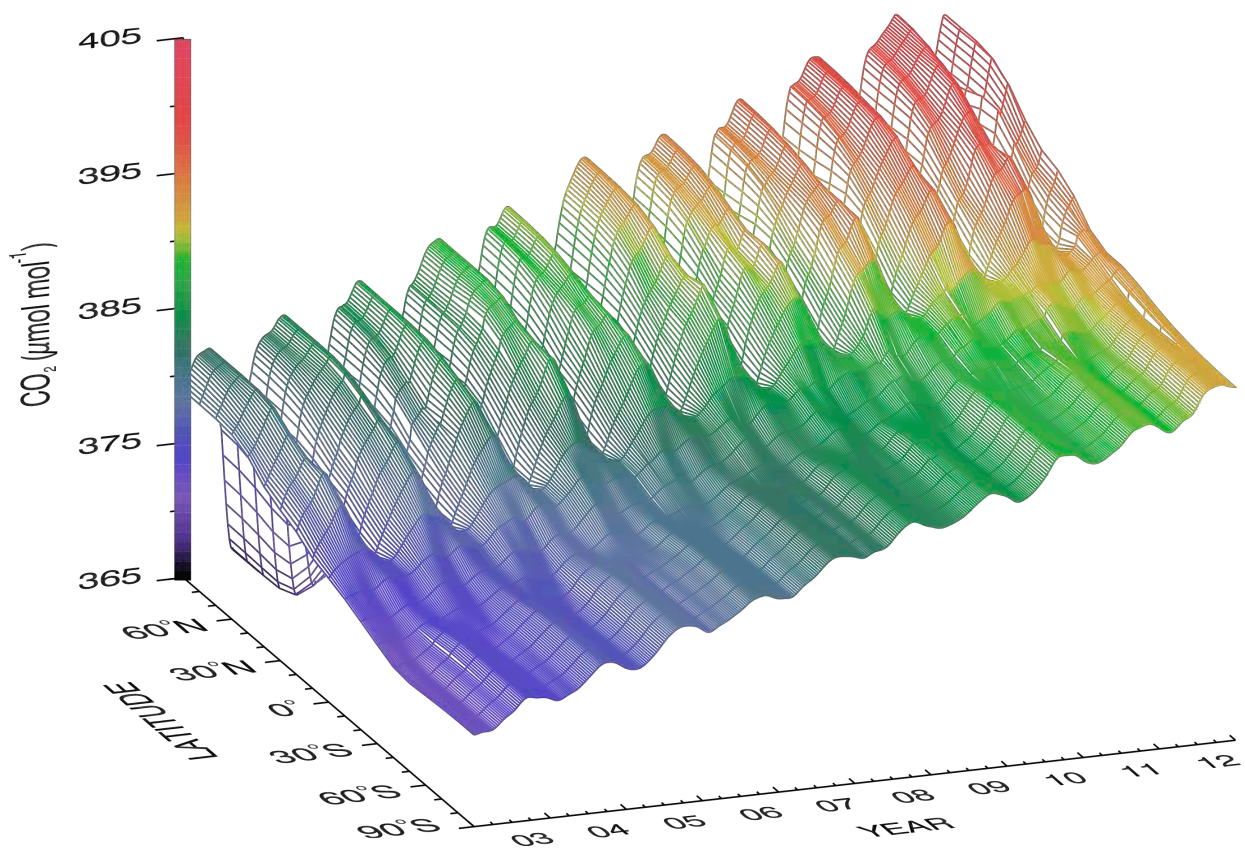
CFC – Chlorofluorocarbon  
CHBr<sub>3</sub> -- Bromoform  
CH<sub>2</sub>Br<sub>2</sub> -- Dibromomethane  
CH<sub>3</sub>I – Methyl Iodide  
CH<sub>4</sub> – Methane  
CO – Carbon Monoxide  
<sup>14</sup>C – Carbon-14, or radiocarbon  
<sup>14</sup>CO<sub>2</sub> – Carbon-14 CO<sub>2</sub>  
CO<sub>2</sub> – Carbon Dioxide  
O<sub>3</sub> – Ozone  
OH – Hydroxyl (radical)  
N<sub>2</sub>O – Nitrous Oxide  
NF<sub>3</sub> – Nitrogen Trifluoride  
NO<sub>x</sub> – Nitrogen Oxides  
SF<sub>6</sub> – Sulfur Hexafluoride  
VOC – volatile organic carbon

## **Satellites and Satellite Sensors**

AIRS – Atmospheric InfraRed Sounder; satellite sensor  
CALIOP – Cloud-Aerosol Lidar with Orthogonal Polarization (sensor on CALIPSO)  
CALIPSO – Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations  
CERES – Clouds and the Earth's Radiant Energy System satellite  
CloudSat – Part of EOS, uses radar to observe clouds  
EOS – Earth Observing System satellites  
GOES, GOES-R, GOES-8 – Geostationary Operational Environmental Satellites  
GOSAT – Greenhouse gases Observing SATellite  
MODIS – MODerate resolution Imaging Spectroradiometer satellite  
MOPITT – Measurements Of Pollution In The Troposphere satellite  
OCO-2 - Orbiting Carbon Observatory satellite  
SAGE – Stratospheric Aerosol and Gas Experiment satellite  
SBUV2 – Solar Backscatter Ultraviolet Radiometer satellite  
SCHIMACHY - SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY  
SNPP – Suomi National Polar Partnership satellite  
TES – Tropospheric Emission Spectrometer sensor  
TOMS – Total Ozone Mapping Spectrometer sensor  
UARS – Upper Atmosphere Research Satellite

## **Other**

AAO – Airborne Atmospheric Observatory  
AGGI – Annual Greenhouse Gas Index  
AR4 – Fourth Assessment Report of the IPCC  
ARO – Atmospheric Research Observatory  
asl – above sea level  
CAS – clean air sector  
CT – CarbonTracker  
GHG – Greenhouse Gas  
HAP – Hazardous air pollutant  
NOAA FPH – NOAA GMD Frost Point Hygrometer  
ODGI – Ozone-Depleting Gas Index  
ODS – Ozone-Depleting Substance  
PgCyr-1 – Petagrams of Carbon per year, or Billion Tonnes of Carbon per year  
ppb – parts per billion  
ppm – parts per million  
ppmV – parts per million (by volume)  
RF – Radiative Forcing  
TOA – Top of Atmosphere  
UAV – Unmanned Ariel Vehicle  
UTLS – Upper Troposphere/Lower Stratosphere  
UV – Ultraviolet  
W m<sup>-2</sup> – Watts per meter squared, unit of radiative forcing  
WLG – Mt Waliguan, China, Observatory



Smoothed representation of the north-south distributions of CO<sub>2</sub> (top) and CH<sub>4</sub> (bottom) between 2003 and 2012. Measurements of CO<sub>2</sub> and CH<sub>4</sub> at remote sites are smoothed in time and then smoothed in latitude (north-south). Warmer colors in the Northern Hemisphere for both CO<sub>2</sub> and CH<sub>4</sub> are indicative of the presence of emissions. Both gases also exhibit strong seasonal cycles in their atmospheric abundances.



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