Global Monitoring Division
GMD Overview (Butler) and Theme1-3 PPT Presentations
2013-2017 Review
May 21-24, 2018

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Outline

• Summary of Previous (2013) Panel Report
• Mission of NOAA’s Global Monitoring Division
• Organization and Management
• How We Plan, Ensure, and Measure Success
• Transformative Opportunities
• Upcoming Sessions
2009-2013 Review Panel Summary

- **Relevance:**
  - “Environmental Security of the nation”
  - “Essential to the NOAA mission”

- **Quality:**
  - “GMD has become a NOAA/ESRL star”
  - “pushing the frontiers in Climate, Greenhouse Gases, Ozone Depletion, and Air Quality”
  - “will be used by the international community for decades to come”

- **Performance:**
  - “The investments into GMD have been well optimized in an underfunded environment”
  - “The work ... is of the highest caliber”
  - “The scientific community, nation, and beyond are reaping the benefits, and are heavily dependent on GMD. Now is the time to strengthen the capacity of GMD even further to maintain its global lead in these activities”

2013-2018 Panel Recommendations

**Recommendations:**

- **Expand** the science that GMD does to support other science and regulatory agencies (state, national, and international)
- **Sustain** operations, scientific analysis, and technological development required for its mission.
- **Add** additional resources into all aspects of GMD operations, scientific analysis, and innovation.
- **Recruit** new talent and reinvigorate the both CIRES and NOAA positions
- **Ensure** continuity in observing network
GMD Mission

NOAA Program Plan 71-1
“Geophysical Monitoring for Climatic Change”

• “This plan, Geophysical Monitoring for Climatic Change, is NOAA’s program for global monitoring of man’s inadvertent modification of weather and climate.”
  — Robert White, Acting Administrator, NOAA

• “Determination of the trends of the climatically important burden of atmospheric contaminants and resolution into natural vs. man-induced sources is essential to the preservation of environmental quality.”
GMD Origins

“. . . We must achieve a new awareness of our dependence on our surroundings and on natural systems which support all life, but awareness must be coupled with a full realization of our enormous capability to alter these surroundings.”

Richard M. Nixon, 1970

“It is the objective of the GMCC program to respond to the need for this new awareness by providing a portion of the quantitative description and analysis needed. Specifically, it is our objective 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.”

“This program has its special focus in establishing a long-term time series from ground-based information.”

Geophysical Monitoring for Climate Change
First Summary Report, 1972

GMD Vision and Mission

Vision

GMD providing and society using the best possible information to inform climate change, weather variability, carbon cycle feedbacks, and ozone depletion

Mauna Loa Carbon Dioxide

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
How GMD sets priorities

- Legislative mandates
- Consistency with NOAA’s and OAR’s strategic plans and priorities
- Relevance to interagency and international plans
- Relevance to national and international assessments
- Within the framework of GMD’s mission:
  - Align research along Grand Challenges
  - Identify key scientific questions
  - Determine role of long-term observations to answer those questions
  - Sustain quality and continuity of observations
  - Understand the observed distributions and trends
    - Expand networks as needed
    - Conduct periodic regional-scale studies

Key Legislative Drivers of GMD’s Research

- GMD’s research contributes to fulfilling requirements for over 25 laws
- Four pieces of US legislation stand out
  - National Climate Protection Act (1978)
  - Global Climate Change Program Act (1990)
  - Global Change Research Act (1990)
  - Clean Air Act (1990)
Plans and Agreements

**United States**
- National Global Change Research Program Research Plan
- US Carbon Cycle Science Plan
- NOAA Next Generation Strategic Plan
- NOAA Research Plan & OAR Priorities
- NOAA/ESRL GMD Research Plan

**International**
- WMO Global Atmosphere Watch Strategic Plan
- GCOS Implementation Plan
- GEOSS Strategic Plan
- GEO Carbon Strategy
- WCRP Strategic Plan

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**NOAA Plans**

**NOAA Next Generation Strategic Plan**

- **Goal:** Climate Adaptation and Mitigation
  - **Primary Objective:** Improved Understanding of Climate Change and its Impacts
  - **Other Objectives:** Assessments, Mitigation and Adaptation, Climate-Literate Public, Partnerships

- **Goal:** Weather Ready Nation
  - **Objectives:** Reduced loss from high impact events, improved water management and air quality, healthy people and economy, and improved transportation

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**OAR Strategic Plan**

- **Aim:** Climate Adaptation and Mitigation
  - What is the state of the climate system and how is it evolving?
  - What causes climate variability and change on global to regional scales?
  - What improvements in global and regional climate predictions are possible?

- **Aim:** Weather Ready Nation
  - How does climate affect seasonal weather and extreme weather events?
  - How can we improve forecasts for freshwater resource management?
  - How are atmospheric chemistry and composition related to each other and ecosystems, climate, and weather?
OAR Priorities

- Sustain the long-term observations of the Earth System
- Improve the accuracy of weather forecasting and climate predictions
- Provide the environmental information needed by decision makers
- Sustain and enhance ocean exploration and research infrastructure
- Provide the essential scientific understanding of ecosystem processes and change
- Enhance marine resources management
- Detect, and provide early warning information for ocean, weather and climate events

GMD Research Plan

- Documents GMD’s purpose
- Built around recognized Grand Challenges*
- Identifies key scientific questions
- Shows how GMD activities help answer those questions
- Provides a path forward
- Includes milestones as measures of performance

*Weatherhead et al 2017, Earth’s Future, Nov 2: WCRP
https://www.wcrp-climate.org/grand-challenges/grand-challenges-overview
GMD Research Themes and Applications

- Tracking Greenhouse Gases and Understanding Carbon Cycle Feedbacks
- Monitoring and Understanding Trends in Surface Radiation, Clouds, and Aerosols
- Guiding Recovery of Stratospheric Ozone

Standards

NOAA/ESRL Global Monitoring Division
Laboratory Review, 21-24 May 2018
Scientific Questions

(Details in Research Plan)

Greenhouse Gases and Carbon Cycle Feedbacks

- How do oceanic and terrestrial carbon fluxes vary in a changing climate?
- How spatially and temporally variable are anthropogenic inputs of greenhouse gases?
- How is upper tropospheric and lower stratospheric water vapor interacting with climate change?

Recovery of Stratospheric Ozone

- How well is the Montreal Protocol working to reduce ozone depletion?
- Is stratospheric ozone recovering as expected?
- How is climate influencing Brewer-Dobson circulation and its feedbacks?
- How sensitive is the oxidative capacity of the atmosphere and how is it changing over time?

Surface Radiation, Clouds, and Aerosols

- How does surface radiation vary in space and time?
- How do climate change and variability work to redistribute clouds?
- How do aerosol optical properties vary as a function of location, time, and atmospheric conditions?
- How does black carbon influence lower atmospheric heating and cloud prevalence?
- How do changing sky conditions affect ultraviolet radiation at the Earth’s surface?
- How can information on surface radiation improve renewable energy predictions?
How We Plan, Ensure, and Measure Success

Path To Success

- **Rigor** – role as a world leader in measurements that we do
- **Excellence** – in the science that comes from the measurements
- **Pathfinder** – for new technology to enhance and sustain measurements
- **Transparency** – making measurements, methods, scientific findings accessible to the public
- **Leadership** – providing guidance to the rest of the scientific community to ensure compatibility of global measurements
How We Measure Success

• **Sustained** high-quality long-term records of atmospheric composition
• **Preeminence** of our science as documented through the peer-review process
• **External recognition** of staff
• **Ability to update** products regularly
• **Use of products** by external partners
• **Leadership** on councils, advisory groups, and committees
• **Contributions** to assessments

Some Substantive Accomplishments of GMD

• **Magnitude of the terrestrial, northern hemispheric sink** for atmospheric carbon dioxide
  – Continuing to provide on-going, solid evidence that half of the CO$_2$ emitted to the atmosphere is taken up by land and oceans
  – Continuing to investigate the reliability of sinks
• **Turnover of ozone-depleting gases** and the onset of ozone recovery
  – Annually quantifying the contributions of Montreal Protocol and other gases to potential ozone recovery
• **Stability of oxidizing capacity of the troposphere** largely derived from these ozone-depleting gases and their replacements
  – Affects lifetimes of many gases in the atmosphere
Some Substantive Accomplishments of GMD

- **Large increase in radiative energy** at the surface across the United States over the past 15 years (equivalent to twice the forcing from a doubling of CO₂)
  - This, while noting a decrease in aerosol radiative forcing
  - Caused by variability of clouds on decadal scales
- **Improving satellite retrievals** through continuous evaluation of retrievals for O₃, UV, surface radiation, water vapor, and GHGs
- **Primary source for information and data** on hundreds of variables in the atmosphere
  - Virtually all of these are identified as GCOS Essential Climate Variables

Publications Keep Increasing

- These are publications with GMD authorships.
- The number has increased at ~7 per year since 2013, our last review.
- That’s the same rate of increase since 2008.
Staff Performance – Hirsch Index

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*As of Dec 2017

On-line Products

- Interactive Data Visualization
- Annual Greenhouse Gas Index
- Ozone-Depleting Gas Index
- South Pole Ozone
- GLOBALVIEW and ObsPak
- Mauna Loa and Global Trends
- GMD 3 Dimensional Maps of Composition
- Solar Calculator
Awards Summary 2013-2017

- DOC Bronze Medal Award (1)
- NOAA/CIRES Silver Medal Award (1)
- Yoram J. Kaufman Award (1)
- OAR Outstanding Paper (2)
- CIRES Outstanding Service Awards (6)
- Governor’s Award for High Impact Research (2)
- AGU Excellence in Refereeing (3)
- Vaisala Award (1)
- Total of 28 External Awards honoring 61 individuals in GMD over past 5 years

Partners

- GMD operates instruments or collects samples at 78 locations in 35 states in the US
- Nearly all of the 13 US agencies participating in the USGCRP make use of GMD’s data and products
- GMD operates similarly at 161 locations in 67 countries
- Over 100 partnering scientists worldwide, many in association with WMO Global Atmospheric Watch

- NOAA/ESRL Global Monitoring Annual Conference
  - Essentially GMD’s annual meeting to engage with partners contributing to, sharing, or using GMD’s data and data products routinely.
National and Global Leadership

- **WMO Commission for Atmospheric Science**
  - US Lead Delegate
  - WMO Global Atmosphere Watch (Four members of Scientific Advisory Groups (2 chairs)
  - Many members of GHG Measurement Techniques Group
- **European Research Infrastructures**
  - Advisory Boards for 3 EU Infrastructures
- **Global Climate Observing System (GCOS)**
  - Atmospheric Observation Panel for Climate
- **US Global Change Research Program**
  - Carbon Cycle Interagency Working Group
  - Carbon Cycle Scientific Steering Group
  - North American Carbon Program Scientific Steering Group
  - SOCCR Co authors (3 co-leads)
- **Group on Earth Observations**
  - GEO Carbon
- **WCRP Baseline Surface Radiation Network**

Assessments

- Our contributions to **Assessments are the highest level product** and ultimate transition for our research:
  - Provide evaluations and syntheses of the most recent research
  - Operate at the interface of science and policy, providing policy-relevant information
- **IPCC Assessments**
  - Inform nations through UNFCCC on climate and climate change mitigation
    - Significant vehicles for educating global society on climate change
- **Ozone Assessments**
  - Inform nations through the Vienna Convention on the Ozone layer
    - Resulted in significant amendments to the Montreal Protocol
    - Led to acceleration of production phaseouts, most recently HCFCs
- **National Assessments**
  - Provide US policy-makers with climate-relevant information
ESRL Student Program 2013-2017

- CIRES/CIRA
- Educational Partnership Program
- High Schools
- Hollings Scholars

339 Students served in 2013 – 2017

Research Experience for Undergraduates
Science and Technology, Corp.
Significant Opportunities in Atmospheric Research
Tribal College Collaboration

GMD Outreach

Building Global Capacity
- Coordinates with scientists, universities, agencies around world to add sites to measurement networks
- Trains emerging scientists abroad and WMO partners

Public Outreach
- GMD Observatories provide tours, community presentations, student field work
- 29,485 visitors to our facility in 2013-2017 were shown SOS, the GMD “Wall”, and other activities
- Organized NOAA activities for Native American students and minority groups (e.g., AISES, Howard)
- Served as panelists and presenters in local high school science classes
- Presented GMD science at TEDx Boulder Salon
- Hosted anniversary events with Boulder media
Organization and Management

GMD Organization

- Deputy Dir Science & GMG Pieter Tans
- Deputy Dir Planning & Admin Diane Stortini
- Director James H. Butler
- Senior Scientist Pieter Tans
- Information Technology Chris Cornwall
- Carbon Cycle & GMG Pieter Tans
- Global Radiation Allison McComiskey
- Halocarbons & Other Trace Species James W. Elkins
- Ozone & Water Vapor Inna Petropavlovskikh
- Aerosols Pat Sheridan
- Observatory Operations Brian Vasel

- South Pole
- Lt. Cherisa Friedlander

- Mauna Loa
- Darryl Kuniyuki

- Samoa
- Lt. Ben Kaiser

- Barrow
- Bryan Thomas
GMD Income

- OAR Base
- Clim. Prog. (also OAR)
- Reimbursable
- Total NOAA Funding
- Total Funding

*NOAA funds only. External funding adds another 15-20%*

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Expenditures by Function

2017

- Fed Salaries/Benefits: 26%
- CIRES: 17%
- Contract/Services: 9%
- Facilities / Rent: 6%
- NOAA Overhead: 5%
- Supplies: 2%
- Equipment: 1%
- Shipping: 1%
- Travel: 1%

2012

- Fed Salaries/Benefits: 34%
- CIRES: 24%
- Contract/Services: 14%
- Facilities / Rent: 7%
- NOAA Overhead: 5%
- Supplies: 2%
- Equipment: 1%
- Shipping: 1%
- Travel: 1%

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Budget distribution in GMD (2018)

- 5 Research Groups
- Observatory Operations
- Director’s Office and IT
  - Includes Admin & Budget
  - Largely non-scalable

Workforce Profile

2017
- Federal (with NOAA Corps x2)
- CI (CIRES & JIMAR)
- Contractor (STC)
- PhD
- Masters
- Bachelors
- Other

Total “FTE” = 107

2012
- Federal (with NOAA Corps x2)
- CI (CIRES & JIMAR)
- Contractor (STC)
- PhD
- Masters
- Bachelors
- Other

Total “FTE” = 115
Workforce Demographics

2017

- Male: 68%
- Female: 32%

- Caucasian: 66%
- Asian: 4%
- Pacific Islander: 4%
- Hispanic: 6%

2012

- Male: 71%
- Female: 29%

- White: 90%
- Asian: 4%
- Pacific Islander: 3%
- Hispanic: 3%

Workforce Age Distribution

- Non-Fed Median = 49 yrs
- Fed, Median = 53 yrs

2017

- GMD Leadership (n=12)

2012

- GMD Leadership (n=12)
Our Challenge Ahead

- Inflationary erosion (2%/yr) impinges heavily on GMD
  - Extent of observations
  - Quality of observations
  - Number of personnel
- Steady funding means $2M loss in 5 years, $4M in 10 years.
- Steady funding puts GMD on a path to lose 1/3 of current scientific personnel in 10 years.

How are we addressing decreasing resources?

- Reimbursable projects
- Increasing efficiency
- Reducing redundancy
- Collaborating with other labs
- Cutting back on sites
- Renewing aging workforce
Renewing the workforce

**Why**
- New ideas
- New technology
- New energy
- Training leaders for future
- Protecting a 50 year investment that NOAA has made

**How**
- Postdoc programs
- Outside grants
- Collaborations with universities

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The Future

**Operational Challenges**
- Sustaining long-term observations in global networks
- Ensuring a world-class research workforce
- Addressing succession

**Transformative Opportunities**
- **Build** commercial aircraft capability
- **Expand** C-14 efforts
- **Augment** Surface Radiation Network to improve predictions
- **Enhance** upper atmospheric research
- **Support** renewable energy evaluation
- **Advance** US tall tower network for boundary layer composition studies
Questions?

NOAA Global Monitoring Division

- Providing the best possible information to inform 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 solar radiation in a manner that allows the causes and consequences of change to be understood.
Theme 1: Tracking Greenhouse Gases and Understanding Carbon Cycle Feedbacks

Take Home Messages

- We are creating an unassailable and well-documented record of greenhouse gases.
- We try to help society deal with the climate problem:
  - Create a quantitative record of climate forcing.
  - Quantify and diagnose the response of the natural carbon cycle and greenhouse gas budgets to climate change.
  - Evaluate potential “surprises” and give early warning if warranted.
  - Support mitigation by providing objective and transparent verification of emissions.
- Close relationships between measurers and modelers have kept us at the forefront of carbon science and are crucial to continued success.
- NOAA anchors the global and US atmospheric carbon observing network. We established multiple comparisons with Environment Canada, Earth Networks and university researchers. We rely on partnerships with other labs and institutions.
- We have just begun to reap the scientific rewards of our investment in North American monitoring – multiple-species analysis will provide critical process constraints and enable improved source attribution.
Outline

• Tracking Greenhouse Gases at Regional to Global Scales
• Understanding Carbon Cycle Feedbacks
• Monitoring Greenhouse Gases in the Upper Atmosphere
• Looking Forward

Quality, Transparency, Availability, Capacity Building

Tracking Greenhouse Gases at the Global Scale

Mauna Loa Observatory: Photograph by Forrest Mims III

“Science-driven monitoring of the atmosphere, responding to societal needs”
Data are carefully calibrated relative to WMO scales
Intra-laboratory and cross laboratory comparisons with other labs ensure data compatibility
Whole air samples are analyzed for many species

Air sampling at Crozet Island

Weekly whole air samples capture the variability at remote sites.
Local sources and sinks are avoided.
WMO compatibility goals for remote sites:

- CO$_2$: ±0.10 ppm Northern Hemisphere, ±0.05 ppm Southern Hemisphere
- CH$_4$: ±2 ppb
- N$_2$O: ±0.10 ppb

Global Means computed from the MBL reference surface are made readily available with minimal delay.
Global Mean Values for the Major Long-Lived Greenhouse Gases

Global Mean Values for the Major Long-Lived Greenhouse Gases

NOAA Annual Greenhouse Gas Index

As of 2016, radiative forcing from anthropogenic greenhouse gases is up by 40% over 1990 levels.

Earth’s Surface: 510.1 trillion m²
Understanding Carbon Cycle Feedbacks

Grand Challenge: Carbon Feedbacks in the Climate System

• What biological and abiological processes drive and control land and ocean carbon sinks?
• Can and will climate-carbon feedbacks amplify climate changes over the 21st century?
• How will highly-vulnerable land and ocean carbon reservoirs respond to a warming climate, to climate extremes, and to abrupt changes?

Global carbon sinks are increasing

Carbon sinks keep increasing as fossil fuels keep rising. Global C uptake now ~4 PgC/yr.

~50% of fossil fuel emissions are still taken up by sinks.

Year-to-year variability driven by land uptake. We cannot yet attribute land uptake to specific processes.

**Globally averaged CH₄ and its growth rate**

![Graph showing CH₄ concentration and growth rate over time with labeled events such as Collapse of USSR, Biomass burning/ENSO, and ENSO.](chart.png)

**CH₄ data from Ed Dlugokencky**

**GMAC Presentation by Lori Bruhwiler**

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**CH₄ from Fossil Fuels?**

- Not consistent with fossil fuel source
- Must be microbial source

![Graph showing CH₄ concentration with δ¹³C values over time.](chart2.png)

**Source: INSTAAR**
Estimating Emissions and Removals

Observational Constraints on the Global Atmospheric CO₂ Budget
PIETER P. TANS, INEZ Y. FUNG, TARO TAKAHASHI

“...a large amount of the CO₂ is apparently absorbed on the continents by terrestrial ecosystems.”

1439 citations!
CarbonTracker CT2016

CarbonTracker is a CO2 measurement and modeling system developed by NOAA to keep track of sources (emissions to the atmosphere) and sinks (removal from the atmosphere) of carbon dioxide around the world. CarbonTracker uses atmospheric CO2 observations from a host of collaborators and simulated atmospheric transport to estimate these surface fluxes of CO2. The current release of CarbonTracker, CT2016, provides global estimates of surface-atmosphere fluxes of CO2 from January 2000 through December 2015.

What is CarbonTracker?

CarbonTracker is a global model of atmospheric carbon dioxide with a focus on North America, designed to keep track of CO2 uptake and release at the Earth’s surface over time. [read more]

Who needs CarbonTracker?

Policy makers, industry, scientists, and the public need CarbonTracker information to make informed decisions to limit greenhouse gas levels in the atmosphere. [read more]

What does CarbonTracker tell us?

North America is a source of CO2 to the atmosphere. The natural uptake of CO2 that occurs mostly east of the Rocky Mountains removes about a third of the CO2 released by the use of fossil fuels. [read more]

What is new in this release of CarbonTracker? NEW!

This release of CarbonTracker (CT2016) uses new hourly observations from GLOBALVIEW+ and refined first-guess flux models. [read more]

NOAA’s CarbonTracker provides up to date estimates of regional carbon fluxes:
CT2017 is the first CarbonTracker release to simulate impacts of a large El Niño. In 2015 and 2016, we find about 1.2 PgC/yr extra CO₂ in the atmosphere due to this event.

- All of the GGRN CO₂, CH₄, N₂O, SF₆ data are archived and available in ObsPack format
- Near-real time products support OCO-2 retrieval evaluation and data analysis
- GLOBALVIEWplus products are a multi-laboratory community product
- Campaign ObsPacks are available, e.g. ATom, ACT-America
"Consider uptake of CO₂ due to woody encroachment... 0.12 GtC/yr... spread out over an area the size of Texas, the annual mean decrease of CO₂ in the column would be 0.11 ppm/day... The associated depletion in atmospheric CO₂ over 1000 km could be 0.6 ppm in the lowest 3 km, comparable to the CO₂ from fossil fuels... A total of 30 sites for North America are anticipated... Vertical profiles should be obtained at frequency of every other day..."

- 0.1 ppm measurement comparability to resolve the signal of important processes
Tall tower in situ and flask sampling

- All NOAA tall tower sites have continuous CO₂ and CO and flask measurements (every other day sampling, Δ¹⁴CO₂ 3x per week)
- Three sites also have continuous CH₄
- Additional mountaintop sites have continuous CO₂ and/or flask
- Many partners!

Aircraft sampling with “Programmable Flask Packages”

- Nominal schedule 2 flights per month
- Most aircraft max altitude 6000 to 8000 masl
- Twelve flasks per package
- Flasks measured for CO₂, CH₄, CO, N₂O, SF₆, H₂, stable isotopes of CO₂ and sometimes CH₄, Δ¹⁴CO₂ (subset of samples), hydrocarbons (recently added ethane!), halocarbons

Aircraft program PI: Colm Sweeney
The past decade has seen major expansion of the North American atmospheric carbon observing system:

- Growth of surface network has exceeded expectations >100 sites in 2015/2016
- NOAA aircraft network: 14 sites profiling once or twice per month up to ~8 km

Many different laboratories are providing data, with different levels of quality assurance and stability of funding:

Data Providers

In Situ:
- Environment and Climate Change Canada (D. Worthy)
- Penn State University (N. Miles, S. Richardson, K. Davis)
- NCAR (B. Stephens)
- Oregon State University (B. Law, A. Schmidt)
- Lawrence Berkeley National Lab (S. Biraud, M. Fischer, M. Torn)
- Earth Networks (C. Sloop)
- California Air Resources Board (Y. Hsu)
- Harvard University (J. W. Munger, S. Wofsy)
- U of Minnesota (T. Griffis)
- Scripps (J. Kim, R. Keeling, R. Weiss)
- NASA JPL (C. Miller, K Verhulst)

Remote Sensing:
- TCCON (D. Wunch, P. Wennberg, G. Toon)
- GOSAT-ACOS (C. O’Dell)
- OCO-2 team

Comparability among datasets is crucial for flux estimation and trend detection.
What do the data tell us?

Average Seasonal Cycle of CO₂ above Homer, Illinois:

Sweeney et al., JGR, 2015
Multi-species profiles provide powerful constraints on flux estimates:

Eastern USA (NHA) Nov 2005

Strong anthropogenic influence

Surface uptake

Multiple species aid in quantitative source attribution for carbon gases.

Courtesy of Steve Montzka
CO\textsubscript{2} and $^{13}$CO\textsubscript{2} anomalies over North America are correlated with large-scale climate anomalies:

- Monthly anomalies (thin lines) of atmospheric CO\textsubscript{2} and $\delta^{13}$CO\textsubscript{2} averaged across North American sampling sites.
- $\delta^{13}$CO\textsubscript{2} provides information about how plants respond to drought stress.

Radiocarbon over North America shows decreasing trend due to fossil fuel emissions and local depletion due to local fossil fuel sources:
Methane and Hydrocarbon trends over North America:

- Methane trends are only observed at a few sites near oil and gas development
- Increasing propane and ethane trends are observed at many sites

GMAC Presentation by Xin Lan

http://www.esrl.noaa.gov/gmd/ccgg/carbontracker-lagrange/
CT Lagrange versus CT2016 Fluxes: Long-term mean

• Net biospheric uptake is similar despite very different atmospheric transport models

CT2016: -0.56±1.29 PgCyr\(^{-1}\)
CT-L: -0.70±0.92 PgCyr\(^{-1}\)

CT-L terrestrial CO\(_2\) fluxes show emergent and persistent response to ENSO

GMAC Presentation by Lei Hu
Recent papers using the CarbonTracker-Lagrange Framework highlight our close and mutually beneficial relationships with academic researchers.

We plan to collect top-down emissions estimates from all of these studies and make them available for download.
Satellite Retrieval and Model Evaluation

The challenge for satellite column CO$_2$ sensors:

- Mass balance: on average, the total column enhancement of CO$_2$ downwind of the U.S. is ~0.7 ppm for 1.4 Gton C/yr of emissions.
- For a 20% reduction in emissions, column would change by ~ 0.14 ppm.
OCO-2 V7
• CarbonTracker-NearRealTime is one of a suite of models used to evaluate and bias-correct OCO-2 retrievals
• CarbonTracker-NRT work is funded by NASA OCO-2 project and enables quick evaluation of retrievals and assessment of information content
• The CarbonTracker Team prepares observations and provides to all the other modeling teams along with information about CarbonTracker data selection and weighting

OCO-2 V8

Temporal sampling biases cause apparent relative trends.
Choice of inappropriate background contributes to spurious trend
Monitoring the Upper Atmosphere

**Long-Term Monitoring of Upper Troposphere/Lower Stratosphere (UTLS) Water Vapor**

Net increase in UTLS water vapor: Positive climate forcing feedback
- Strong absorber of outgoing long wave radiation, weak thermal emission to space
- Climate change warms the tropical tropopause layer, increasing UTLS water vapor
- Additional UTLS water vapor absorbs more outgoing long wave radiation

Changes in UTLS water vapor have a significant impact on surface temperatures
- The ~1 mmol mol⁻¹ (~25%) increase in [UTLS water vapor] between 1980 and 2000 would have enhanced the rate of surface warming in the 1990s by ~30%  
  *Solomon et al. (2010)*

*GMAC Presentation by Dale Hurst*
Long-Term Monitoring of UTLS Water Vapor

Validation of Satellite-Based Measurements

Satellite-based instruments provide near-global coverage but are susceptible to biases and/or drifts in their measurements.

Differences in Coincident Measurements: FPH-MLS

Statistical Breakpoints

Post-breakpoint Trends

updated from Hurst et al. (2016)

AirCore for Surface to Stratosphere GHG Sampling: CO₂, CH₄, CO

- >70 flights starting in 2012
  - New twin AirCore provides paired sampling to ensure repeatability
- OCO-2 Science Team
  - Direct comparison with TCCON & OCO-2 underflights
  - Improved stratospheric prior
- Analysis of stratospheric Mean Age as a tracer of the Brewer-Dobson circulation
- Evaluation of stratospheric simulations in CarbonTracker and other models
Intensive Field Campaigns & Capacity Building

GMD Participation in Intensive Measurement Campaigns Leverages and Complements our Monitoring Efforts

ECO
East Coast Outflow

LA Megacities

NASA DC-8

NSF HIAPER GV

NOAA Twin Otter

CARVE

ACT1 America

INFLUX

ABOVE

ARCTIC - BOREAL VULNERABILITY EXPERIMENT

OCAS

C/N2 Ratio and CO2 Aqueous Sediments Ocean Salinity GS-1
Brazilian Replica of the NOAA Flask Analysis Lab:

Laboratory Review, May 21-24, 2018

NOAA/ESRL Global Monitoring Division

Carbon Cycle Greenhouse Gases

Brazilian Replica of the NOAA Flask Analysis Lab:

Lab. de Química Atmosférica CQMA/IPEN
Réplica do Laboratório da NOAA/ESRL/GMD
(National Oceanic Atmospheric Administration / Earth System Research Laboratory / Global Monitoring Division)

Luciana V. Gatti , Andrew Crotwell, Kirk Thoning, Ed Dlugokencky, John B. Miller, and many others
Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements


10+ year collaboration has enabled creation of aircraft network and new insights into Amazonian fluxes.

Looking forward
1) Develop Partnerships and Links with Regional Networks

- Obtaining tower leases through the federal government is cost prohibitive and slow. Better to work with partners whenever possible.
- Opportunities exist to strengthen ties with regional monitoring efforts already underway: California Air Resources Board, Earth Networks, Baltimore/DC, Oregon State University, Penn State University

2) Increase radiocarbon sampling to constrain estimates of fossil fuel CO₂ emissions

Separation of biospheric and fossil fuel fluxes of CO₂ by atmospheric inversion of CO₂ and ¹⁴CO₂ measurements: Observation System Simulations

Sourish Basu¹,², John Bharat Miller¹,², and Scott Lehman³

¹Global Monitoring Division, NOAA Earth System Research Laboratory, Boulder CO, USA
²Cooperative Institute for Research in Environmental Science, University of Colorado, Boulder CO, USA
³Institute for Arctic and Alpine Research, University of Colorado Boulder, Boulder CO, USA

www.atmos-chem-phys.net/16/5665/2016/
doi:10.5194/acp-16-5665-2016
© Author(s) 2016. CC Attribution 3.0 License.
3) Commercial Aircraft Measurements of CO$_2$, CH$_4$ and H$_2$O

Japanese and European programs already exist for a limited number of long-haul aircraft (5 CONTRAIL and 10 IAGOS aircraft):

The US National Weather Service has a regional commercial aircraft program to measure water vapor:

Science Priorities

Vulnerable Carbon Reservoirs

- Arctic: Track Emissions from Permafrost Release
- Amazon: Monitor Uptake from Tropical Forests

Carbon Accounting for Decision Support

- CONUS

Estimated Cost: < $10M per year

5 year goal: Implementation on 10 aircraft covering CONUS and Alaska
10 year goal: Establish international partnerships to extend coverage over Arctic and Amazon.
GMD’s Role in an Integrated Multi-platform Greenhouse Gas Observing System

Take Home Messages

• We are creating an unassailable and well-documented record of greenhouse gases.
• We try to help society deal with the climate problem:
  – Create a quantitative record of climate forcing.
  – Quantify and diagnose the response of the natural carbon cycle and greenhouse gas budgets to climate change.
  – Evaluate potential “surprises” and give early warning if warranted.
  – Support mitigation by providing objective and transparent verification of emissions.
• Close relationships between measurers and modelers have kept us at the forefront of carbon science and are crucial to continued success.
• NOAA anchors the global and US atmospheric carbon observing network. We established multiple comparisons with Environment Canada, Earth Networks and university researchers. We rely on partnerships with other labs and institutions.
• We have just begun to reap the scientific rewards of our investment in North American monitoring – multiple-species analysis will provide critical process constraints and enable improved source attribution.
Monitoring and Understanding Trends in Surface Radiation, Clouds, and Aerosols
Monitoring and Understanding Trends in Surface Radiation, Clouds, and Aerosols

GMD Measurement Networks for Radiation, Clouds, and Aerosols

The NOAA Federated Aerosol Network
'A collaborative effort that benefits all parties'
GMD Measurement Networks for Radiation, Clouds, and Aerosols

Broadband Shortwave and Longwave Radiation Networks

Properties – Measured and Derived:
- Surface Radiation Budget - components
- Sky Cover/Cloud Fraction
- Cloud Optical Depth (overcast)
- Cloud Radiative Effect
- Aerosol Optical Depth (AOD) - spectral
- Surface Albedo - spectral
- UV-B
- PAR
- Vegetation Indices

Continental U.S., regionally representative

SURFRAD

Continental U.S., urban environment

SOLRAD

12 stations of 59 directly operated by NOAA ESRL GMD, the largest single contributing organization

Support measurements at an additional 9 sites

GMD is associated with 21 of the 59 sites that have contributed to the BSRN Archive (35%)
Global All- and Clear-sky Estimates using Observations and Models

New estimates for global mean radiation budget without cloud effects
*Wild et al. submitted*

Combined with all sky budgets provides estimation of global mean surface, atmosphere, and TOA cloud radiative effects
*Wild et al. 2015 Clim. Dyn.*

Surface Radiation Variability over the U.S.

*Augustine and Dutton 2013 JGR*

Updated from Augustine and Dutton 2013 JGR

Surface downwelling solar radiation anomalies (W m⁻²)

No significant aerosol effect

*R² = 0.05*
Surface Radiation Variability over the U.S.

updated from Augustine and Dutton 2013 JGR

Persistent Model Biases – Relationships to Surface Radiation Budget

CAUSES: Cloud Above the United States and Errors at the Surface

Ma et al. 2018, JGR
Persistent Model Biases – Relationships to Surface Radiation Budget

CAUSES: Cloud Above the United States and Errors at the Surface

Ma et al. 2018, JGR

SURFRAD Observations in Numerical Weather Prediction Model Development

NOAA NWP Rapid Refresh Model (RAP) – SURFRAD comparisons

NOAA operational weather forecast

100-200 Wm⁻² mid-day bias

GMD observations
SURFRAD Observations in Numerical Weather Prediction Model Development

NOAA NWP Rapid Refresh Model (RAP) – SURFRAD comparisons

- Large sensible heat fluxes
- More turbulent mixing
- Warmer/drier land surface
- Excessive SW-down
- Reduction of low-level clouds
- Deepers/drier PBL

SURFRAD Observations in Numerical Weather Prediction Model Development

- Monitoring changes
- Process understanding
- Model development
- Satellite evaluation

~70% reduction in bias

Benjamin – Session 7
Model treatments and parameterizations addressed:

- Cloud cover – amount, nature, timing
- Land surface cover – albedo
- Aerosol – burden, transport, physical and optical properties
- Radiative transfer – link to cloud and aerosol properties, cloud overlap assumptions
- Diurnal cycles – shortwave and longwave fluxes and relationship to boundary layer growth and decay
- Meteorological regimes – e.g., cold pools

GOES-16 Data Products for Validation:

- Downwelling Shortwave Radiation
- Aerosol Optical Depth (AOD)
- Land Surface Temperature
- Downwelling Longwave Radiation
- Upwelling Longwave Radiation
- Surface Albedo
- Vegetation Index (Planned)
- Green Vegetation Fraction (Planned)
- Aerosol Particle Size (Planned)
Operational Satellite Product Evaluation

Global Operational Satellite Products:
- GEWEX Surface Radiation Budget (SRB) Product
- Geostationary Surface and Insolation Product (GSIP)

Global Operational Satellite Products:
- GEWEX Surface Radiation Budget (SRB) Product
- Geostationary Surface and Insolation Product (GSIP)

Trends in Aerosol over the U.S.

Clean Air Act of 1990 and other regulatory efforts

Augustine – Session 3
Pagowski – P-7

Haller – Session 3
Sherman – Session 7
Trends in Aerosol over the U.S.

mostly anthropogenic

mostly natural

NOAA Federated Aerosol Network Observations in AEROCOM Experiments

14 global climate models – in situ observations at surface:
- model median values
- models underestimate observed SSA
- models simulate darker aerosol than observed
Mauna Loa Transmission and the Stratospheric Aerosol Record

Mauna Loa Solar Transmission

Mauna Loa Observatory Lidar

Climate Intervention: Solar Radiation Management

Hughhunt

Barnes – P-43
Keen – P-41

monitoring changes process understanding model development satellite evaluation

DRIVERS AND ENVIRONMENTAL RESPONSES TO THE CHANGING ANNUAL SNOW CYCLE OF NORTHERN ALASKA

Christopher J. Cox, Robert S. Stone, David C. Douglas, Diane M. Stewart, Georgia J. Dickey, Geoff S. Dutton, Colin Sweeney, J. Craig Geoges, and David U. Langenbrunner

Cox – Session 3
Morris – Session 3

monitoring changes process understanding model development satellite evaluation
Looking Forward
New Instrumentation for Cloud Properties at SURFRAD Sites

**Measurements and Data Products**
- Surface Radiation Budget – all components
- Sky cover/cloud fraction
- Cloud optical depth (overcast)
- Aerosol Optical Depth (AOD)
- Surface in situ aerosol optical properties
- Spectral Surface Albedo
- UV-B
- PAR
- Vegetation Indices (NDVI, GVF)
- Spectral UV irradiance, Ozone, UV Index
- Cloud Height, Cloud Layers (overlap)
- Boundary (mixing) Layer Height
- Cloud optical depth (broken cloud)
- Cloud microphysics – effective radius, drop size, phase
- Cloud liquid water path (derived)
- Ambient Column Aerosol Size Distribution, Single scattering Albedo, Asymmetry Parameter
- Spectral AOD – UV to NIR (aerosol type/composition)
Looking Forward
An Expanded Aerosol Optical Depth Monitoring Network

Instrument upgrades, new deployments, and development of aerosol optical property retrieval algorithms will result in an expanded network.

- use of newly expanded spectral measurements at SURFRAD and DOE ARM sites for routine retrievals of improved aerosol microphysical and optical properties
- addition of refurbished instruments to SOLRAD sites for expanded spatial coverage of aerosol optical depth
- development of a spectral ultraviolet aerosol optical depth product from Brewer spectrophotometers in the NEUBrew Network for information on aerosol composition and its radiative impacts

Looking Forward
A NOAA Surface Energy Budget Network for Improving Weather and Climate Predictability

- existing radiation measurements
- existing heat flux measurements
- proposed new sites
# WCRP Grand Challenge: Clouds, Circulation, and Climate Sensitivity

How the interaction between clouds, greenhouse gases, and aerosols affect temperature and precipitation in a changing climate

## WCRP Initiatives:
- Climate and hydrological sensitivity
- Coupling clouds to circulation
- Changing patterns
- Leveraging the past record
- Towards more reliable models

## GMD Research:
- Small- and large-scale atmospheric dynamical effects on cloud properties
- Regionality of cloud and aerosol responses to local and large-scale forcing
- Decadal to multi-decadal observations to constrain cloud processes and feedbacks
- Persistent model biases evaluation and improving physical understanding

[https://www.wcrp-climate.org(gc-clouds)](https://www.wcrp-climate.org(gc-clouds))
Guiding Recovery of Stratospheric Ozone at GMD

GMD plays a central role in the global effort to monitor stratospheric ozone, ozone-depleting gases, and other processes affecting stratospheric ozone

Our focus:

– **global-to-regional scale observations** to assess global changes and influences from specific processes and regions (e.g., U.S.)
– **Diagnosing observed changes** to clarify the relative influence of policy decisions, other human behaviors, and natural processes
– **To provide the highest-quality, policy-relevant science**

→ Guiding the recovery of the ozone layer by informing Parties to the Montreal Protocol on the progress of recovery
**Stratospheric ozone depletion**

→ *a threat to life on Earth.*

- **1950s:** NOAA begins measuring total column ozone
- **1970s:** Theory suggesting CFCs will deplete ozone
  - NOAA and NASA begin measuring CFCs
- **1980s:** Severe ozone depletion reported in Antarctica
  - Montreal Protocol controls CFC production
  - Antarctic ozone hole attributed to CFCs and other chemicals
- **1990s:** US Clean Air Act Amended:
  - **NOAA and NASA**
    - to monitor: tropospheric chlorine & bromine, & stratospheric ozone depletion
    - to project: peak chlorine
    - the rate of chlorine decline after 2000
    - the date when chlorine returns to two ppb

* 1996: tropospheric chlorine peaks (NOAA-GMD publication)
* 2003: tropospheric bromine peaks (NOAA-GMD publication)

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**Guiding Recovery of Stratospheric Ozone at GMD**

**A) Measuring chemicals that cause stratospheric ozone depletion**

→ One of two global networks tracking long-term changes in ozone-depleting gases

**B) Measuring long-term changes in stratospheric ozone**

→ Providing reference-quality long-term measurements of stratospheric ozone

**C) Advancing scientific understanding**

→ Understanding causes of atmospheric composition change
  and improving our understanding of atmospheric processes

**D) Communicating results to a broader audience (stakeholders)**

→ through simple indices, web presence, open data policies, publications,
  and by contributing to national and international Scientific Assessments
A) Measuring chemicals that cause stratospheric ozone depletion

- Concentrations of ozone-depleting chemicals for which PRODUCTION IS CONTROLLED by the Montreal Protocol

All major ozone-depleting gases are measured at NOAA/GMD.

Emphasis is on high precision and accuracy.

→ the better the measurement, the more one can learn...

Recent related pubs: Montzka et al., 2015; 2018; Rigby et al., 2017

See talks by S. Montzka, and by P. Yu
A) Measuring chemicals that deplete stratospheric ozone

– Concentrations of halogenated chemicals **NOT CONTROLLED** by the Montreal Protocol, but that can influence stratospheric ozone:

Shorter-lived gases also add chlorine and bromine to the atmosphere.

→ having human and natural sources.

→ changing over time?

Also: N₂O, COS

See poster by G. Dutton

Recent related pubs: Hossaini et al., 2016; 2017

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A) Measuring chemicals that deplete stratospheric ozone

– Changes in “controlled” tropospheric chlorine and bromine:

→ Sum of all controlled gases measured at GMD

→ directly addressing Congressional mandate


Decline in total Chlorine

Decline in total Bromine

Science 1996; Nature 1999

GRL 2003
A) Measuring chemicals that deplete stratospheric ozone

- Distilling GMD measurements of controlled gases into a single index:

The Ozone Depleting Gas Index

Measuring progress in the decline of ozone-depleting halogen back to 1980 concentrations (pre-ozone hole)

In 2017:
- Antarctic ODGI was 80
- Mid-latitude ODGI was 56

Annually updated at http://www.esrl.noaa.gov/gmd/aggi/

A) Measuring substitute Hydrofluorocarbons

- Concentrations of chemicals for which PRODUCTION IS CONTROLLED by the Montreal Protocol, but that do NOT deplete ozone

Recently added to the Montreal Protocol list of controlled substances.

These results enable a tracking of radiative forcing from ODS substitution.

Most substitute HFCs are measured at NOAA/GMD.
B) Measuring long-term changes in stratospheric ozone

Providing reference-quality long-term measurements of stratospheric ozone

Using a range of techniques to obtain:

- Ozone total column density:
  - Dobson
  - Brewer

- Ozone concentration vertical profile:
  - Ozone Sondes (highest vertical resolution)
  - Umkehr

Ozone concentrations near Earth’s surface

To allow an understanding of ozone concentration changes:

- over time: developing and applying statistical models to provide trend estimates
- as a function of altitude: stratospheric changes (upper vs lower stratosphere), tropospheric changes (pollution-related or transported from stratosphere)
- as a function of latitude: future ozone changes are expected to be latitude-dependent (aerosol, GHGs, circulation...)

NOAA-GMD Dobson ozone program:
- Forms a global backbone of robust, calibrated total column ozone data
- Provides an essential reference for other ozone measurements (satellites, other Dobsons, etc.) through calibration transfers
- Maintains the WMO reference Dobson instrument (#D083)

NOAA-GMD ozone sonde program:
- adds high vertical resolution (data were recently homogenized)
- Strengthens and augments the SHADOZ program for tropical ozone data

Recent Dobson- and sonde-related pubs: Petropavlovskikh et al. (2015), Nair et al., 2015; Evans et al., 2016, Thompson et al., 2017, Sterling et al. (2018)
B) Measuring long-term changes in stratospheric ozone

- To allow an understanding of ozone column changes by altitude (ODS+GHG+transport)

LOTUS 2018 and Ozone Assessment 2018 used GMD data and developed statistical models to derive trends in ozone profiles and total column.
B) Measuring long-term changes in stratospheric ozone

– To allow an understanding of ozone column changes by altitude (ODS+GHG+transport)

Is ozone in lower stratosphere still decreasing? Ball et al (2018) analyses are based on satellite records

Homogenization for GMD (Sterling et al, 2018) and SHADOZ (Witte et al, 2017) ozonesonde data - improved records for future trend analyses

SHADOZ Sites: https://tropo.gsfc.nasa.gov/shadoz

Oral presentation by Witte

Satellite and CCM model averaged trends (LOTUS, 2018, Ozone Assessment) - disagreement between models and observations?

Trends in the low stratosphere will be soon assessed from homogenized ozone-sonde data in tropics and middle latitudes.

B) Measuring long-term changes in stratospheric ozone

– Ozone, vertical profiles from ozone sondes on balloons

Pre-1971 (pre ozone-hole)

Ozone-hole conditions

Focus on depleted layer:

See talk by B. Johnson, poster by P. Cullis

Recent related pubs: Solomon et al. 2016 – ozone-sonde detected recovery, observed in September. Hofmann (2010)? Recovery after the September depletion rate is less than 2.7 DU/day
**C) Advancing scientific understanding (Q3 & Q4 in New Research Plan)**

- Understanding the cause of atmospheric composition changes
- Sources, sinks, and transport

**Improving our understanding of trace-gas sources and sinks**

**Sinks:** Measuring the atmospheric oxidation capacity over time

- **budget analyses of long-lived gases**

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**The exponential decline in CH$_3$CCl$_3$**

![Graph showing the decline in CH$_3$CCl$_3$ over time](image)

**Inferred [OH] inter-annual changes**

![Graph showing inferred [OH] changes over time](image)

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**Alternative approaches to CH$_3$CCl$_3$:**

- Deriving OH loss from consideration of hemispheric mole-fraction differences
  - Long-lived gases (Liang et al., 2017)
  - Short-lived gases from network and special projects (e.g., Atom)

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**Inferred [OH] from: CH$_3$CCl$_3$, CH$_4$ (const. emissions), CH$_4$ (varying emissions), Prinn et al. (— — —), Bousquet et al. (ーーー)**

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**Science 2000; Science 2011; PNAS 2017**
C) Advancing scientific understanding (Q3 & Q4 in New Research Plan)

- Understanding the cause of atmospheric composition changes
- Sources, sinks, and transport

Improving our understanding of trace-gas sources and sinks

Sources, particularly U.S. contributions, but also on a global scale

Why are CCl₄ emissions continuing now that CFC production is negligible?

SPARC Report focus in 2016

**What we found:**

US emissions are 10% of global total

* associated with chemical industry

* this process likely accounts for much of the remaining global emissions

(Hu et al., 2016)

Other similar findings related to CFC-11 will be discussed in meeting

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C) Advancing scientific understanding (Q3 & Q4 in Research Plan)

- Understanding the cause of atmospheric composition changes
- Sources, sinks, and transport

Improving our understanding of trace-gas sources and sinks

Surface measurements are influenced by variations in sources *and* sinks:

![Diagram showing CFC-11 emission trends and stratospheric and tropospheric emissions in different hemispheres.](image)
D) Communicating results

- **Providing expertise** to national and international Assessments on Ozone and Climate:
  - *GMD scientists* have been lead authors, co-authors, contributing authors, and contributors to these Assessments
  - *GMD data* are prominent in these Assessments

Also:
- UNEP/WMO, 2018 Scientific Assessment of Ozone Depletion—lead authors
- UNEP/WMO, Twenty questions and answers about the ozone layer, 2015

Guiding ozone layer recovery in the future at GMD:

- **Continue ongoing programs to:**
  - Monitor effectiveness of the Montreal Protocol for diminishing ozone-depleting gases
  - Accurately measure the response of stratospheric ozone to decreasing halogen and increasing greenhouse gas concentrations

- **Especially to address newly emerging issues:**
  - increases in CFC-11, CH₂Cl₂, & CH₃Br; and in future for VSLS-bromine?
  - HFCs and Kigali Amendment — locking in climate gains from the Montreal Protocol
  - lower stratospheric ozone declines (Ball et al. 2018)? Assess better-positioned GMD measurements (Unkehr; ozone-sonde)

- **Add capabilities where possible:**
  - increased sampling frequency in tropics
  - validation of new instruments (*i.e.* Pandora)
  - validation of new operational NOAA satellite products (*i.e.*, IPSS)

- **Participate in periodic field campaigns to:**
  - extend an understanding of surface-based results vertically
  - improve process-based understanding of the atmosphere
  - gauge the atmospheric response to increasing greenhouse gas concentrations
Guiding Recovery of Stratospheric Ozone at GMD

GMD plays a central role in the global effort to monitor stratospheric ozone, ozone-depleting gases, and other processes affecting stratospheric ozone

**Our focus:**

- *global-to-regional scale observations* to assess global changes and influences from specific processes and regions (e.g., U.S.)
- *Diagnosing observed changes* to clarify the relative influence of policy decisions, other human behaviors, and natural processes
- *To provide the highest-quality, policy-relevant science*

→ Guiding the recovery of the ozone layer by informing Parties to the Montreal Protocol on the progress of recovery