Earth System Research Laboratory
Global Monitoring Division

Summary Report No. 28
2004 - 2013

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
Office of Oceanic and Atmospheric Research

Global Monitoring Division
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2004–2013

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Preface

The Earth System Research Laboratory (ESRL), Global Monitoring Division (GMD) is located in Boulder, Colorado, with Atmospheric Baseline Observatories in Barrow, Alaska; Summit, Greenland; Trinidad Head, California; Mauna Loa, Hawaii; Cape Matatula, American Samoa; and South Pole, Antarctica. ESRL is one of seven research laboratories within the Office of Oceanic and Atmospheric Research (OAR) of the National Oceanic and Atmospheric Administration (NOAA). GMD conducts research related to atmospheric constituents capable of forcing change in the climate of the Earth through modification of the atmospheric radiative environment, for example, greenhouse gases and aerosols, and those that can cause depletion of the global ozone layer (e.g., chlorine- and bromine-containing compounds).

This report is a summary of GMD activities for calendar years 2004 to 2013. It is the 28th consecutive report issued by this organization and its Climate Monitoring and Diagnostics Laboratory and Geophysical Monitoring for Climatic Change predecessors since formation in 1972 (Nos. 1 through 22). The organization issued the first 22 reports from 1972 through 1993 annually; thereafter, they issued the reports on a biennial basis until 2003. A ten-year gap exists, with the 28th report filling in operational information for that time period. At GMD's Internet home page (www.esrl.noaa.gov/gmd/) you will find information about our major groups and observatories, the latest events and press releases, publications, data availability, personnel, and previous summary reports (Nos. 1 through 27). Numerous data graphs and ftp data files are available. You can obtain information (program descriptions, accomplishments, publications, plans, data access, etc.) on GMD parent organizations via the Internet (OAR: www.oar.noaa.gov; NOAA: www.noaa.gov).

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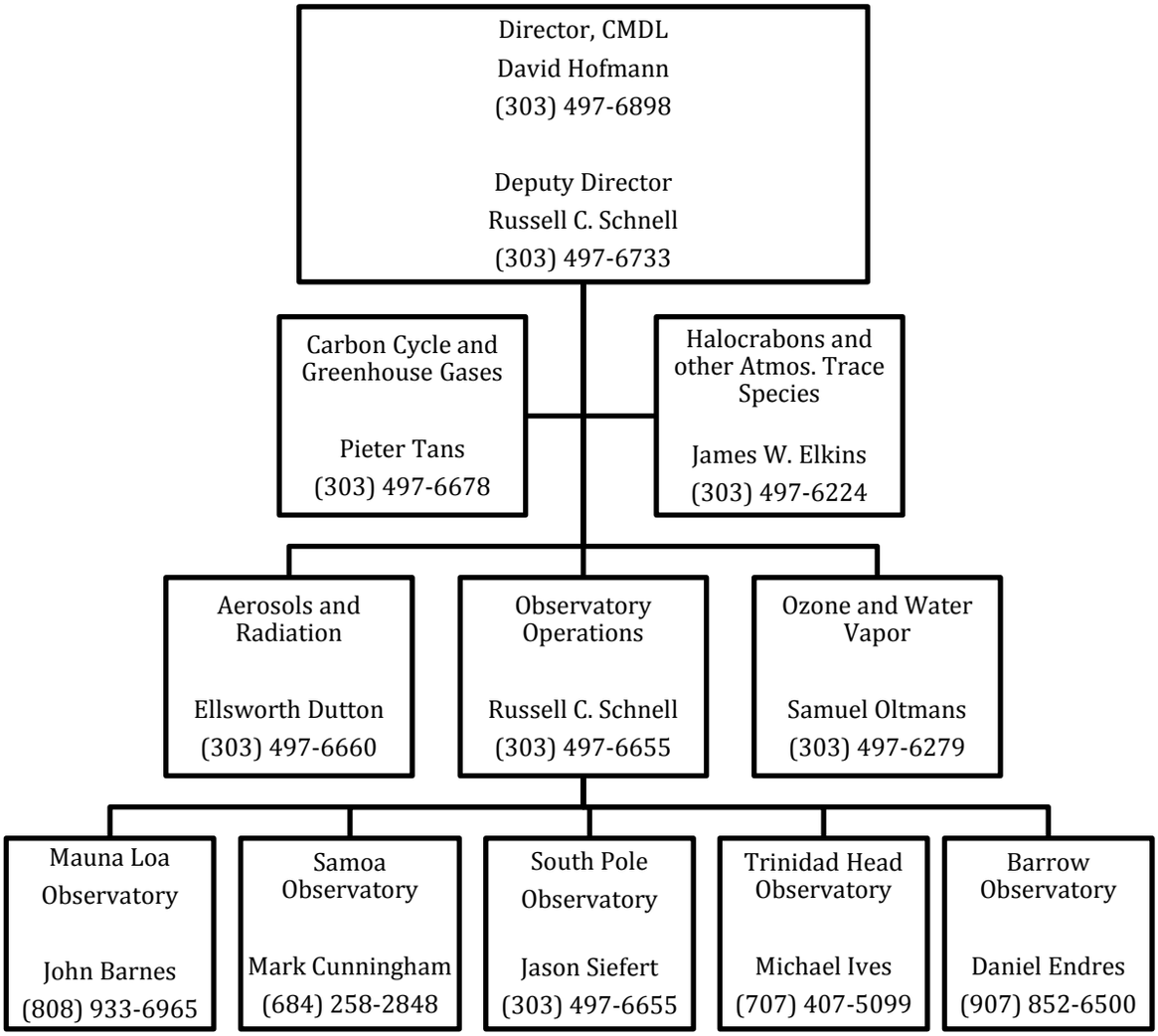

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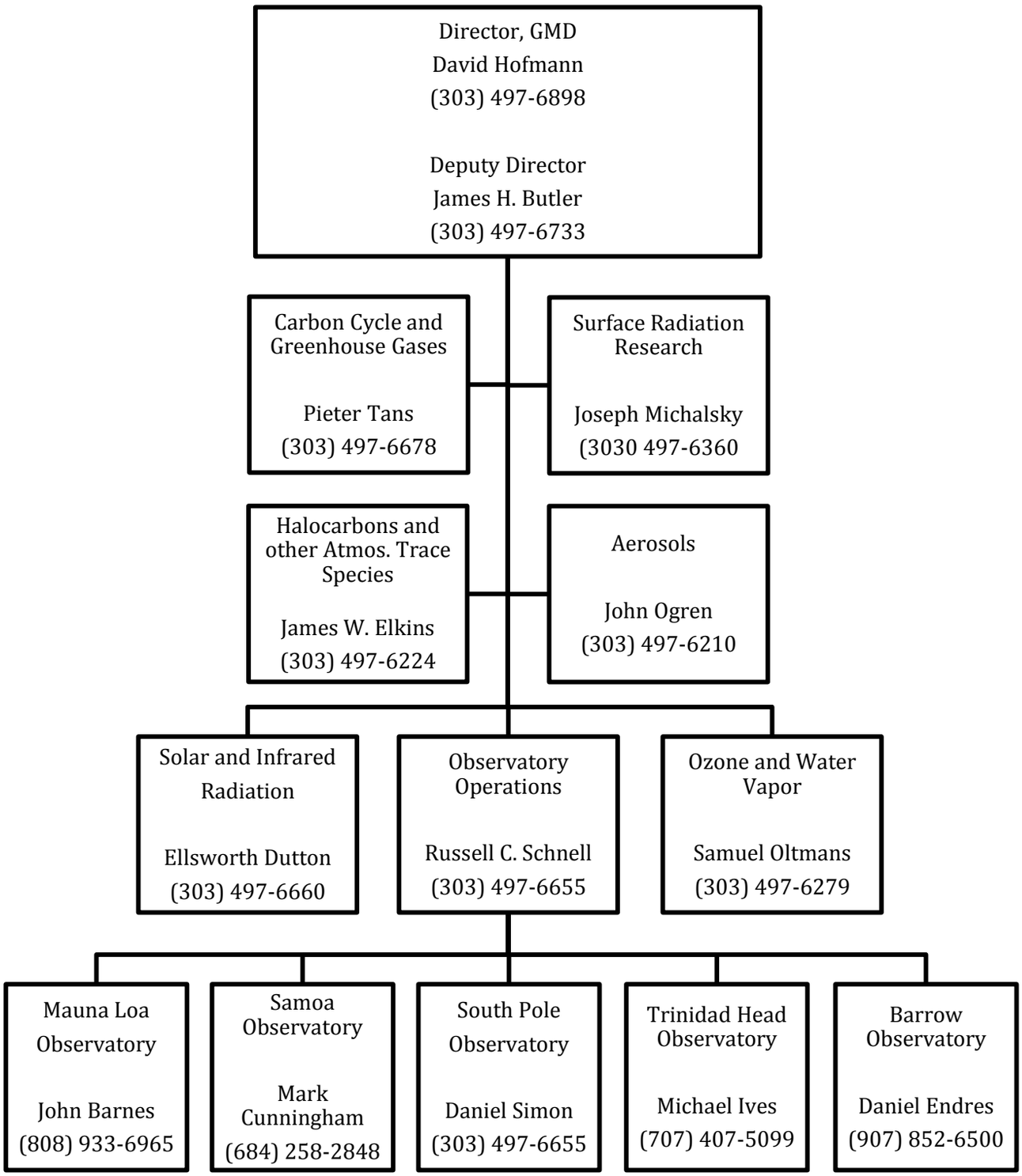

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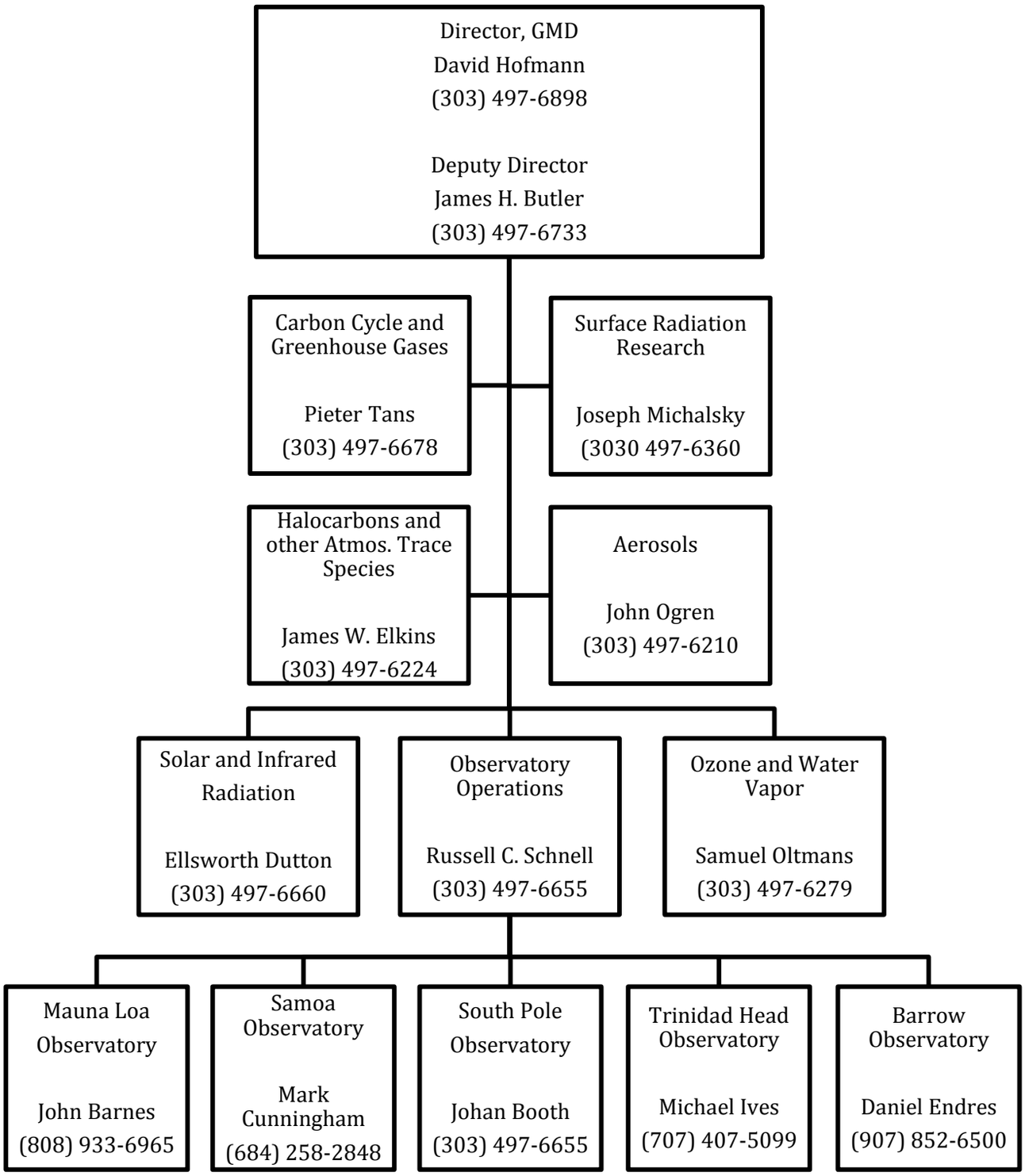

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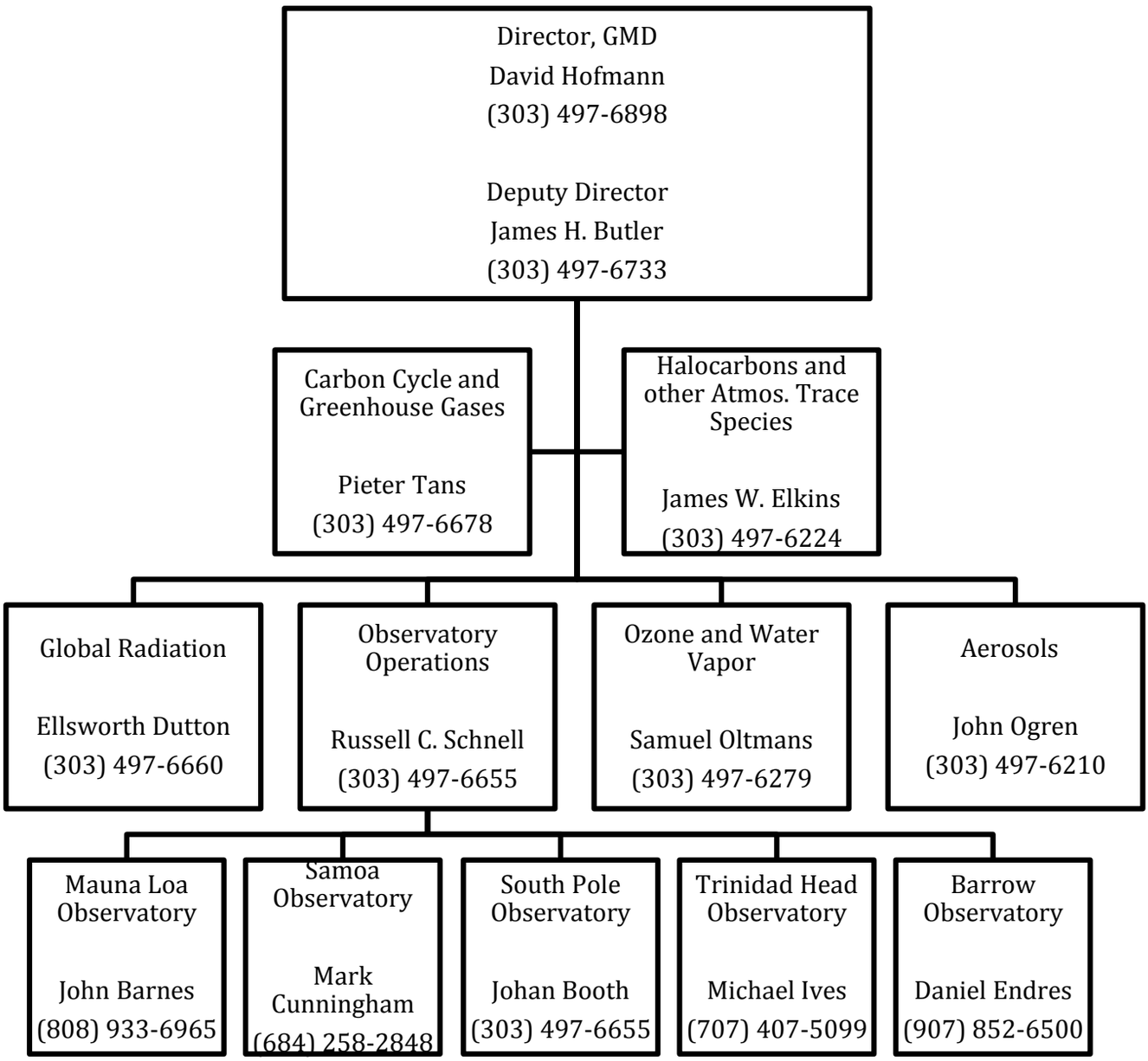

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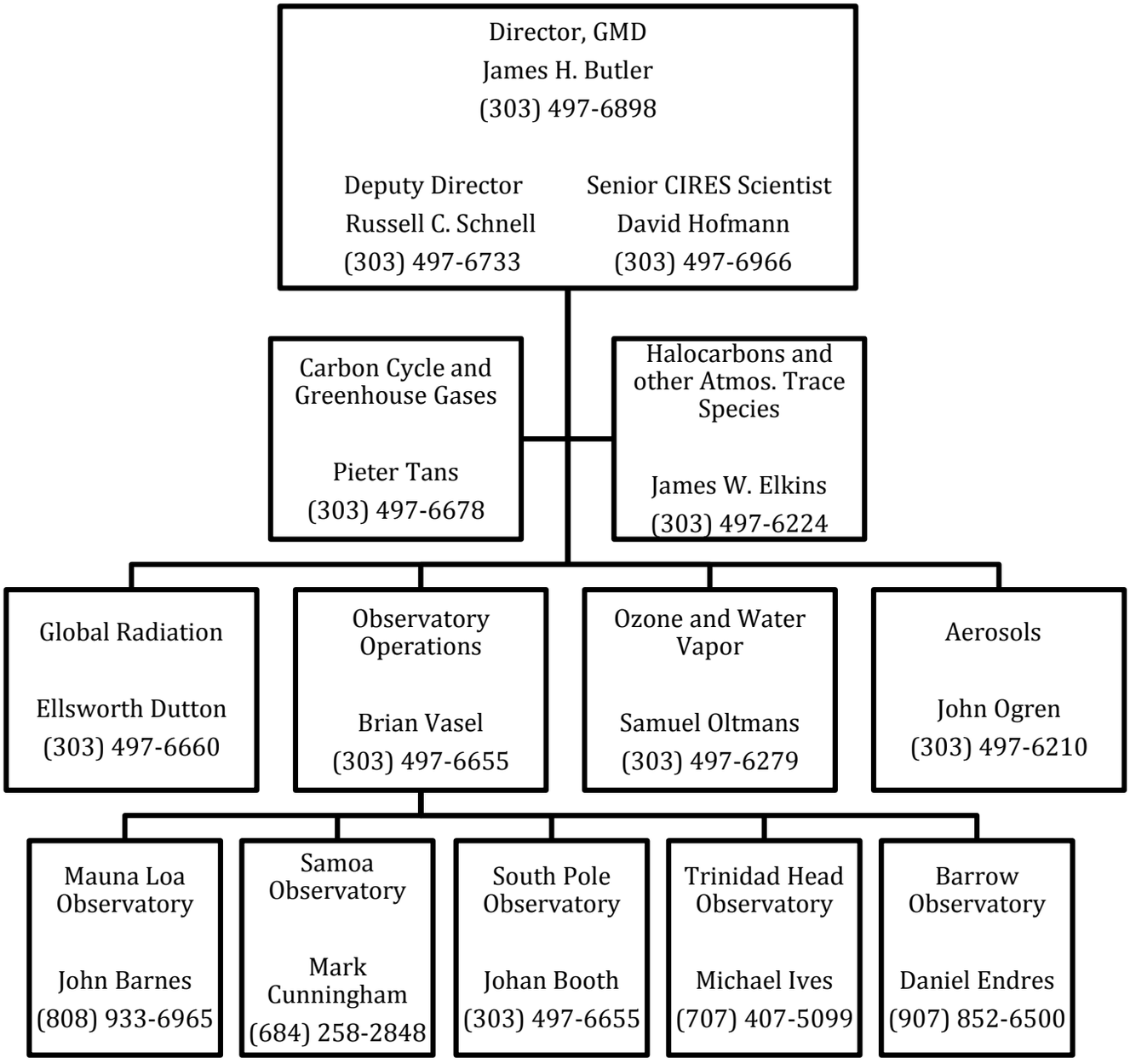

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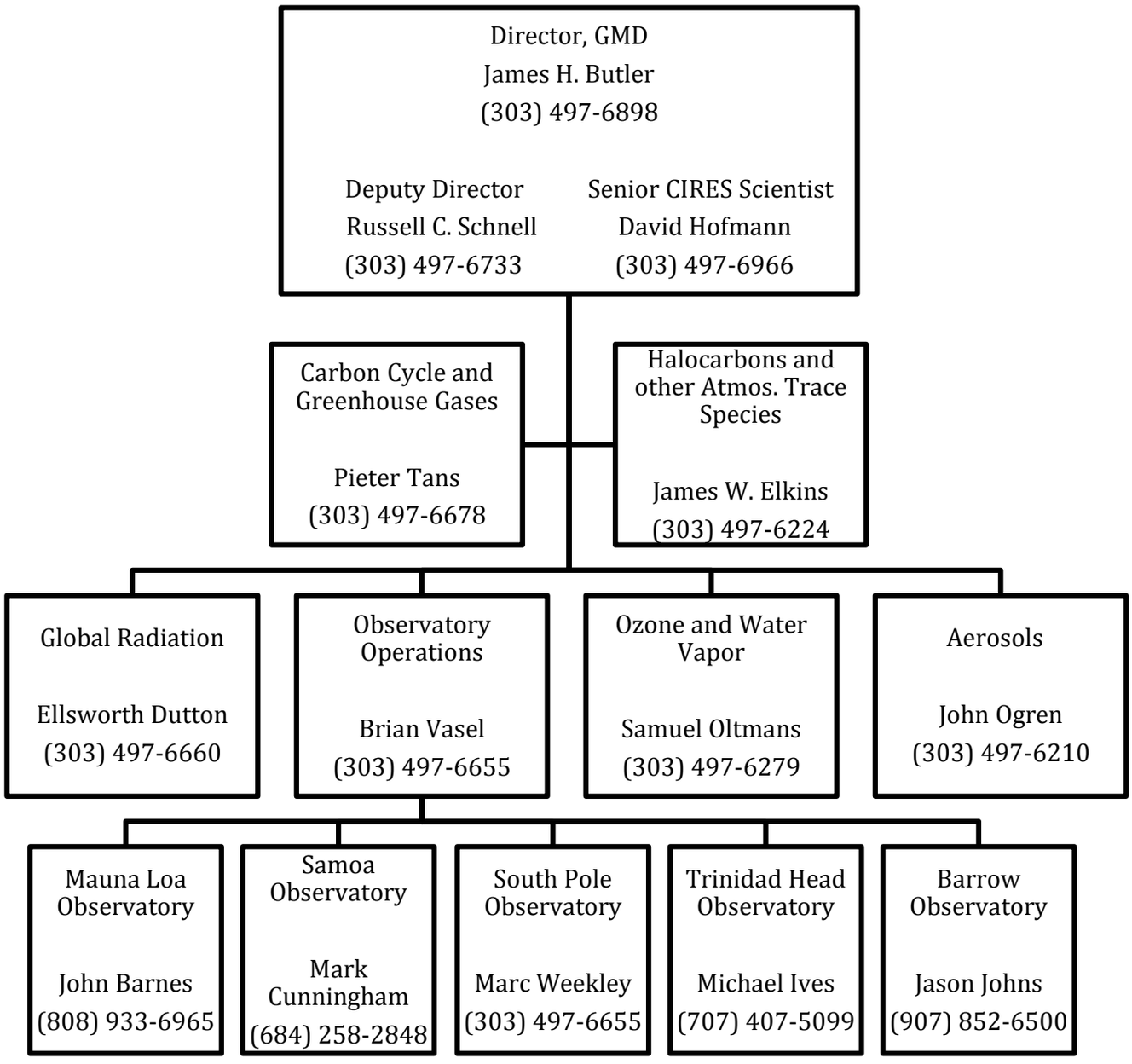

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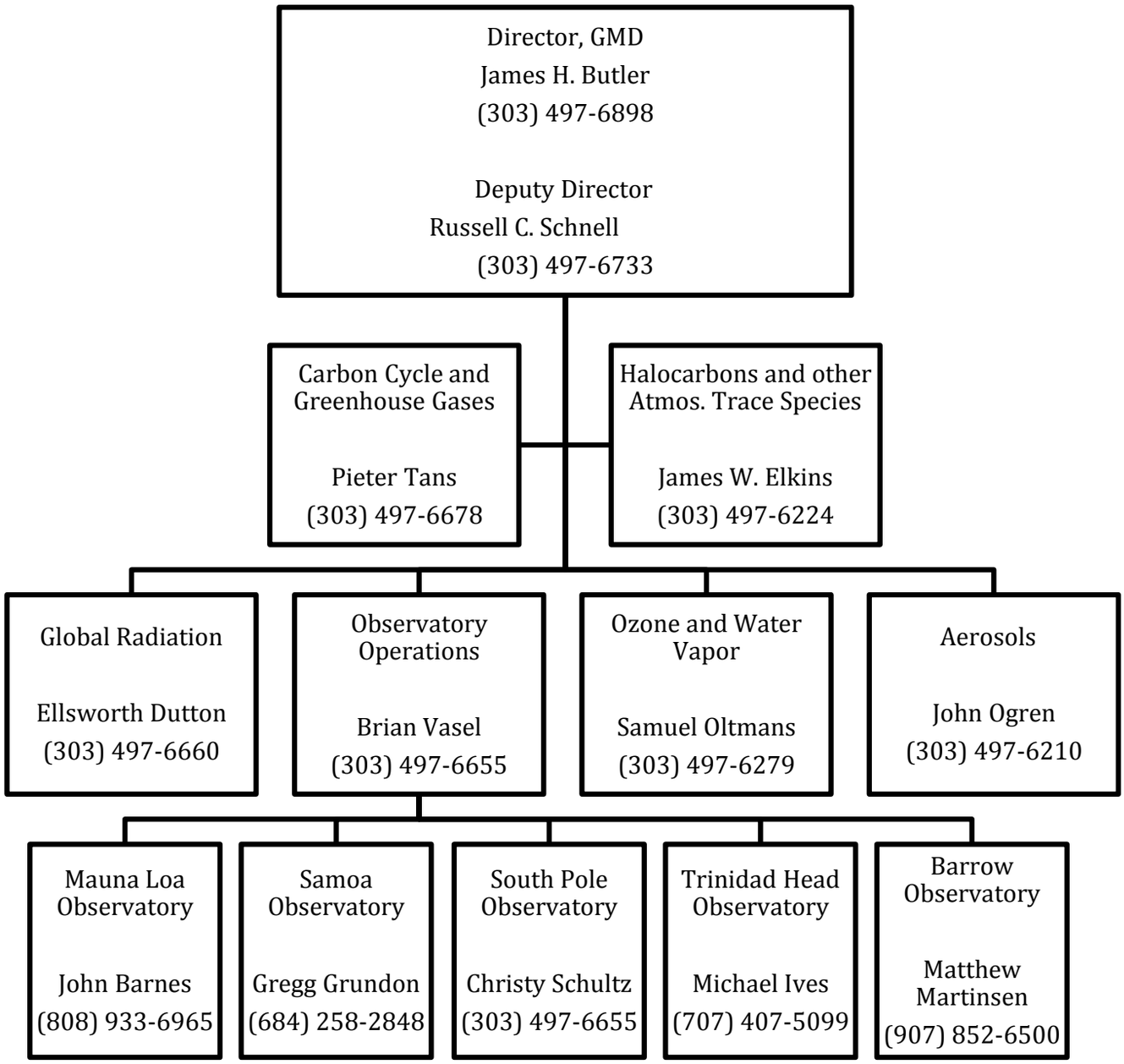

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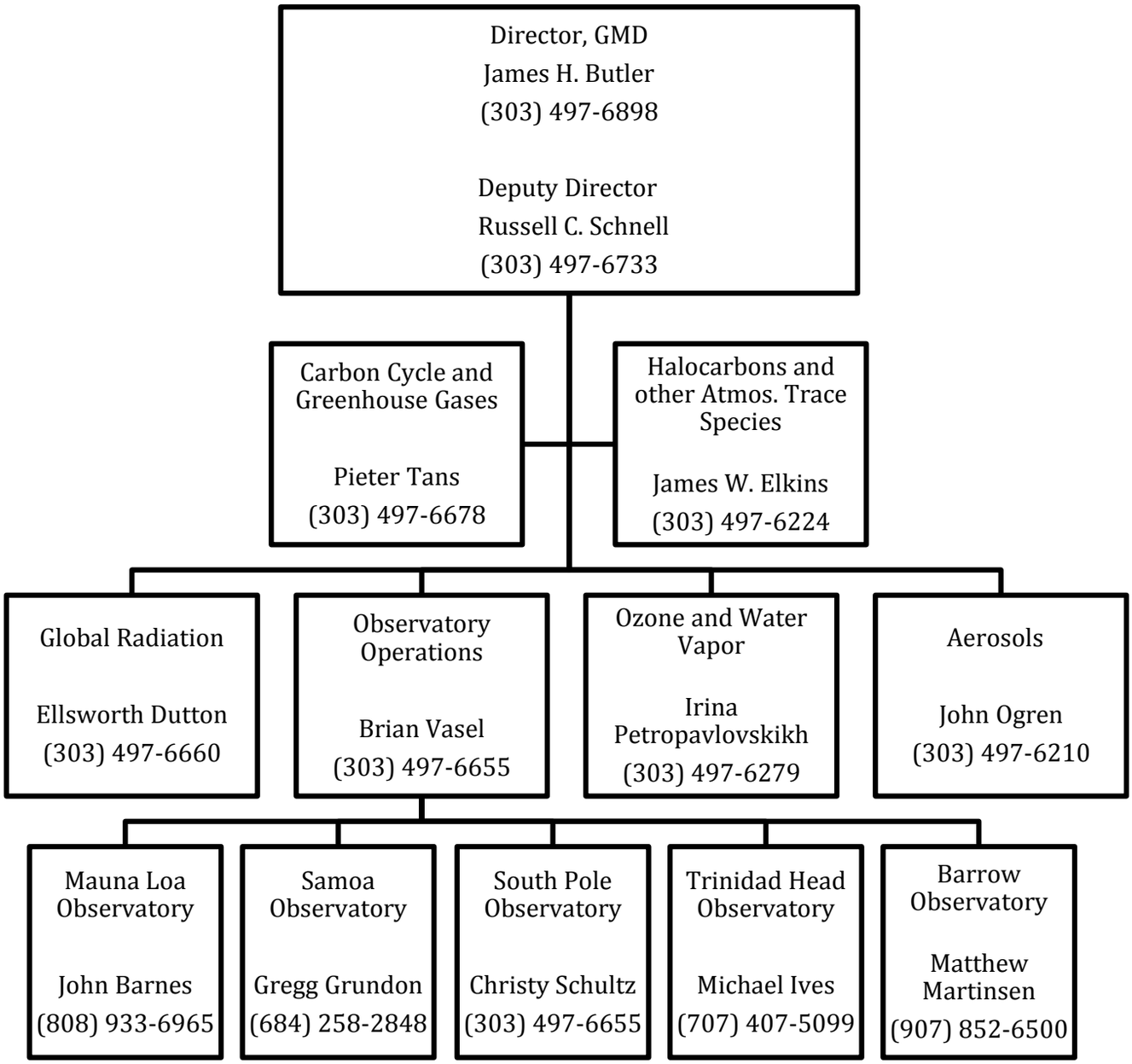

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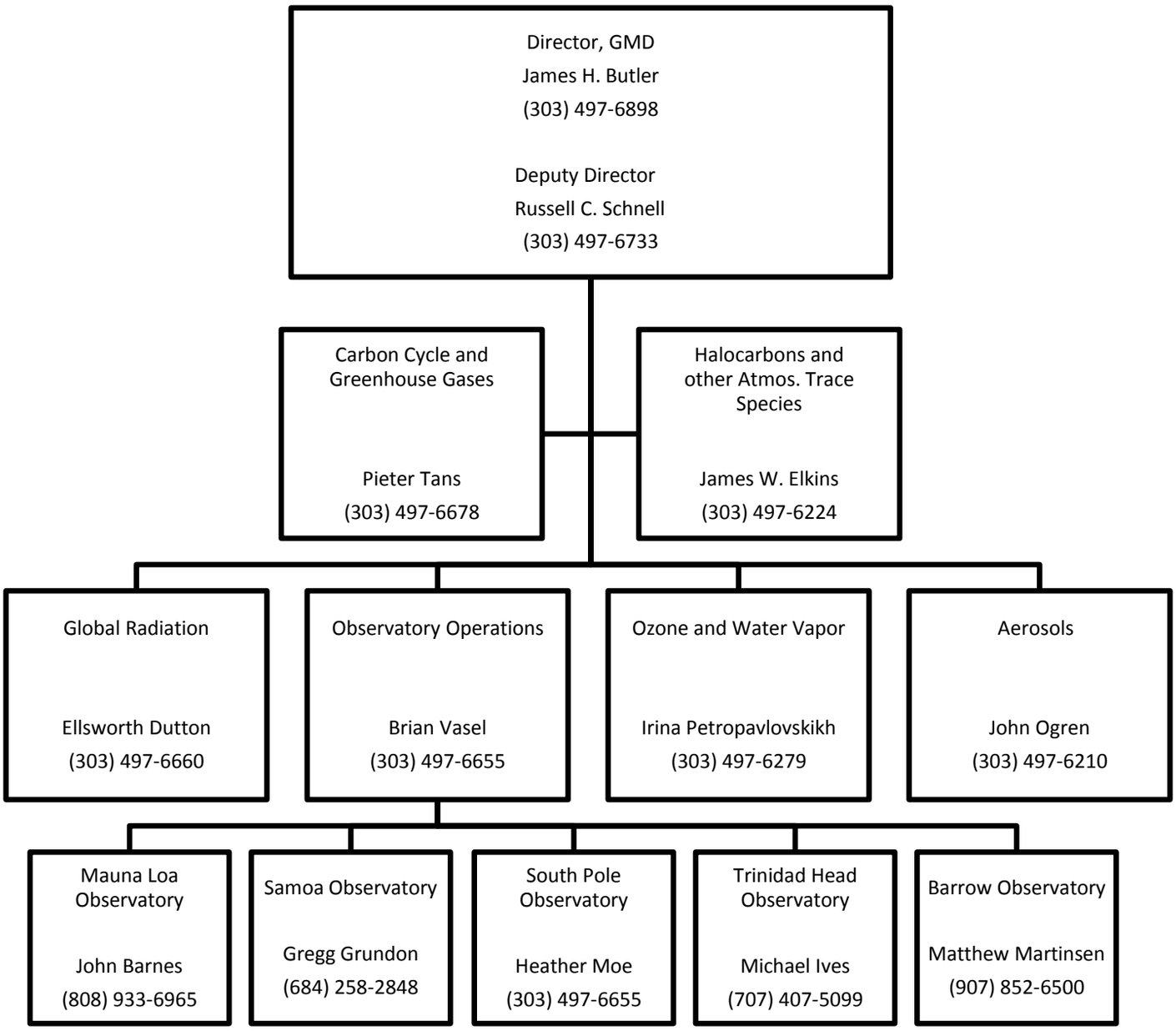

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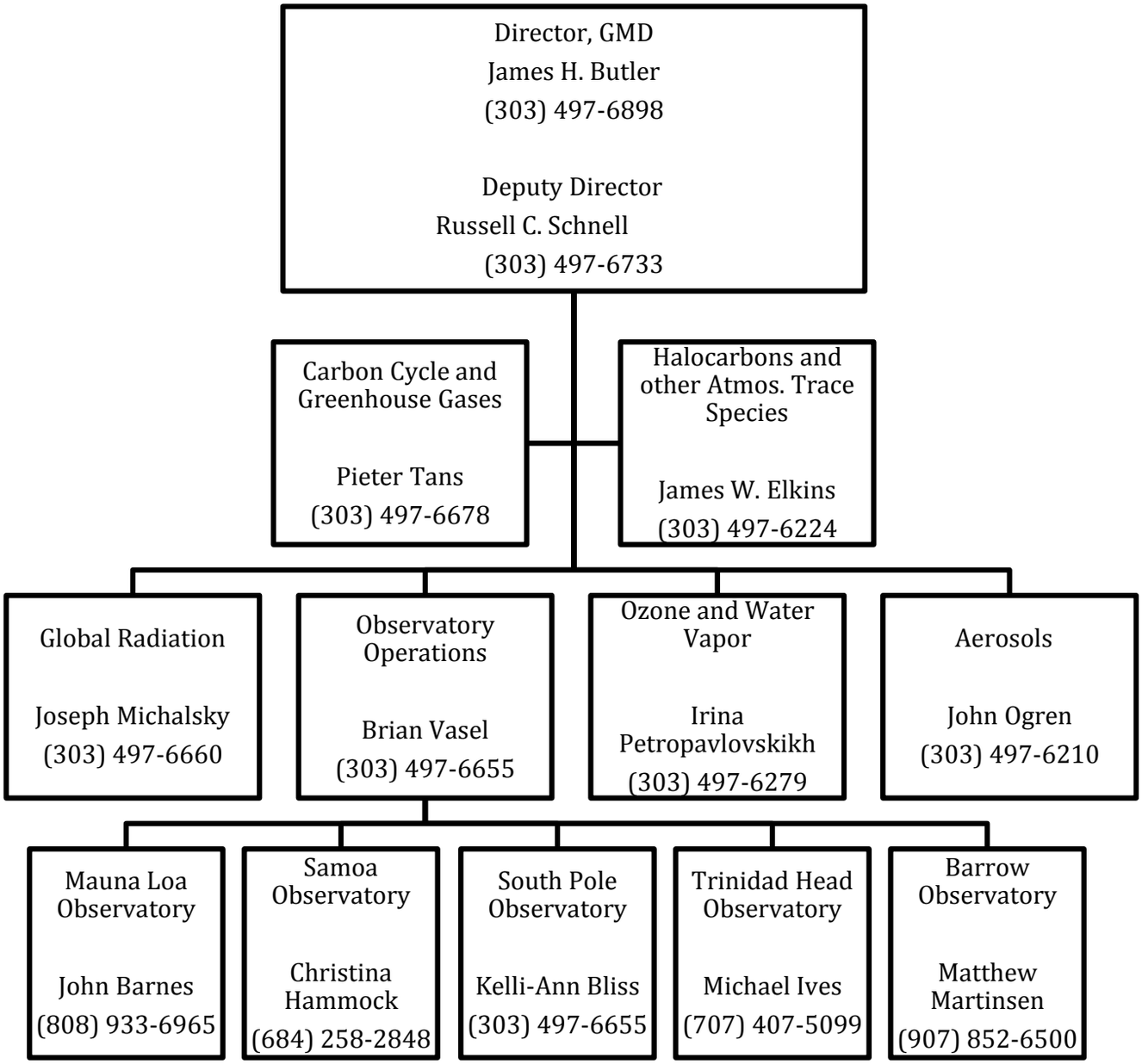

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SECTION 1 - INTRODUCTION

1.1 DIRECTOR'S INTRODUCTION

The Geophysical Monitoring for Climatic Change (GMCC) program, GMD's original predecessor, started the tradition of writing "Summary Reports" in 1972, two years after the formation of NOAA. The first report described the beginnings of an emerging organization designed "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. The program has its special focus in establishing a long-term time series from ground-based measurements". This document contained information on the instruments, operations, and data obtained at three atmospheric baseline observatories (Mauna Loa, Barrow, and South Pole) and it noted progress in establishing a fourth in the Samoan Islands.

A series of annual summary reports through 1993 documented subsequent advances in operations and data when, under the new name, Climate Monitoring and Diagnostics Laboratory (CMDL), they became biennial reports. That continued until 2003, when summary reports ceased altogether. There were several reasons for this, but one was the growing need for our scientists to publish results in the refereed literature. The data being produced were becoming increasingly relevant in all areas and we realized the importance of making not only the data, but also our first-hand interpretations and analyses available to all. Our publications increased substantially, but, as a consequence, less and less time was available for preparing annual or biennial reports. Uncertainty as to the nature of our organization under various NOAA and OAR restructurings led to further delay in preparing summary reports of operations.

Although most, if not all, of our changes in instrumentation and operations have been recorded in the literature, we realize that, since 2003, there has been no single location denoting those changes at locations key to these increasingly valuable data. This report, covering the ten years of 2004–2013, is designed to remedy that. Here we record significant changes at our observatories and in our observing systems that may bear upon interpretations of the data, today or in the future. We will assemble subsequent reports over shorter intervals to ensure robust documentation of our records and procedures. - *J.H.B.*

1.2 REPORT RATIONALE

The last summary report written, Summary Report No. 27, covering the years 2002–2003, is a decade old. The long-term mission and research themes of GMD have not wavered and are summarized in the GMD Research Plan that was updated in 2013. However, the operational changes that have occurred over the last decade are not succinctly captured in one place. While the vision and mission of the organization has not changed, the way we get the job done certainly has evolved over the last decade.

This report serves to bridge the gap from 2004–2013 and document the operational details that might otherwise be lost. This operational report is not intended to be a detailed list of when every instrument was calibrated, shipped, upgraded, etc., as these details are already well documented by each research project and integral to the data sets. Instead, this document complements the GMD Research Plan by summarizing how we operationally accomplish our mission and capture summary details not documented elsewhere.

1.3 GMD RESEARCH PLAN AND SCIENCE THEMES

GMD's research networks are focused on 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 Atmospheric Trace Species (HATS), Ozone and Water Vapor (OZWV), Aerosols (AERO), and Global 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. Much of GMD's research crosscuts

the groups, and this operations report will highlight the synergy of the research projects, calibrations, and baseline observatories.

1.4 GMD PRODUCTS

Monitoring and Diagnostics Laboratory (CMDL) research programs with the addition of the Air Resources Laboratory (ARL) Surface Radiation Research Branch.

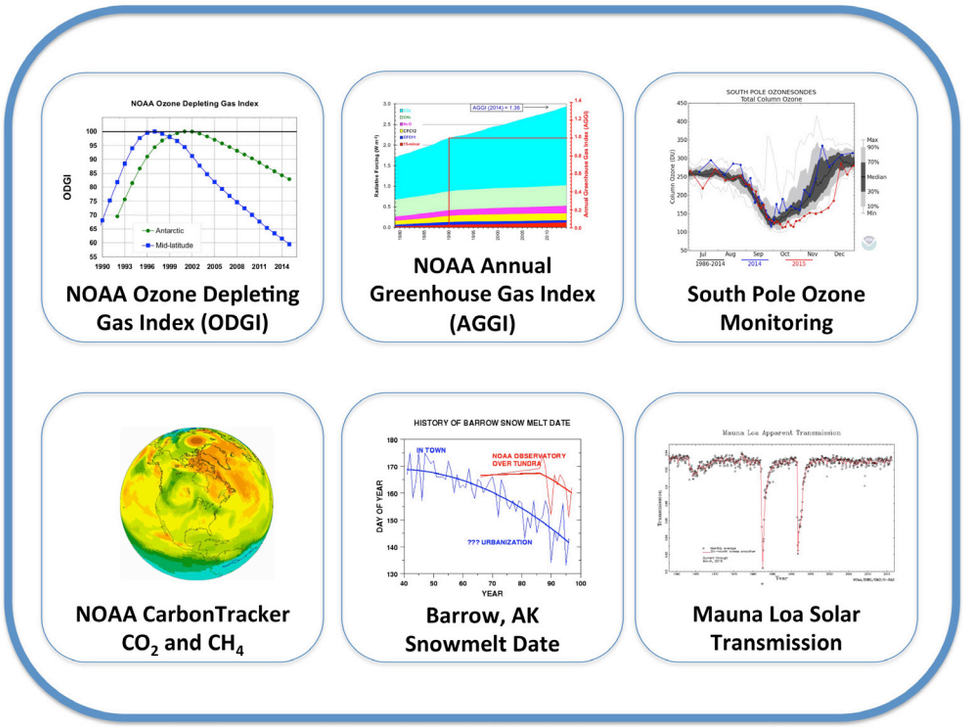


Fig. 1-1: Examples of GMD Products at www.esrl.noaa/gov/gmd/dv/

1.5 PUBLICATIONS & REFERENCES

We have placed a complete GMD publications database on the GMD homepage at: http://esrl.noaa.gov/gmd/publications/. Refer to figure 1-2.

Because this report is focused on operations, we do not include references in this document.

1.6 CREATION OF THE EARTH SYSTEM RESEARCH LABORATORY

On 1 October 2005 the Earth System Research Laboratory (ESRL) was created to pursue a broad and comprehensive understanding of the Earth system. This system comprises many physical, chemical, and biological processes that require dynamic integration to better predict their behavior over scales from local to global and periods of minutes to millennia. The Global Monitoring Division (GMD) is one of the four research divisions within ESRL and has a unique mission to focus on long-term observations. GMD consists of the former Climate

1.7 GMD ORGANIZATION

The GMD structure features five research areas focused according to scientific discipline and one observatory operations group as follows:

(1) Observatory Operations and Meteorology

(2) Aerosols

(3) Carbon Cycle and Greenhouse Gases

(4) Halocarbons and other Atmospheric Trace Species

(5) Ozone and Water Vapor

(6) Global Radiation

1.8 OUTREACH AND EDUCATION ACTIVITIES

Since its formation in 2005, ESRL has actively supported the NOAA Office of Education's Hollings and Educational Partnership (EPP) Scholarship

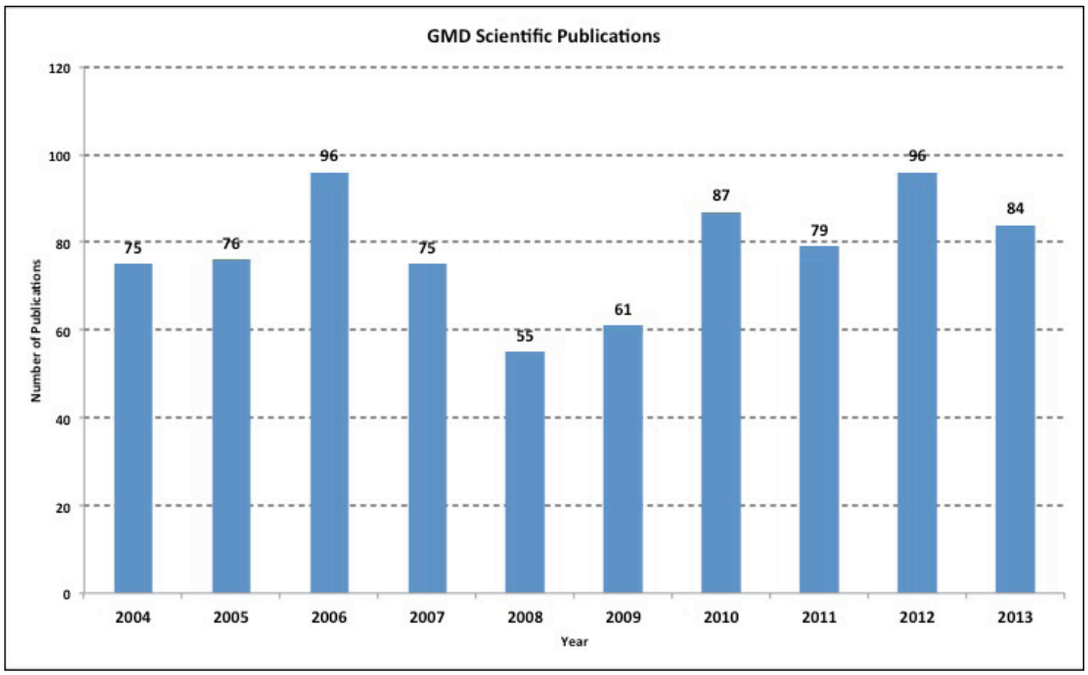


Fig. 1-2: GMD scientific publications per year, 2004 - 2013

Programs by providing a multitude of scientific, engineering, mathematics, computer science, policy and public outreach summer internship opportunities for participants. Recognizing a need to expand upon both the number of participants in internship programs and to attract a broader spectrum of students, we created the NOAA/ESRL Student Program Office. Our student program continues to provide opportunities for Hollings and EPP Scholars who opt to come to the NOAA Boulder Laboratories. The Student Program Office, housed in the ESRL Global Monitoring Division, now offers intern placement, logistics, and assistance to all NOAA entities in Boulder as it administers or oversees ten internship programs.

We have expanded the program by attracting non-traditional students and educators. Through a partnership with the Boulder Valley School District (BVSD), we currently host students who come from alternative public high schools. Presented with many obstacles to their academic development, the students in this program receive additional attention in the areas of science and mathematics so they can improve academically and achieve the goals to reach their full potential. In addition, the Student Program Office works with K-12 STEM educators through the STAR program at CalPoly San Luis Obispo to bring teachers into the Laboratory for research experience they can then take back into the classroom, making them more effective STEM educators. We have seen great success in both areas. Our BVSD students proceed to universities or community colleges and our educators have reported increased productivity in the classroom.

The NOAA Boulder Student Program Office works closely with local scientific organizations such as the National Center for Atmospheric Research (NCAR), National Ecological Observatory Network (NEON), University NAVSTAR Consortium (UNAVCO), and the Cooperative Institute for Research in Environmental Sciences (CIRES) to place students into appropriate internships that benefit both the organizations and the students.

1.9 GMD BASELINE OBSERVATORY INFORMATION

Table 1-1: GMD Baseline Observatory Information

	Barrow	Summit
Latitude	71.3230 N	72.5800 N
Longitude	156.6114 W	38.4800 W
Time Zone (UTC)	+ 9 hours	+ 2 hours
Elevation	3 masl	3216 masl
Postal Address	P.O. Box 888 Barrow, AK 99723	CH2M Hill Polar, 109 SAT BLDG 20 Stratton Air National Guard Base 1 Air National Guard Road Scotia, NY 12302
Freight Address	P.O. Box 888 Barrow, AK 99723	CH2M Hill Polar, 109 SAT BLDG 20 Stratton Air National Guard Base 1 Air National Guard Road Scotia, NY 12302

	Trinidad Head	Mauna Loa
Latitude	41.0541 N	72.5800 N
Longitude	124.1510 W	38.4800 W
Time Zone (UTC)	+ 8 hours	+ 10 hours
Elevation	107 masl	3397 masl
Postal Address	HSU Marine Lab 570 Ewing Street Trinidad, CA 95570	1437 Kilauea Ave. #102 Hilo, HI 96720
Freight Address	HSU Marine Lab 570 Ewing Street Trinidad, CA 95570	1437 Kilauea Ave. #102 Hilo, HI 96720

	American Samoa	South Pole
Latitude	71.3230 N	72.5800 N
Longitude	156.6114 W	38.4800 W
Time Zone (UTC)	+ 11 hours	- 12 hours
Elevation	42 masl	2840 masl
Postal Address	P.O. Box 2568 Pago Pago, AS 96799	NOAA/ESRL Project O-257-S South Pole Station PSC 768 Box 400 APO, AP 96598
Freight Address	C/O FedEx Office CSL First Road Pago Pago, AS 96799-2568	NOAA/ESRL Project O-257-S South Pole Station PSC 768 Box 400 APO, AP 96598

SECTION 2 – OBSERVATORY OPERATIONS AND METEOROLOGY

2.1 AMERICAN SAMOA

BACKGROUND

The American Samoa Observatory (SMO) is located in the middle of the South Pacific, about midway between Hawaii and New Zealand. It is characterized by year-round warmth and humidity, lush green mountains, and strong Samoan culture. The observatory resides on the northeastern tip of Tutuila Island, American Samoa, at Cape Matatula. Established in 1974 on a 26.7-acre site, the observatory has survived two major hurricanes, an earthquake, and a tsunami. Generally, a staff of three operates the facility year round. This observatory has the distinction of obtaining some of its daytime power from solar panels.

The largest earthquake recorded, a magnitude 8.1, occurred on 29 September 2009, ~120 mi offshore from American Samoa. The earthquake and subsequent four tsunami waves (each reportedly ~15–20 ft in height) hit the island, knocking out roads, power, water, and causing landslides. The earthquake afflicted the observatory with considerable physical damage and destroyed both vehicles. Because the observatory is situated on high ground and retained backup power generation and working restroom facilities, the site, primarily the carport, functioned as a FEMA shelter for residents of the eastern end of Tutuila for months after the tsunami.

For the first time in the history of the Atmospheric Baseline Observatories, we temporarily shut down for ~2.5 months (April to June 2010). A resident of Tula Station physically assaulted Chief Mark Cunningham on the observatory driveway on 29 March 2010. With the assistance of Russ Schnell and Brian Vasel from GMD in Boulder, Mark and family departed American Samoa permanently on 11 April, and we temporarily closed the observatory for operations. Village Chief Iuli maintained site security in the absence of GMD staff. During the closure, we shut down all instruments but kept the station power and A/C running to protect the instruments and facility from the tropical environment. On 21 June 2010, GMD technician Jason Johns reopened the site, and brought instrument systems back online over the course of a few weeks.

Table 2-1: American Samoa Observatory Staff, 2004-2013

Year	Station Chief	Electronics Technician	Grounds Maintenance
2004	Dan Simon, NOAA Corps (arrives Aug) Jason Siefert (departs Aug)	Mark Cunningham	Lafaele Silao Lafaele Silao
2005	Stephanie Koes (arrives Aug) Dan Simon, NOAA Corps (departs Aug)	Mark Cunningham	Lafaele Silao
2006	Mark Cunningham (began Aug) Stephanie Koes (departs Aug)	Mark Cunningham	Lafaele Silao
2007	Mark Cunningham	None	Lafaele Silao
2008	Mark Cunningham	None	Lafaele Silao
2009	Mark Cunningham	None	Lafaele Silao
2010	Mark Cunningham (departs Mar) Jason Johns (June - Nov) Gregg Grundon (arrives Oct)	None	Lafaele Silao
2011	Gregg Grundon	Andy Clarke (Jun- Aug) Jason Johns (arrives Aug)	Lafaele Silao
2012	Christina Hammock (arrives Aug) Gregg Grundon (departs Sep)	Jason Johns (departs Mar) Lance Roth (May-Jul) Andy Clarke (Sep-Oct)	Lafaele Silao
2013	Jesse Milton, NOAA Corps (arrives Jun) Christina Hammock (departs Jul)	Gataivai Talamoa (began Feb)	Lafaele Silao

FACILITIES

2003

- Corrected station billing errors. eliminating them from the three previous years. The observatory appeared to be roughly $20,000 in debt to the utilities companies due to billing errors. Blue Sky accounts reconciled leaving the station with a current $500 credit.
- Repainted the tech room and back supply room inside the main laboratory.
- Repainted the outside concrete stairway with anti-slip material to eliminate slip hazard during and after rainstorms.
- Cleaned and resealed the rooftop surface with deck paint.
- Repainted and removed rust from the Dobson dome.
- Secured cylinder areas created in Hudson building to store full tanks.
- Stripped, sanded, and varnished wooden support pillars.
- Found a leak on the Hudson Building flat stack cover and replaced with a slanted cover for water runoff.
- Replaced the corroded and leaking cold water line to the observatory with PVC piping outside and laid new line within the building.
- Pumped, cleaned, and inspected the station's fresh water supply cistern.
- Pumped the septic tank to clear the obstructed connection to the dry well.
- Repaired faulty assembly relay on backup generator.
- Measured 55 VAC on the ground feeding the network/MET/Solar equipment and installed a new ground at the observatory.
- Upgraded tech house:
    - Termites infested the walls and mold and mildew permeated the building.
    - Gutted the rear 2/3 of the building and floor down to the concrete.
    - Pruned and landscaped the yard and removed brush overgrowth from the house.
    - Rebuilt the window frame.
    - Framed walls floor to ceiling with heavy-duty, treated lumber.
    - Replaced 400' of double-layer screen wire.

2004

- January: Cyclone Heta made landfall at American Samoa and:
    - Destroyed lower four flights of stairs completely.
    - Severely damaged the pump building.
    - Significantly damaged numerous instrument systems.

As a result, we:

- Replaced the lower four flights of stairs down onto the point after Heta.
- Cleared the generator shack area and painted the diesel tank.
- Recast the main building windowsills with concrete and painted the building.
- Had a local vendor empty and clean the station's 14,000-gal cistern.
- Removed the old generator from the observatory on 15 July after it threw piston # 3.
- Cleaned, painted, and prepped the generator building for the addition of a new 40-kW Kohler diesel generator that arrived on the island 23 July. We placed it in the building where it awaits installation of fuel and electricity lines.
- Installed alarm systems in chief and tech houses and added watchdogs to the premises.
- Finished remodeling tech house.
- Started clearing lot T-9 to build lidar lab.

- September: Completed the roof on T-9 and continued contract work with the installation of walls, a window, and large door for eventual additional secured storage for houses and possibly lidar equipment.
- December: Installed new 4" underground conduit from main building to Hudson building.
- December: Installed, tested, and brought generator back on line. After receiving the final fuel system parts, we restored backup power to the observatory.
- December: Installed T-9 electrical power and lidar hatch now ready for instrument installation. We strengthened the roof, started to landscape and remove the jungle.

2005

- Swapped the naming convention of Tafuna houses with Mark Cunningham who assumed the station chief position. The chief house is now the unit along the fence and the tech house is now located across the street from T-9 lidar lab.
- December: Noted a buildup of rust under the paint on several areas of the Dobson dome. Stripped off all of the paint on the dome and found four areas to cut out and replace. Worked with a local welder and laborers for repairs.

2006

- Put new roofs on both houses in Tafuna.
- Removed termite-infested garage adjacent to chief house to allow air circulation around the house.

2007

- Completely rebuilt the observatory inside and out. Installed new metal roof and roof decking for instruments. Installed new electrical, lighting, windows, doors, drop ceilings, flooring, and painted throughout the building. Completely remodeled bathroom. Anchored roof supports deeper into the ground to withstand future cyclone-force winds.

2008

- Reroofed the Hudson building.

2009

- Spring: Painted the observatory exterior.
- 29 September at 6:48am: Magnitude 8.1 earthquake occurred approximately 120 mi SW of the island. Forty-five minutes after the earthquake, a series of four tsunami waves (~15 to 20 ft high) hit the island, knocking out roads, power, and causing landslides. The quake damaged the observatory considerably, destroying both vehicles.
- October: Purchased one new replacement vehicle for the observatory after the September tsunami destroyed both government vehicles.

2010

- February: Replaced Aerosol inlet with one now supported by the Blue Sky tower. The 2004 cyclone damaged the original guyed inlet, which the 2009 earthquake further weakened.
- 29 March: Local Tula resident attacks station chief Mark Cunningham.
- 11 April: Mark Cunningham and family depart island. Observatory placed into temporary mothball status with no on-island staff. All instruments are shut down. Power and A/C left on, Chief Iuli protecting facilities/instruments.
- 21 June: Jason Johns reopened station.
- Purchased solar panels (5.25 kW) for observatory with matching funds from NOAA Green Grant program for carport roof.

2012

- March: Completed post-2009 earthquake observatory repairs.
- May: Back-up generator failed. Replaced windings and control board.
- November: Purchased new Ford truck in HI (2nd truck for SMO) shipped to the site by the Navy.

2013

- June: Got backup generator on line again.
- Upgraded the tech house as termites infested all wood structures in the house. Gutted and rebuilt the building with new bathroom, exterior cement walls, home office, water plumbing, new windows and frames, and replaced damaged roof.
- Began plantation installation in Tafuna. Removed heavy overgrowth along the station chief housing fence to install a plantation. Removed garbage from the site. Dug up and cleared the area of rocks and roots, and planted the cleared and cleaned sections with taro and bananas.
- Cleaned up NOAA housing yard: demolished and removed dilapidated greenhouse and fire pit structures; removed years of vegetation debris from under bushes and trees; trimmed large mango tree above the station chief house as well as other small trees and bushes.
- Completely wiped clean two rooms in the station chief house of a year's worth of rubbish. Turned one room into a guest bedroom and the other into a home office.
- Rewound and serviced the generator, bypassing the fuel line going into the backup generator day tank to run straight into the engine, thus preventing a fuel oil spill. Replaced the rat wire on the generator room's windows. Treated the 1000-gallon fuel tank with fuel stabilizer.
- Repainted and removed rust from the Dobson dome.

- Deep cleaned mold and mildew with bleach and water on the inside of the Dobson dome.

COOPERATIVE PROJECTS

2004

- Installed auto sampler for the Princeton flasks. Ran a line from the Blue Sky Tower to the main observatory for sampling.

2005

- Discontinued DOE Sampling Paper Filters project.
- 24 October: Ada Kong terminated the SASP project.
- Started sampling for Dr. Stan Tyler (UC-Irvine).

2006

- Suspended Department of Homeland Security Fabian Raccah's project.

2007

- With his team from Scripps Institute of Oceanography, Ray Weiss installed MEDUSA. Installed new Mass Spectrometer – Gas Chromatograph in the Hudson building.
- Florida State University ran a short-term project measuring atmospheric mercury isotopes.

SPECIAL EVENTS

2004

- Visitors: James A. Kelly – Assistant Secretary of State, Bureau of East Asian & Pacific Affairs

2005

- 7 April: The Federal Aviation Administration (FAA) conducted a surprise audit as a result of our shipping pressurized cylinders via Hawaiian Airlines. Mark Cunningham provided the FAA compliance officer with his current DOT Hazardous Material Shipping training certification and additional documentation regarding cylinder shipments. The FAA informed the observatory of the requirements for maintaining paperwork regarding all shipments. No further action necessary.
- Deputy Assistant Secretary of Commerce for Oceans and Atmosphere Timothy Keeney visited while on the island, attending the Ocean Symposium.

2009

- June: Advanced Global Atmospheric Gases Experiment (AGAGE) network #39 meeting held at Tradewinds Hotel and included station tour and logistical help.

OUTREACH

2009

- September: Observatory served as the second largest shelter on the island following the earthquake/tsunami. More than 50 local villagers camped at the observatory under the carport for access to high ground, clean water, working bathrooms, back-up generator power, and basic medical supplies. FEMA officially designated the site as a shelter location for the Tula end of the island.

2012

- Christina Hammock served as an after-school tutor at local high school.

2013

- Jesse Milton worked with other NOAA staff on island to create a "One NOAA" community. They held monthly meetings to learn what other NOAA staff was doing and how each line office could better support one another.

2.2 BARROW, ALASKA

BACKGROUND

Barrow Observatory (BRW), established in 1973, is located near sea level 8 km east of Barrow, Alaska at 71.32°N. Two employees staff this facility year-round. Due to its unique location, dedicated and highly trained staff, and excellent power and communications infrastructure, BRW hosts numerous cooperative research projects from around the world. Being about 8 km northeast of the village of Barrow and having a prevailing east-northeast wind off the Beaufort Sea, BRW has the distinct advantage that it is minimally influenced by anthropogenic effects.

After many years of planning, construction finally began on the new staff housing in the Spring of 2010. NOAA secured eight parcels of land for 20 years in Browerville and built seven new housing units. One house was not built due to increased project costs. NOAA completed the units (five for the NWS and two for OAR) in February 2011 at a cost of ~$1M. In March, the OAR staff collected their keys and moved into the units; one, a three-bedroom with heated garage and the other, a two-bedroom, also with heated garage.

FACILITIES

Table 2-2: Barrow Observatory Staff, 2004-2013

Year	Station Chief	Electronics Technician
2004	Daniel Endres	Teresa Winter
2005	Daniel Endres	Teresa Winter
2006	Daniel Endres	Teresa Winter
2007	Daniel Endres	Teresa Winter
2008	Daniel Endres	Jason Johns
2009	Steve Grove	Jason Johns Matthew Martinsen
2010	Steve Grove	Matthew Martinsen
2011	Steve Grove (departs Jul) Matthew Martinsen (began Aug)	Matthew Martinsen Ross Burgener (arrives Oct)
2012	Matthew Martinsen	Ross Burgener (departs Jan) Christina Hammock (Jan-Jul) Shannon Coykendal (Sep-Dec)
2013	Matthew Martinsen	Shannon Coykendal (Sep-Dec) Ross Burgener (arrives Dec)

2007

- December: We found that the heat trace for the water line in the crawl space under the house had shorted out and burned the fiberglass insulation. Each time the power to the heat trace cycled on, it burned more insulation. Luckily, since fiberglass does not sustain fire, the burning stopped each time the power cycled off again.

2010

- BLM Withdrawal renewed for observatory property.
- Spring: Construction began on seven new staffing housing units for OAR and NWS.
- July: Painted the observatory building.
- Summer: Completed DOE/ARM-funded observatory road upgrade project.
- Summer: Replaced aluminum stairs at main observatory entrance.
- Summer: Created and installed new observatory sign.

2011

- February: Completed new housing units and issued Substantial Completion and Beneficial Occupancy certificates.
- March: GMD staff moved into new housing units.
- March: Upgraded power line infrastructure, with new (DOE/ARM-funded) cross supports and insulators.
- Summer: NESDIS built deck extension with additional storage shed.
- Summer: USGS completed new Magnetometer/Absolutes building.
- Summer: Tightened guide wires on aerosol stack and replaced wood supports on air-line chase to tower.

2012

- Summer: Completed additional power line work and new (UIC-funded) neutral line.
- Summer: Painted observatory roof deck.
- Summer: Removed corroded deck shelter, defunct high-volume air sampler; removed corroded electrical panel and power runs on rear deck.
- Fall: Installed housing attic gable vents and added electrical circuit and insulation to attics.

2013

- Summer: Transferred power over to DEW Line power lines. Changed utility provider from UIC to Barrow Utilities.
- Fall: Replaced guy lines on walk-up tower and main observatory stack.
- Fall: Completed housing soffit venting.
- Fall: Added Arctic Cat 570XT snowmobile to observatory.

COOPERATIVE PROJECTS

* Records incomplete for 2004–2013 time period.

2006

- San Diego State University ran a weeklong intercomparison of carbon flux with Ameriflux instrumentation. They completed the intercomparison in July.
- Scripps Institution of Oceanography began a two-year long project to measure organic and dust aerosols using a filter system.

2007

- Oregon State University began study of atmospheric transport, deposition, and retention of bio-accumula-

tive contaminants using a high-volume air sampler with glass fiber filters.

- Florida State University ran a short-term project measuring atmospheric mercury isotopes.

2009

- NOAA PMEL ran a one-year project to study atmospheric nitrate and sulfate stable isotopes during and after the OASIS research campaign.

2010

- University of Utah deployed a system of multiple cameras to obtain high-resolution stereoscopic photography of falling hydrometeors to calculate their fall speed over a one year period.
- Japan's Research Institute of Global Change installed a continuous water vapor isotope analyzer to better understand the evaporation of water from the Arctic Ocean, funding the project for one year.
- The Keeling Group at Scripps Institution of Oceanography began sampling additional flasks to measure global O_2 abundances in the atmosphere.

2011

- High school student/University of Washington conducted a one-year study of air temperature for a climatological comparison with historical data from the HMS Plover.

SPECIAL EVENTS

2009

- Summer: NOAA Administrator Jane Lubchenco visited the observatory.

2013

- Summer: NOAA Administrator Kathryn Sullivan visited the observatory.

OUTREACH

2012

- Summer: Observatory supported a day for Ilisagvik summer camps (STEM Camp and Climate Change Camp).

2013

- Summer: Observatory supported a day for Ilisagvik summer camps (STEM Camp and Climate Change Camp).

2.3 MAUNA LOA, HAWAII

BACKGROUND

Mauna Loa Observatory (MLO) is located on the Island of Hawaii at an elevation of 3397 m on the northern flank of Mauna Loa volcano at 20°N. Established in 1957, MLO has grown to become the premier long-term atmospheric monitoring facility on Earth and is the site where concentrations of global atmospheric carbon dioxide are monitored. The observatory consists of ten buildings from which up to 250 different atmospheric parameters are measured.

In 2005, the Federal Building in Hilo was remodeled and GSA requested that NOAA found a new location for the MLO office facility. NOAA Real Estate secured a new lease and we moved to the new office at 1437

Table 2-3a: Mauna Loa Observatory Administrative Staff, 2004-2013

Year	Station Chief	Station Manager	Secretary	IT
2004	John Barnes	Darryl Kuniyuki	Leslie Pajo	
2005	John Barnes	Darryl Kuniyuki	Leslie Pajo	
2006	John Barnes	Darryl Kuniyuki	Leslie Pajo Kalei Lau	Preston Sato
2007	John Barnes	Darryl Kuniyuki	Kalei Lau Connie Craig	Preston Sato
2008	John Barnes	Darryl Kuniyuki	Kalei Lau Lillian Kamigaki	Preston Sato
2009	John Barnes	Darryl Kuniyuki	Lillian Kamigaki	Preston Sato
2010	John Barnes	Darryl Kuniyuki	Lillian Kamigaki	Preston Sato
2011	John Barnes	Darryl Kuniyuki	Lillian Kamigaki	Preston Sato
2012	John Barnes	Darryl Kuniyuki	Lillian Kamigaki	Preston Sato
2013	John Barnes	Darryl Kuniyuki		Preston Sato

Table 2-3b: Mauna Loa Observatory Technician Staff, 2004-2013

Year	Facility Maintenance & Electrical Engineer	Chemist	Atmospheric Scientist	Physical Scientist	Electronics Technician	Mechanical Technician
2004	Paul Fukumura-Sawada	Alan Yoshinaga	Aidan Colton	Steve Ryan	Bob Uchida David Nardini	
2005	Paul Fukumura-Sawada	Alan Yoshinaga	Aidan Colton	Steve Ryan	Bob Uchida David Nardini	
2006	Paul Fukumura-Sawada	Alan Yoshinaga	Aidan Colton	Steve Ryan	Bob Uchida David Nardini	
2007	Paul Fukumura-Sawada	Alan Yoshinaga	Aidan Colton	Steve Ryan	Bob Uchida David Nardini	Nash Kobayashi
2008	Paul Fukumura-Sawada	Tom Davis	Aidan Colton	Steve Ryan	Bob Uchida David Nardini	Nash Kobayashi
2009	Paul Fukumura-Sawada	Tom Davis	Aidan Colton	Steve Ryan	Bob Uchida David Nardini	Nash Kobayashi
2010	Paul Fukumura-Sawada	Tom Davis	Aidan Colton	Steve Ryan	David Nardini	Nash Kobayashi
2011	Paul Fukumura-Sawada		Aidan Colton	Steve Ryan	David Nardini	Nash Kobayashi
2012	Paul Fukumura-Sawada		Aidan Colton		David Nardini	Nash Kobayashi
2013	Paul Fukumura-Sawada		Aidan Colton		David Nardini Greg Rose	Nash Kobayashi

Kilauea Avenue in January 2006. The new space was better suited to the MLO office needs because it provided more space and a loading dock.

FACILITIES

2004

- February: Deconstructed DOE tower.
- November: NRL set up new webcam at their site.

2005

- 3 March: Installed lighting detector system at observatory.
- 3 March: Set up power logger in computer room to monitor power at observatory.
- May: Constructed (AMiba) facility.
- August: Set up surveillance computer in Hilo.
- September: Set up mountain surveillance system at observatory. This system uses the existing web cameras, recording images whenever movement is detected.
- 12 October: Switched telephone network from Verizon to Hawaiian Telcom for Hilo office. Reassigned all new IP addresses.

2006

- 10 January: Took all computers off line for the office move from the Federal Building to the new

Kilauea Financial Plaza on Kilauea Avenue. Royal Hawaiian Movers moved office goods 11–13 January. The elevator in the Federal Building broke during the move, delaying the move of shop equipment and the large UPS. Didn't connect telephone service to the new office space until 20 January.

- 14 February: Brought new Hilo office internet back on line after one month without service from Verizon and Hawaiian Telcom. Verizon failed to inform staff that the modem from the old office would not work at the new office. The update package from Verizon contained all of the instructions and connectors, but Verizon failed to pack the modem. We received the modem one week later and the office was able to connect to the internet.
- 16 & 30 June: In anticipation of getting the observatory site to look its best for the upcoming 50th anniversary, the MLO staff dedicated two "workdays" at the site when we scraped, prepped, primed, and painted. Prepped, primed, and partial painting of the Keeling Building and resurfaced top of NDSC water tank with fiberglass, NDSC water tank stairs, and old lidar building stairs.
- 8 August: All shop equipment and materials moved to new office; completed move from the Federal Building.
- 10–24 August: A contractor from New Hampshire erected two 16' x 14' metal buildings, donated by Keck Observatories. Bob Uchida oversaw and inspected the project.
- 15 October: Earthquake shifted AEC building's platform top rail about six inches northward; entrance to platform chained.
- 16–20 October: Moved the balloon equipment to the new Hilo NWS facility. The new location, about 1 km east of the old facility, is closer to the "new" terminal. We installed a new antenna and preamp about three meters off the ground on a ten meter tower, and pulled cables to our desks in the new office building. MLO staff launched a first balloon from the new balloon inflation building on 26 October, using a hydrogen generator, superior to the old facility's used H_2 cylinders.

2007

- 10 February: C & I Janitorial ended their service to MLO due to staff retirement.
- 12 February: Paul Fukumura installed first of two 360° pan, tilt, and zoom cameras purchased by the Navy. The camera is on the NDSC deck.
- 5 March to 10 April: Continued road paving.
- 20 August: Army contractors relocated radio repeaters into the previously installed container that has limited access to MLO, Army, and Navy staff.
- 25–27 September: Yamada filled hole on side of MLO access road and repaired potholes.

2008

- 13 August: Filled potholes on MLO access road.
- 23–24 October: Completed chip and seal roadwork.
- 30 June: Ended custodial service with Arc of Hilo for Hilo office. Began search for new custodial contractors for Hilo and Mountain sites.

2009

- June: Anchored and cemented MLO Observatory sign bases and installed new sign.
- 1 September: Hawaiian Tel installed new microwave dish and equipment.
- 29 September: Vandals broke into the Hilo office. Day Lum Property Management Inc. replaced the glass.
- 3 November: Hawaiian Tel switched to new radio equipment.

- Worked on saddle road realignment.
- 29 December: Transferred the MLO website from Hilo to Boulder.

2010

- 13 April: Started MLO Sharepoint server.
- 12 May: Vandals broke into the MLO van.
- June: Replaced Dobson Dome floor tiles.
- 30 July: Lars Lisell of NREL performed a renewable energy site assessment for solar voltaic panels at Mauna Loa Observatory and published assessment report at the end of September.
- 7 December: Hawaiian Tel installed new fiber optic line to NCAR observatory.

2011

- 3 October: Army removed old radio equipment and antennae from AEC and AEC deck.
- 1 December: Hawaiian Tel installed fiber optic lines at MLO mountain site.

2012

- 4 January: Increased MLO network to 5 Mbps.
- 21 May to 3 August: Paved road from four to six mi in from saddle road.

2013

- 1 July: Returned Optics Lab and Electronics Lab back to landlord vacating the space on 28 June.
- August: National Park Service painted white line on MLO access road for NOAA. This took several days throughout the month.
- October: Installed GPS time servers at the Hilo office and observatory sites for on-site time synching.
- October: U.S. Patent awarded to John Barnes for his Polar Nephelometer instrument, only one in NOAA this year.
- 23 November: Boy Scouts repaired potholes on the MLO access road.

COOPERATIVE PROJECTS

2003

- March: Stopped DOE high-volume and ion exchange.

2004

- 6 May: Installed EPA Spectrum Aethalometer.
- 10 November: Installed FSL's GPS-MET system at MLO site.

2005

- February: Rich Arimoto (New Mexico State University) installed a high-volume aerosol collector and trained Trevor Kaplan and Darryl Kuniyuki on its use. He was looking for Radionuclides from historical nuclear weapons tests.
- 9 May: Steve Howell, John Zhuang, and Bob Cary installed an Organic Carbon Elemental Carbon (OCEC) instrument, a laptop, and an aethelometer for lead investigator Barry Huebert (University of Hawaii, Manoa), housing them on a new stainless steel shelving system at the southwest corner of the Keeling Building.
- August: Prof. Bo Reipurth (University of Hawaii, Manoa) installed his 40-cm telescope for the Vari-

able Young Star Optical Survey (VYSOS) and measuring atmospheric extinction during the nighttime. The telescope and supporting equipment all fit in the Arizona dome. He removed a small extension that was built into the wall of the dome to install the telescope with no major problems.

- 12–21 September: Installed solar-powered Climate Reference Network instruments above and to the east of the NDSC building. These use a satellite link to transmit data.
- 4 November: Sent sensor head and circuit from the Multi-Filter Rotating Shadowband Radiometer (NASA Langley/CERES) back to Fred Denn.
- 1–9 December: Matt Landis (EPA) installed the ambient ion monitor instrument along with an ICS-2000. He performed maintenance and instructed Aidan on how to run the machine. Machine became operational at the end of December or early in January because some equipment and parts had to be sent from his lab. Matt Landis and Aidan Colton also built the decking at Hakalau Forest Reserve to support the precipitation collector that arrived from University of Michigan in 2006.
- December: Cleared Hg precipitation collector at Hakalau site and dug a trench with power lines to the instrument. We also built decking to support instrument. Instrument was still in Michigan at the time and there was no timeline for when it would be ready for sampling.

2006

- 7 February: On orders from Dave Moss, we turned off the old Applied Physics vacuum tube analyzer that had run at MLO since spring of 1958. Their Ultramat 6 analyzer, which had been running without problems for almost a year, continued the Scripps record with vastly improved data quality, much less maintenance, and much lower operating costs (reduced calibration gas consumption, reduced electrical consumption, without need for a temperature-stabilized cabinet environment, and fewer man hours).
- 20 February to 1 March: Dave Moss visited MLO, unhooked and removed the old CO_2 analyzer, and switched the system to exclusive use of the Ultramat 6.
- 23 February (week of): [MLO, Cape Kumukahi] - Normal operation. Ralph Keeling installed a new aspirated intake line at MLO.
- 26-28 September: Barry Huebert's group worked on the nitrate filter sampler and installation of a second elemental carbon sampler.
- October: Installed containers of purified water on the rooftop of the old lidar building for a University of Arizona program to measure cosmic ray flux (Chronus).
- October: Dedicated Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) Array for Microwave Background Anisotropy (AMibA) project and started operations.
- 10 November: Connected University of Hawaii aethalometer.
- Took last State University of New York (SUNY) Program sample that was discontinued due to lack of funds.

2007

- 12 February: Installed two chemical samplers for Environment Canada's Global Atmosphere Passive Sampling (GAPS) Network.
- 24 April: New Mexico Aerosol (Carlsbad Environmental Monitoring & Research Center-R. Arimoto) – Removed the final monthly filter, bringing this cooperative program to a close. The equipment remained at the MLO site until Rich Arimoto ordered it to be turned off and unplugged.
- 6 June: Sent sequential fine particle sampler (SFPS) back to EPA.
- August: Sent back ion chromatograph (IC) for EPA.

2008

- 9 January: Sent back divalent mercury instrument to EPA.
- 12 February: Started mercury precipitation collection at Hakalau site.

2009

- 5 March: Dave Moss finished modifying CO_2 tank system.
- March: Per instructions from the USEPA, discontinued EPA precipitation collector at Hakalau Rain Forest. We disassembled the collector, cleaned the site, turned off power, and informed the staff at the wildlife refuge.
- December: Shut down dichotomous partisol sampler and sent it back to EPA.

2010

- Shut down ground winds in 2010 due to lack of funds.
- 12 January: Began Pacific Tsunami Warning Center (PTWC) seismometer installation, which Roger Gernold completed between 15 and 18 June.
- January: Began recording WxCoder Max/Min Temperature & Rain (NOAA-NWS), the first year we recorded snowfall measurements at Mauna Loa Slope Observatory. MLO became the only NWS cooperative station in the state of Hawaii to report snowfall readings.
- 5–9 May: David Noone (University of Colorado) installed water isotope instrument.

2011

- 1 March: Shut down Organic Carbon/Elemental Carbon (University of Hawaii).
- 25 April to 27 May: Torbjorn Wiesel (Earthshine) installed and set up instrument.

2012

- 9 January: Began measuring ARL surface ozone and SO_2.
- 10 January: Began measuring ARL High-volume.
- 19 January: Ended EPA aethalometer project and returned instrument to EPA.
- 2012 March: Stopped measuring EPA surface ozone and changed instruments back to GMD protocols, ending EPA to GMD data conversion.
- April: Sent EPA SO_2 analyzer back to EPA.
- May 23: Started up NASA Sun photometer Si-Chee.
- June 18: Removed police repeater.
- November: Installed Earth Networks CO_2 system.

2013

- 9–16 January: George Janson (Colorado State University) installed additional equipment on the solar radiation deck.
- 12 March: Shut down University of California Davis IMPROVE sample.
- 7 August: Ended University of California Davis Drum filter program.
- 2 October: Began taking ATLAS (University of Hawaii IFA) measurements with simple camera in preparation for scientific equipment.

NDACC PROJECTS

2005

- 13 June: Paul Johnston installed upgraded BrO instrument.
- 5 August: Terminated M11 NO_2 instrument (back of Denver dome) and sent it back to NIWA.

2009

- 26 April: Installed new National Institute of Water and Atmospheric Research (NIWA) (NO_2/BrO) instrument called DAOS that measures both NO_2 and BrO.
- November: Changed FTS from University of Denver to NCAR.
-

SHORT-TERM PROJECTS

MLO hosts numerous short-duration solar radiation instrument calibrations each year. Partners that typically visit MLO each year include:

- NASA
- Environment Canada
- University of Maine
- Meteorological Research Institute, Japan
- Solar Light Company, Inc.

2005

- 20 July: The Army conducted a second test of the Enhanced Position Location Reporting System (EPLRS) checking three MLO instruments for noise before, during, and after the test. Two of the three chosen (CMDL lidar and the NIWA New Zealand Ultraviolet spectrometer) had interference problems in the past with radio repeaters. The third instrument (CMDL sun photometer) and its cables are exposed on the rooftop platform that would tend to make it more susceptible than instruments in the buildings. None of the instruments reported any unusual noise. The army will probably propose a permanent repeater for training at Pohakuloa Training Area.
- September: Virginia Garrison (USGS) visited the Hilo office. MLO staff had been taking samples for her coral reef project to support
her research into long-range transport of spores and pollutants.

2006

- 12 June: A group from the High Altitude Observatory (NCAR) installed some meteorological equipment, including sonic anemometers, to quantify the optical "seeing" of the daytime MLO sky on the tower. The project lasted about six weeks.
- 29 November to 12 December: Forrest Mims worked on the 50th anniversary book.

2008

- 7–11 April: Georgia Tech conducted an experiment on infrared detection of targets.
- April 18: Seismometer (USGS/NOAA) installed next to old seismometer.
- May 2: Paul Okubo (USGS Hawaiian Volcano Observatory) installed a seismometer to do tests with the NOAA Tsunami Center.
- 19–24 May: Nimmi Sharma, Central Connecticut State University (CCSU) visited to work on Clidar project.
- 25–26 May: Joe Shaw (Montana State University) tested an all-sky polarization camera.

- 18 September to 31 November: Tested Air Force project.
- 9 October to 6 November: University of New Mexico Joe Galewsky; Picarro Inc.; JPL; Los Gatos Inc.; and University of Colorado David Noone began the water vapor isotope measurement campaign and set up instruments in Network for Detection of Atmospheric Composition Change (NDACC) building in lidar control room.

2009

- 30 April to 28 May: Installed mercury isotope monitoring device for the Florida State University project, working with contacts, Professor A. Leroy Odom and Sulata Ghosh.
- 23 July to 8 August: Tested communications equipment for US Air Force (USAF) project (COMBAT) between Haleakala and MLO.

2010

- 10–23 February: USAF completed the COMBAT-2 project that tested laser communications between MLO and Haleakula.
- 8–14 July: Dr. Kaya (Kobe University) performed an experiment with microwave transmission to Haleakula.

2011

- 25– 29 April: Xianming Zhang (University of Toronto) installed filter devices around the island and at Kumukahi and MLO.
- 14 March to 26 April: Installed "new EPA aerosol sampler" at mountain site and shipped the filters to Bob Willis.

2012

- 26 August to 2 September: Bob Stone conducted the Lunar Photometery campaign.
- 30 October to 28 November: NASA Goddard implemented the first phase of lidar intercomparison.

2013

- 22–25 January: Ivan Dors (University of New Hampshire) evaluated equipment for restarting Groundwinds system.
- 11 February to 13 March: Winston Luke, Paul Kelly, Xinron Ren (ARL) installed second mercury analyzer at MLO and on Mauna Kea Smithsonian Institute observatory for a special study. They also installed a carbon monoxide analyzer at MLO.
- 28 January to 15 February: NASA Goddard started the second phase of lidar intercomparison.
- 15 & 26 February: Compared Global Hawk flight with water vapor balloon launches.
- 18–22 March: Restarted groundwinds project after a few years to repair the Doppler lidar.
- April to 31 July: Emily Wilson (NASA/Goddard) installed a temporary laser heterodyne and AERONET type CO_2 and Methane spectrometer.
- 27 April to 25 May: NASA began the third lidar intercomparison.
- 25 July to 8 August: NASA/Goddard with Jet Propulsion Laboratory (JPL) started the fourth lidar intercomparison campaign.

SPECIAL EVENTS

2005

- 10–11 January: A snowstorm closed the road. On 12 January, Steve Ryan and Bob Uchida reached

the station after a 50-min walk on the frozen road. All programs were operating normally except that the network and phone lines had gone down.

2006

- 2 June: MLO staff met with Forest Mimms, who was contracted to write a book on MLO's history for the upcoming 50th anniversary. He came to discuss the preliminary layout of the book.
- 28 June: MLO 50th anniversary. We held an informal video teleconference session between Boulder and the Hilo office. Pre-schoolers who came to visit the site sang songs for those in Boulder. We treated the children to various activities followed by a hot dog lunch. In the afternoon, MLO hosted an open house for everyone associated with observatory, and many previous MLO staffers came. We capped off the event with an informal barbeque dinner for the MLO staff and their families.
- 15 October: We experienced a magnitude 6.7 earthquake centered offshore to the northeast that caused no damage to the office or observatory, but power outages resulted in some damage to devices (UPS).

2007

- November: MLO exhibited a 50th anniversary display at the Wailoa Center. The event, open to the public, exhibited other displays that included the NOAA 200th Anniversary.
- 1–2 December: John Ogren held the Global Atmosphere Watch (GAW) aerosol conference at Hilo office. The group of 16 met in the eating/conference area. We provided a screen and projector and wireless internet access.
    - 3 December: Gave visiting group mountain tour.
    - 4–5 December: Met for the Aerosol Audit, and CO_2 conference in Kona. Four of MLO staff attended to assist with the conference and the rest of the staff continued with the disassembly of the Wailoa center and worked duties at the observatory. Darryl Kuniyuki assisted John Ogren for the duration of the conference, and David Nardini went up to the observatory on Saturday to assist with the tour from the CO_2 conference.

2008

- 10 March: Held a time capsule dedication at observatory site that concluded the MLO 50th anniversary events.

2013

- November: UH Press printed and released the MLO book by Forrest Mims in 2013.
- 18 December: Dr. Sullivan (Acting NOAA Administrator) visited to give all-hands meeting for Hilo offices.

OUTREACH

John Barnes generally leads weekly tours of MLO. On average, MLO receives about 300 visitors per year to the observatory site and occasional walk-ins at the Hilo office.

Visitors to the Mauna Loa Observatory:

2004

- Peter Michoud (Gemini Observatory) filmed the view towards Mauna Kea for the Hawaii Public Television station. He shot a high quality, 14-hour sequence of the inversion layer shown by the clouds. A copy is available on the Gemini web site.

Table 2-4: Mauna Loa Observatory Visitors, 2004-2013

Year	Total Number of Visitors
2004	350
2005	345
2006	264
2007	320
2008	456
2009	398
2010	238
2011	320
2012	322
2013	405

2005

- 22 April: MLO staff participated in the Earth Day Fair at the University of Hawaii campus.

2007

- 16 & 26 January: Two commercials were filmed on the access road. The filming company made donations to the road-patching fund.
- 5 March: Bill Wiecking, Hawaii Preparatory Academy (HPA), visited MLO with his class for the "Alaska Scientists of the Future" project. His students conducted interviews and gave a tour of the MLO facility to students in Alaska via videoconference.
- 20 April: Earth Day – Participated in Earth Day activities at Hawaii Community College.
- John and Darryl gave three local radio interviews about the 50th anniversary and the Wailoa display.
- 27 November to 1 December: Held the CO_2 conference in Kona.
- Participated in the MLO 50th/NOAA 200th exhibit at Wailoa Center.

2008

- 18 April: MLO participated in Earth Day Fair.
- 3 May: MLO participated in AstroDay Fair.

2009

- 24 April: MLO staff participated in the 2009 Earth Day Fair at the University of Hawaii campus.

2010

- 16 April: Participated in Earth Day at the University of Hawaii-Hilo Campus.
- 1 May: Participated in the AstroDay Fair.

2011

- 19 February: Participated in a science fair.
- 15 April: Participated in Earth Day Fair.
- 14 September: Al Gore's Foundation presented a webcast from MLO office: 24 hours of Reality.

2012

- 27 March: John Barnes gave a webcast talk on the Scientist-to-Scientist webcast.

- 20 April: Participated in Earth Day Fair.
- 5 June: Hosted Venus transit live webcast from observatory site with the Exploratorium.

2013

- 19 April: MLO participated in Earth Day Fair.

2.4 SOUTH POLE, ANTARCTICA

BACKGROUND

The South Pole Observatory (SPO) is located at the geographic South Pole on the Antarctic plateau at an elevation of 2837 m above sea level. The South Pole Station was established at the geographic South Pole in 1957 as part of the International Geophysical Year. The National Science Foundation provides the infrastructure for the GMD scientific operations including a state-of-the-art science building named the Atmospheric Research Observatory (ARO) and the Balloon Inflation Facility (BIF). The GMD observatory regularly sends staff members to spend one-year tours of duty at the station that includes a nine-month period of isolation and six months of darkness. The ARO facility is approximately 500 m east-northeast of the new, elevated station. This location is generally separated and upwind from station operations. There is a Clean Air Sector (CAS) defined as the area beyond the ARO facility from grid 340° to grid 110°. The prevailing winds at the South Pole are from the CAS nearly 90% of the time. The CAS preserves the unique atmospheric and terrestrial conditions from South Pole Station influences. Except for special circumstances, access to the CAS is prohibited. This includes foot and vehicle traffic. Aircraft activity is limited in the CAS, and guidelines for scientific or other activities are strict to ensure that the pristine nature of the CAS is meticulously preserved, not just for the current scientific activities, but also for future science conducted at the South Pole.

South Pole Station Modernization (SPSM) construction activities that began in 1999 continued in 2004 and beyond, completing a second berthing wing of the elevated station in 2005 and other outbuildings (cargo and logistics) as late as 2009. Two other large research projects were installed at the South Pole in the mid-2000s: the IceCube Solar Neutrino Observatory was built between 2004 and 2010, and the 10-m diameter South Pole Telescope was constructed during the austral summers 2005–2007. Peak construc-

Table 2-5: South Pole Observatory Staff, 2004-2013

Year	Station Chief	Electronics Technician
2003-2004	Jason Seifert, NOAA Corps	Glen Kinoshita
2004-2005	Dan Simon, NOAA Corps	Glen Kinoshita
2005-2006	Stephanie Koes, NOAA Corps	Johan Booth
2006-2007	Johan Booth	Emrys Hall
2007-2008	Amy Cox, NOAA Corps	Johan Booth Andy Clarke (Dec-Jan)
2008-2009	Marc Weekley	Patrick Cullis
2009-2010	Nick Morgan, NOAA Corps	Johan Booth
2010-2011	Christine Schultz, NOAA Corps	Johan Booth Andy Clarke (Nov-Jan)
2011-2012	*Heather Moe, NOAA Corps	Johan Booth Don Neff (Nov-Jan)
2012-2013	Kelli-Ann Bliss, NOAA Corps	Ross Burgener
2013-2014	Joseph Phillips, NOAA Corps	Johan Booth Lance Roth (Nov-Jan)

* NSF Winter Station Science Lead

tion activity at the South Pole can be measured in multiple ways with station population and fuel consumption as two of the easiest metrics to track. On both counts, the peak time period of activity at Pole occurred from mid 2005 through 2008.

During the summer of 2010, three explosions were triggered on 1, 4, and 7 December to collapse the original South Pole Station (used from 1957 to 1974). It was completely buried under almost 10 m of snow and had become a safety hazard. Unfortunately, all three explosions occurred during times in which winds were not coming from the CAS and contamination was visibly seen entering the sector and easily recorded (aerosol record) at ARO.

FACILITIES

2004

- November: Began renovation of lidar Room B to make room for an All-Sky Camera. Roof-mounted equipment cables now enter ARO through hole in Dobson room roof.
- December: Completed renovation of lidar Room B without noticeable effect on data.
- December: Replaced the "forked" cargo doors with new ones.

2005

- 28 January: Experienced unscheduled power outage that resulted in damage to specific instruments; downstairs UPS failed.
- 30 June: Wired downstairs UPS circuits into upstairs UPS to temporarily resolve failed downstairs UPS.
- 4 December: Upgraded upstairs UPS system with a new power module and batteries.
- 23 December: Reinstalled downstairs UPS.
- 8 August: Unscheduled power outage showed a failed downstairs UPS unit. Took unit off line.
- 20 November: Replaced batteries in upstairs UPS.

2008

- February: Installed new batteries on the downstairs UPS.
- 31 August: Balloon Inflation Facility furnaces failed. Ozonesonde solutions froze.
- 15 December: Installed met tower extension.

2009

- January: Installed NOAA firewalls at ARO; one active and one spare unit.
- September: Cycled ARO building heater into manual mode a couple times this month.

2010

- February: Replaced batteries in the upstairs UPS.

2011

- 5 September: Loose connection in second floor UPS bypass switch; arced and burned insulation.
- November: Removed dome and dome covers from roof for Sivjee project.
- December: Began to reposition Met department tower.

2012

- January: Completed repositioning of Met department tower.
- February: Repaired hatch for the Dobson zenith observations.
- February: Swapped out thermostat in the UV Monitor's penthouse heater after it got stuck in "on" and overheated the penthouse, roofbox, and monochromator.
- 14 July: Replaced faulty penthouse heater.
- December: Installed SuperDARN downwind of ARO.
- 4 December: Raised power on met tower so 2-m instruments could sit at 2-m without cord replacements.

2013

- 26 January: Restarted upstairs instruments because power was lost while electricians were working on the upstairs UPS.
- 8 February: Rerouted downstairs UPS to upstairs when it locked out (due to failed fans).
- March: Repaired heating system at ARO.
- May: Replaced thermostat and fan motor in the UV penthouse.
- July: Replaced thermostat in UV penthouse.
- 29 December: Installed new lidar tube on the roof of ARO. Old system still online for overlap period.

COOPERATIVE PROJECTS

2004

- October: Masataka Shiobara from the Japanese National Institute of Polar Research arrived to install a new computer for the Micropulse lidar system and to test the All-Sky Camera.

2005

- November: Martin Buhr arrived to install a new NO_{xy} system. Due to problems with similar equipment in McMurdo, he removed the system and transported it to McMurdo for use.
- 10 December: Andy Clarke arrived to install a new All-Sky Camera for a project with Masataka Shiobara.

2006

- 1 February: Martin Buhr arrived to install the NO_{xy} system.
- 1 February: Tony Hansen and Joseph Mastroianni arrived to upgrade the aethalometer.
- 15 November: Installed new aspirated inlet lines on the roof and ground for Scripps sampling.
- 24 November: Completed University of California Irvine flask sampling project.

2007

- 1 January: Discontinued New Mexico State University project.
- 23 January: Took NO_{xy} instrument off line and shipped it back to Colorado.

2008

- 10 February: Tom McElroy from Environment Canada installed a Brewer Ozone Spectrophotometer on the roof of ARO.

- Florida State University ran a short-term project measuring atmospheric mercury isotopes.

2012

- January: Installed 30-meter aspirated line on the tower for Scripps flask sampling.

2013

- 29 January: Tony Hansen arrived and installed a new aethalometer.
- 27 December: Sebastian Steward arrived and installed a new Micro Pulse lidar unit.

SPECIAL EVENTS

2006

- 7 January: Three Senators, ten Representatives, the Undersecretary of the Air Force, nine congressional aides, and a number of NSF representatives visited South Pole and were provided a tour of ARO.
- 29 January: New Elevated Station at South Pole became operational with conditional occupancy.
- 20 December: C-17 made its first airdrop since 1999.

2008

- 12 January: Under Secretary of Commerce for Oceans and Atmosphere, Admiral Lautenbacher attended South Pole Station dedication ceremony. He also toured ARO.

2010

- 1 December: Implosion of Old Pole. Old Pole was upwind of ARO during the blast.
- 4 December: Implosion of Old Pole. Old Pole was upwind of ARO during the blast.
- 7 December: Implosion of Old Pole. Old Pole was upwind of ARO during the blast.

2011

- 14 December: Prime Minister of Norway (among others) attended the100th year anniversary of the Amundsen expedition reaching South Pole.

2012

- 17 January: Marked the 100th year anniversary of the Scott expedition to South Pole.

2013

December 2013: Gave Prince Harry (England) and his Wounded Warrior group a presentation of ARO in the B2 science lab.

OUTREACH

2007

- December: GMD partnered with Elke Bergholz, NSF-funded teacher via the PolarTREC program, to sponsor her four-week visit to South Pole. Elke worked with Bryan Johnson on ozone research and conducted multiple live video casts from South Pole to school groups around the world as part of IPY.

2009

- November: LTJG Nick Morgan began a blog on daily life at South Pole in partnership with the Exploratorium (San Francisco).

2010

- October: LTJG Nick Morgan ended his South Pole blog with the Exploratorium.

2.5 SUMMIT, GREENLAND

BACKGROUND

NOAA added the Summit, Greenland Observatory (SUM) in 2005 to provide critical understanding of the Arctic and global climate change over the next several decades. As the only dedicated, staffed observatory operating year-round at high altitudes in the Arctic, Summit offers easy and immediate access to the free troposphere, is relatively free of local influences that could corrupt climatic records, traces averaged trends in the northern hemispheric troposphere, and captures rare phenomena that can represent climatic trends and help scientists understand the impacts of climate change.

The U.S. National Science Foundation (NSF) and the Danish Commission for Scientific Research in Greenland established the Greenland Environmental Observatory (GEOSummit) on the summit of the Greenland Ice Sheet (3200 m above sea level) to provide year-round, long-term measurements for monitoring and investigations of the Arctic environment. The multidisciplinary facility is home to several year-round

Table 2-6: Summit Observatory Staff, 2004-2013

Year and Phase	NOAA Technician	Polar Field Services Tehcnican
2007-2008 Winter I	None	Howie Tobin
		Kathy Kaldor
2007-2008 Winter II	Lana Cohen	Karen Malesky
2007-2008 Winter III	Patrick Cullis	Kat Huybers
2008 Summer	None	Steve Munsell
2008-2009 Winter I	Andy Clarke	Katie Koster
2008-2009 Winter II	Kat Huybers	Lara Koenig (NASA)
2008-2009 Winter III	Amy Cox, NOAA Corps	Kat Huybers
2009 Summer	Lana Cohen	Steve Munsell
		Kat Huybers
2009-2010 Winter I	Johan Booth	Katie Koster
2009-2010 Winter II	Katie Koster	Glenn Grant
2009-2010 Winter III	Sonja Wolter	Christina Hammock
2010 Summer	Lana Cohen	Elizabeth Morton
	Andy Clarke	
2010-2011 Winter I	Adam Maerz	Katrine Gorham
2010-2011 Winter II	Ben Gross	Shannon Coykendall
2010-2011 Winter III	Adam Maerz	Patricia Sanders
2011 Summer	Lance Roth	Marie McLane
2011-2012 Winter I	Sonja Wolter	Christina Hammock
2011-2012 Winter II	Shannon Coykendall	Lance Roth
2011-2012 Winter III	Christine Schultz, NOAA Corps	Adam Maerz
2012 Summer	Andy Clarke	Elizabeth Morton
2012-2013 Winter I	Lance Roth	Jennie Mowatt
2012-2013 Winter II	Brian "Rex" Nelson	Neal Scheibe
2013 Phase-I	Heather Moe, NOAA Corps	Ward Handley
2013 Phase-II	David Benson	Shawntel Stapleton
2013 Phase-III	Brandon Strellis	Jennie Mowatt
		John Lyons

Phase I : Spring, January - June
Phase II: Autumn, June - October
Phase III: Winter, October - February

investigations as well as numerous seasonal campaigns that take advantage of the unique location of the observatory. GEOSummit provides investigators ease of access to the highest site north of the Arctic Circle. Since 1989, when the GISP II ice-coring activities began, the site has hosted numerous atmospheric and glaciological investigations. Following two trial winter-over periods (1997–1998, and 2000–2002), the NSF Long-Term Observatory (LTO) program committed funding to maintain year-round measurements of key baseline variables of climate change at the site. CH_2M HILL Polar Services provides logistical support at Summit, under contract to NSF. NOAA measurements began in the mid-1990s, mainly to conduct greenhouse gas measurements, with NOAA and NSF technicians working together to ensure continuity of data. From 2005 to present, NOAA has provided staff to serve as technicians during various phases throughout the year. Beginning in August of 2009, NOAA staff became a year-round permanent addition to the station crew, ensuring the long-term continuity of NOAA data and providing additional scientific support for the site.

FACILITIES

2005

- GMD installed first instruments at SUM for year-round data collection (meteorology, surface ozone, CCGG flasks, and HATS flask) in the science trench. The trench was an unheated snow cave located ~20 ft below the surface.

2007

- June: The Temporary Atmospheric Watch Observatory (TAWO) was built to provide a warm facility for year-round science. NOAA moved instruments from the trench into the TAWO and additionally installed a four-channel GC for the HATS group.

2008

- Summer: Created Clean Air Sector and Management Plan for clean air and equipment operations.

2010

- Moved building and tower to new location south of borehole and main camp activity.

2013

- 30 July: Raised building and inlets about 10 ft.

COOPERATIVE PROJECTS

2011

- Mike Bergin from Georgia Tech and GMD collaborated to install an aerosol suite at SUM. GMD provided instrumentation and Georgia Tech supplied technical support and data QA/QC. We planned from the beginning for the instruments to remain at SUM after the Bergin grant concluded.

SPECIAL EVENTS

OUTREACH

2011

- July: Brian Vasel worked with students at SUM as part of the NSF-sponsored Joint Science Education Program (JSEP) with students from the U.S., Denmark, and Greenland. Students assisted with a balloon flight and instrument checks at TAWO, and attended a presentation/discussion on climate science.

2.6 TRINIDAD HEAD, CALIFORNIA

BACKGROUND

The Trinidad Head Atmospheric Observatory (THD) is located on Trinidad Head near the town of Trinidad, Humboldt County, California (41° 3.238'N; 124° 9.064'W). The THD observatory consists of a 24 by 8 ft, wood-sided commercial trailer. The instrument trailer was placed in its current location in April 2002, coinciding with the ITCT-2K2 study. Initially two trailers were co-located at the site. However, we removed one of the trailers at the conclusion of the 2004 ITCT-2K2 study.

We had estimated the current trailer to be approximately ten years old when originally sited on Trinidad Head, therefore the structure is now approximately 20 years old. These types of wood-sided trailers were originally designed for a ten-year lifetime. The siding on the trailer is showing some signs of internal fungus growth, perhaps indicating possible structural failure in the future. The trailer is built on a steel C-channel chassis. Due to the highly corrosive environment, the chassis has experienced significant corrosion, however, with recent rust abatement measures, it appears that the rusting stopped.

The THD trailer is located on U.S. Coast Guard property with the solar array located on City of Trinidad property. There has been no change in ownership of these properties.

Table 2-7: Trinidad Head Observatory Staff, 2004-2013

Year	Station Chief
2004-2013	Michael Ives

FACILITIES

2004

- July: Removed second trailer from the site at the completion of the Cloud Indirect Effects Experiment (CIFEX).
- November: Trinidad Bay Construction performed maintenance work on the THD intake stack and tower, replacing and
  improving the attachment of the PVC stack to the tower.

2005

- January: Installed lidar skylight.
- June: 7.2-magnitude earthquake (6/15 at 02:50:53 UTC) recorded 160 km WNW of Eureka, CA (41.284°N, 125.983°W). No significant damage at THD station occurred.
- December: All systems went down due to three-day regional power outage resulting from the 2005 New Year's Eve wind event (31 December 2005 to 2 January 2006). Winds measured at 43 m/s on R/V Coral Sea. THD station sustained no damage.

2006

- January: Station experienced a two-day power outage.
- 26–28 December: Station experienced a three-day power outage.

2007

- October: Designed and installed window washer for Micro Pulse lidar (MPL).
- November: Installed and repolished MPL skylight window.

2008

- November: Applied for and received FAA LNO for MPL operation.

2009

- July: Removed and replaced the two entry doors on the trailer that had rusted through and replaced the thresholds to be properly designed for an out-swinging exterior door. We fabricated and installed small overhangs at each door to shunt the water away from the doorways.
- July: Installed a buried conduit between the trailer and the solar rack and rerouted electrical lines.
- October: Purchased Neighborhood Electric Vehicle (NEV) for use on Trinidad Head to commute between Humboldt State University (HSU) Marine Lab and observatory. Purchased mini-pickup truck with matching funds from NOAA Green Grant program.

2010

- February: Fabricated and installed new frustrum and rain cap for Aerosol intake stack. Installed new anemometer.

2011

- January: Trinidad Bay Construction repaired the gravel road leading to the observatory and installed drainage ditches. They completed the work in collaboration with Scripps AGAGE and the City of Trinidad.
- January: Trinidad Bay Construction built a new foundation pier system for the trailer and installed seismic tie-downs. They also removed visible chassis rust and applied a surface rust inhibitor.
- 2 March: Station experienced a one-day power outage.
- March: Regional tsunami warning issued due to Tōhoku earthquake of 2010.
- September: Original A/C fails and California Heating and Trinidad Bay Construction installed new Bard WA121 A/C with new electronic thermostat.

2012

- October: Vandals broke into the station, removing CIMEL photometer from protective box and destroying MPL window.
- 20–23 November: Station experienced four-day power outage.

2013

- April: Abandoned GOES satellite-based uploading and adopted new Internet CIMEL data uploading protocol.
- June: Rebuilt MPL window washer after original was vandalized.
- 25 September: Station experienced a one-day power outage.
- December: Betsy Andrews made her annual maintenance visit.

2014

- November: Bard WA121 A/C failed, affecting temperature sensitive instruments. California Heating replaced failed compressor under warranty.
- December: Set up VNC to Earth Network's Picarro CO_2/CH_4 instrument housed in the Keeling building.
- 11 December: Station experienced a one-day power outage.

COOPERATIVE PROJECTS

2004

- July to August: Actively participated in the Intercontinental Transport Experiment (INTEX) Ozone-

sonde Network Study (IONS 2004).

2005

- January: Installed Micro-pulse lidar (MPL) skylight on trailer roof.
- February: Installed NASA-GSFC AERONET CIMEL on solar rack.
- February-May: Scripps Institution of Oceanography deployed an automated Eco-Tech rain sample collector (model 200) to collect black carbon.
- May: Installed NASA-GSFC MPL.
- June: University of Wisconsin, Madison installed an outdoor filter sampler to measure aerosol mass, inorganics, and OC/EC as part of the Atmospheric Brown Cloud project.

2006

- June: Ended NOAA-Pacific Marine Environmental Laboratory particulate filter sampling.
- March to September: Actively participated in the Intercontinental Transport Experiment (INTEX) Ozonesonde Network Study (IONS 2006).

2008

- Florida State University ran a short-term project measuring atmospheric mercury isotopes.
- Continued sampling for University of Wisconsin, Madison Atmospheric Brown Cloud study.
- April: Installed CCGG Airkit on R/V Coral Sea for shipboard sampling and trained technicians.

2009

- October: Ended sampling for University of Wisconsin, Madison Atmospheric Brown Cloud study.
- November: NYU School of Medicine ran a one-month study of coarse atmospheric particulates.

2010

- May to June: Launched ozonesondes six times per week in support of the IONS 2010 (CALNEX) study.

OUTREACH

2006, 2009, 2010, 2011, 2013, 2014

- Provided tours and lecture to local high school advanced placement science class.

2013

- August: California Air Resources Board conducted an interview with us for online video presentation.

2.7 METEOROLOGY PROGRAM

INTRODUCTION

The climatology of surface weather observations at the baseline stations is based on hourly average measurements of the wind direction and speed, atmospheric pressure, air and dewpoint temperatures, and the precipitation amounts. As of 1 January 2004, the meteorological data acquisition system collected

data using a rack-mounted computer and RS-485 serial communications to sample all deployed sensors via Keithley MetraByte communication modules . The data acquisition system is described in detail in previous reports and publications. The Tables 2-8 and 2-9 describe the sensor deployment since 1 January 2004. We decommissioned all mercury barometers due to the hazardous nature of mercury.

Table 2-8: Meteorological Instrumentation and Height by Station. See Table 2.9 for abbreviations

BRW	GPS	2M Wind	10M Wind	20M Wind	Bar Press1	Bar Press2	TSL	VaAT	VaRH	RTD2	RTD10	RTD20	Precip1	Precip2	Hg barometer
Heights (M)			**10.5**		**9.5**		**2.9**			**2.4**		**15.7**			
Jan-04			A1		P2		DP1			T2		T2		PRE	P3
Jun-05			A1		P2		DP1			T2		T2			
Aug-07	GPS		A1		P2		DP1			T2		T2			
Jun-09	GPS		A1		P2	P2	DP1			T2		T2			
Apr-13	GPS		A1		P2					T2		T2			

SUM	GPS	2M Wind	10M Wind	20M Wind	Bar Press1	Bar Press2	TSL	VaAT	VaRH	RTD2	RTD10	RTD20	Precip1	Precip2	Hg barometer
Heights (M)			**8**					**2**	**2**		**7.5**				
Aug-05			A1					TRH1	TRH1		T1				P3
Heights (M)			**10**	**15**					**2**	**2**	**10**	**16**			
Aug-08	GPS		A1		P1	P2		TRH1	TRH1	T2	T1				
Sep-13	GPS		A1	A1	P1	P2		TRH1	TRH1	T2	T1				

THD	GPS	2M Wind	10M Wind	20M Wind	Bar Press1	Bar Press2	TSL	VaAT	VaRH	RTD2	RTD10	RTD20	Precip1	Precip2	Hg barometer
Heights (M)			**10**					**2**	**2**	**2**	**10**				
Jan-07			A1		P1	P2		TRH2	TRH2		T3				
Sep-07	GPS		A1		P2	P1		TRH2	TRH2	T2	T3				
Jan-09	GPS		A1		P2	P1		TRH2	TRH2	T2	T3				
Aug-13	GPS		A1		P2	P1		TRH2	TRH2	T2	T2				
13-Dec	GPS		A1		P2	P1		TRH2	TRH2	T2	T2				

MLO	GPS	2M Wind	10M Wind	20M Wind	Bar Press1	Bar Press2	TSL	VaAT	VaRH	RTD2	RTD10	RTD20	Precip1	Precip2	Hg barometer
Heights (M)			**10**	**38.5**						**2**	**10**	**38.5**			
Jan-04			A1	A1	P2		DP1			T2	T2	T2	PRE		P3
Feb-07	GPS		A1	A1	P2		DP1			T2	T2	T2	PRE		
Jul-13	GPS		A1	A1	P2				RH1	T2	T2	T2	PRE		

SMO	GPS	2M Wind	10M Wind	20M Wind	Bar Press1	Bar Press2	TSL	VaAT	VaRH	RTD2	RTD10	RTD20	Precip1	Precip2	Hg barometer
Heights (M)				**22.9**						**1.4**		**22.9**			
Jan-04				A1	P1		DP1					A1			P3
Mar-07	GPS			A1	P1		DP1					A1			
Mar-09	GPS			A1	P1				RH1			A1			
Sep-13	GPS			A1	P1				RH2			A1			

SPO	GPS	2M Wind	10M Wind	20M Wind	Bar Press1	Bar Press2	TSL	VaAT	VaRH	RTD2	RTD10	RTD20	Precip1	Precip2	Hg barometer
Heights (M)			**10.3**	**21.9**			**1.8**			**2.1**	**13**	**21.9**			
Jan-04		A1	A1	A1	P1		DP1			T2	T2	T2			P3
Nov-07	GPS	A1	A1	A1	P1		DP1			T2	T2	T2			
Jan-09	GPS	A1	A1	A1	P1		DP1			T2	T2	T2			
Aug-10	GPS	A1	A1	A1	P1		DP1			T2	T2	T2			
Dec-13	GPS	A1	A1	A1	P1		DP1			T2	T2	T2			

DATA ACQUISITION UPGRADES

Starting in 2007, we deployed a new data acquisition system to the stations employing a Coastal Environmental Systems, Zeno-3200. The Zeno-3200 is a 32-bit data acquisition system designed to collect, process, store, and transmit data from multiple sensors. Table 2-10 shows the meteorology data acquisitions system upgrade time-line and configuration. The data are transmitted via RS-232 communications to a remote computer, which collects the real-time data and transmits it to Boulder for processing. Because of the expanded capabilities of the Zeno-3200, additional sensors could be added to each instrument suite. The existing meteorological instrument suite was kept and adapted to work with the Zeno-3200 at the original Baseline Observatories. We installed the Zeno datalogger at BRW in August 2007, MLO in February 2007, Samoa in March 2007, and South Pole in December 2007. We installed the Zeno-3200 at SUM in August 2005 and THD in February 2007 with different instrument suites.

Table 2-9: Meteorological Instrument Abbreviations

Designator	Instrument	Manufacturer	Model
P1	Pressure Sensor	Honeywell International, inc., Plymouth, MN	PPT
P2	Pressure Sensor	Setra Systems inc, Acton, Massachusetts	270
P3	Pressure Sensor	NWS Standard	Mercurial Barometer
A1	Anenometer	R.M. Young Company, Traverse City, Michigan	5103
T1	Temperature	Vaisala	HMP45A
T2	Temperature	Logan Enterprises, inc., Liberty, Ohio	4150 series
T3	Temperature	R.M. Young Company, Traverse City, Michigan	41342
RH1	Relative Humidity	Vaisala	HMT337
RH2	Relative Humidity	Vaisala	HMP60
RH3	Relative Humidity	Vaisala	HMP155
DP1	Dew Point	Technical Services Laboratory, Fort Walton Beach, FL	1088-400
TRH1	Temp/RH	Vaisala	HMP45DU
TRH2	Temp/RH	R.M. Young Company, Traverse City, Michigan	41382
PRE	Precipitation	NWS Standard	Tipping Bucket
GPS	GPS Sensor	Trimble Navigation Limited, Sunnyvale, CA	Lassen iQ GPS Module

- ***Barrow, Alaska***

We decommissioned the precipitation gauge at Barrow in 2005 and in August 2007 converted the instrument suite over to the Zeno-3200. We added a second Setra 270 pressure sensor in June 2009. It was removed in January 2013. We added a cooperative project's temperature data to the meteorological data stream from September 2011 until October 2014.

- ***Mauna Loa, Hawaii***

Mauna Loa was the first Baseline Observatory converted over to the Zeno-3200 in February 2007. At the time of the conversion, we moved the station pressure sensor from the Keeling building to the base of the tower where the Zeno-3200 was located. We decommissioned the Technical Services Laboratory Hygrothermometer model 1088-400 in June 2013 and replaced it with a Vaisala HMP 60 temperature/ dewpoint probe.

Table 2-10: Meteorology data acquisition system upgrade timeline and configuration.

Station	MetraByte System	Zeno 3200	Zeno Configuration
Barrow	1993-2007	Aug 2007 - present	Baseline Station
Summit		Aug 2005 - Jun 2008	Coastal Environmental Standard
		Jun 2008 - present	Baseline Station
Trinidad Head		Jan 2007 - Sep 2007	Coastal Environmental Standard
		Sep 2007 - present	Baseline Station
Mauna Loa	1993-2007	Feb 2007 - present	Baseline Station
American Samoa	1993-2007	Mar 2007 - present	Baseline Station
South Pole	1993-2007	Nov 2007 - present	Baseline Station

- ***Pago Pago, American Samoa***

Samoa was the second Baseline Observatory converted to the Zeno-3200 in March 2007. The installation was slightly different due to the high humidity of the station. The Technical Services Laboratory Hygrothermometer failed in March 2009 and we replaced it with a Vaisala HMP337 dewpoint temperature probe. The HMP337 failed in late August 2013 and we replaced it with a Vaisala HMP 60.

- ***South Pole, Antarctica***

We updated the South Pole data acquisition system during the Austral summer 2007–2008. The Technical Services Laboratory Hygrothermometer failed in February 2013. We planned to replace the failed instrument with one rebuilt from existing parts of previously decommissioned hygrothermometers and install it in early 2014.

ADDITIONS TO NETWORK

- ***Summit, Greenland***

Summit, Greenland was added to the meteorological network in August 2005. Summit was the first station to exclusively utilize the Zeno-3200. We originally ordered this station with minimal sensors, namely two temperature and humidity sensors, a wind sensor, and a pressure sensor. In 2007, we upgraded this system to a Baseline Observatory-configured Zeno-3200, along with a second wind sensor and pressure sensor. We originally installed the Zeno-3200 and a Honeywell pressure transducer in a snow cave at six meters below the snow surface. In the summer of 2007, the meteorological instruments moved to a new tower adjacent to the Temporary Atmospheric Watch Observatory (TAWO) and we relocated the Zeno-3200 and Honeywell pressure transducer indoors (~3 m above the snow surface).

- ***Trinidad Head, California***

We added Trinidad Head to the meteorological network in February 2007, ordering the system with a minimal sensor suite, namely one pressure sensor, one wind sensor, one temperature/relative humidity sensor, and one temperature sensor. We upgraded the system in September 2007 to a Baseline Observatory configuration and added sensors. During the September 2007 upgrade, we moved the 2-meter sensors away from the building to provide better measurements.

SECTION 3 – AEROSOLS (AERO) RESEARCH GROUP

RESEARCH OVERVIEW

NOAA began making long-term measurements of surface aerosol properties at the four Baseline Observatories in the mid-1970s. Since that time, scientific understanding of atmospheric aerosols has improved significantly. Aerosol particles were found to have an influence on the radiation balance of the Earth, and substantial, albeit uncertain, effects on climate were proposed. Atmospheric lifetimes of aerosol particles are relatively short (on the order of days to weeks) and particle sources are many and varied, leading to considerable inhomogeneity in aerosol distributions around the world. Human activities were found to influence aerosols on regional-to-continental scales more so than on global scales, so fundamental changes were required in NOAA's monitoring strategies if we were to determine anthropogenic effects. In the early 1990s, NOAA came to the realization that the network of baseline stations was inadequate for characterizing the diverse nature of aerosols around the globe. This led to a significant expansion of the aerosol monitoring network with a focus on regional-scale monitoring.

The GMD Aerosols Program evolved out of the Baseline Aerosols Program, with an added emphasis on regional aerosol monitoring stations where measurements had the potential to detect human influences on aerosol properties. Primary goals of the GMD Aerosols Program are to characterize the means, variability, and trends of climate-forcing properties of different types of aerosols, and to understand the factors that control these properties. To accomplish these goals, the GMD Aerosols Group makes collaborative measurements of aerosol properties at stations around the world. It focuses principally on the measurement of aerosol optical (i.e., light scattering and absorption) properties, which are required to calculate the direct aerosol radiative forcing. Additional measurements, including aerosol chemical, microphysical, and hygroscopic property measurements, are made at some of these sites to better understand the optical properties and their radiative effects. We provide a more detailed discussion of the scientific background for GMD aerosol measurements and the methods used at: http://www.esrl.noaa.gov/gmd/aero/science/index.html.

This report documents changes in inlet systems, operations, instruments, and the local station environment that could be useful in interpreting the long-term aerosol data record. We note dates when these changes occurred, so changes in the aerosol record at these times can be better understood.

3.1 FEDERATED AEROSOL NETWORK

THE EARLY NETWORK (1974–2003)

Aerosol measurements at the four original NOAA Baseline Observatories all began in the mid-1970s. When the focus of the Aerosols Program changed in the early 1990s, we clearly saw that more monitoring stations in different parts of the world were necessary. We questioned how to accomplish this network expansion without a significant increase in operating budget.

The solution to this problem was to organize a federated network of scientific collaborators to operate regional aerosol monitoring stations using the same methods as the NOAA stations. The GMD Aerosols Program attempted to find partners with scientific interest in long-term aerosol measurements (e.g., university researchers, other U.S. government agencies, scientific organizations in other countries, etc.) with the capabilities and budgets to operate atmospheric monitoring stations over the long term. Our strategy was to provide partners with the tools necessary to conduct aerosol measurements to the quality standards required by NOAA and GAW operations protocols. These tools include proven designs for aerosol sampling infrastructure (e.g., inlets and sample conditioning, housekeeping data sensors, calibration methodology); a documented set of standardized operating procedures; a GMD-developed and -supported data acquisition, visualization, editing, and archiving software platform; and ongoing training and support in all aspects of station operation.

The benefit of this approach to NOAA is large. NOAA receives access to the data from collaborator stations, yet does not support the major long-term costs of the stations. These major costs include the purchase and maintenance of the key instrument systems, salaries for station personnel, long-term station operation costs (site, power, internet, etc.), and the time and effort required for data quality checking and editing. The result of this collaborative approach is a long-term, cooperative program

with shared data access, making atmospheric measurements that are directly comparable with the other stations in the network and following established aerosol sampling protocols (i.e., NOAA and GAW).

Table 3-1 shows the Federated Network stations at the beginning of 2004 listed chronologically by the start date of the aerosol measurements. The NOAA Atmospheric Baseline Observatories are the first four entries in the table. In the early-to-mid 1990s, several additional stations were added to the network. Sable Island, Nova Scotia (WSA), was the first Aerosol Program collaboration with Environment Canada, and this station operated successfully for about eight years. NOAA made aerosol measurements at the mountain site on Niwot Ridge, Colorado (NWR) for a couple of years, but abandoned that effort because of the strong influence of pollution reaching the site from metropolitan Denver. The Bondville, Illinois (BND) and Southern Great Plains (SGP) stations were started as collaborations where measurements continue to this day, although the BND regional aerosol monitoring station is now fully funded and operated solely by NOAA. In 2002, the fifth NOAA Atmospheric Baseline Observatory at Trinidad Head, California (THD) began operations.

addition of regional aerosol monitoring stations. The sizeable growth beginning in 2004 was largely through partnerships with scientific organizations and universities around the world.

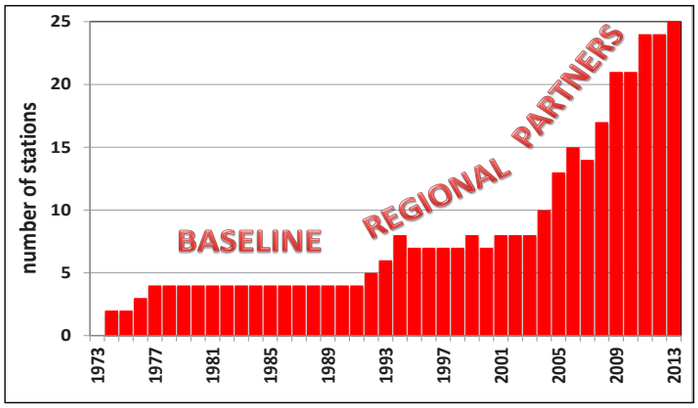


Fig. 3-1: Number of stations by year in the NOAA Global Federated Aerosol Network.

The added monitoring stations greatly improve NOAA's ability to determine aerosol radiative forcing and its effects on regional and global climate. Table 3-2 shows the stations joining the Federated Network during this last decade. Of these 25 sites, 17 are considered long-term monitoring stations and are in operation today. The remaining eight stations are temporary deployments of the U.S.

Table 3-1: Federated Network stations at the beginning of 2004.

Station ID	Station Name	Country	Start Date	End Date
MLO	Mauna Loa	USA	January 1974	Present
SPO	South Pole	Antarctica	February 1974	Present
BRW	Point Barrow	USA	May 1976	Present
SMO	Cape Matatula	American Samoa	July 1977	Present
WSA	Sable Island	Canada	August 1992	May 2000
NWR	Niwot Ridge	USA	October 1993	December 1995
BND	Bondville	USA	July 1994	Present
SGP	Southern Great Plains	USA	July 1996	Present
THD	Trinidad Head	USA	April 2002	Present

NETWORK EXPANSION OVER THE LAST DECADE (2004–2013)

The period 2004–2013 has seen an unprecedented expansion of the NOAA Global Federated Aerosol Network. Figure 3-1 shows the number of stations in the network by year through the end of 2013. Up through the early 1990s, the only stations in the network were the four Baseline Observatories. The period from the early 1990s to the early 2000s saw moderate network growth primarily through the Department of Energy's Atmospheric Radiation Measurement (ARM) Mobile Facility (AMF), which moves around to sample different aerosols and source regions for periods between about 6 to 12 months. The most recent deployment of the AMF began measurements in December 2013 in Brazil. Figure 3-2 shows a map of the GMD Global Federated Aerosol Network as it appeared in December 2013. More information on all of these sites is available at http://www.esrl.noaa.gov/gmd/aero/net/index.html.

Table 3-2: Stations joining the Federated Network during the decade 2004-2013.

Station ID	Station Name	Country	Start Date
ALT	Alert	Canada	March 2004
CPR	Cape San Juan	Puerto Rico	November 2004
PYE	Point Reyes (AMF)	USA	March 2005
WLG	Waliguan	China	August 2005
CPT	Cape Point	South Africa	November 2005
NIM	Niamey (AMF)	Niger	December 2005
KPS	K'puszta	Hungary	May 2006
FKB	Hesselbach (AMF)	Germany	March 2007
ETL	East Trout Lake	Canada	September 2008
WHI	Whistler	Canada	September 2008
LLN	Lulin	Taiwan	October 2008
ARN	El Arenosillo	Spain	February 2009
HFE	Shouxian (AMF)	China	May 2009
APP	Appalachian State Univ.	USA	June 2009
BEO	Moussala	Bulgaria	October 2009
EGB	Egbert	Canada	November 2009
AMY	Anmyeon-do	Korea	December 2009
GRW	Graciosa (AMF)	Azores	May 2010
SPL	Storm Peak	USA	January 2011
SUM	Summit	Greenland	May 2011
PGH	Nainital (AMF)	India	June 2011
GSN	Gosan	Korea	October 2011
PVC	Cape Cod (AMF)	USA	July 2012
RSL	Resolute	Canada	May 2013
MAN	Manacapuro (AMF)	Brazil	December 2013

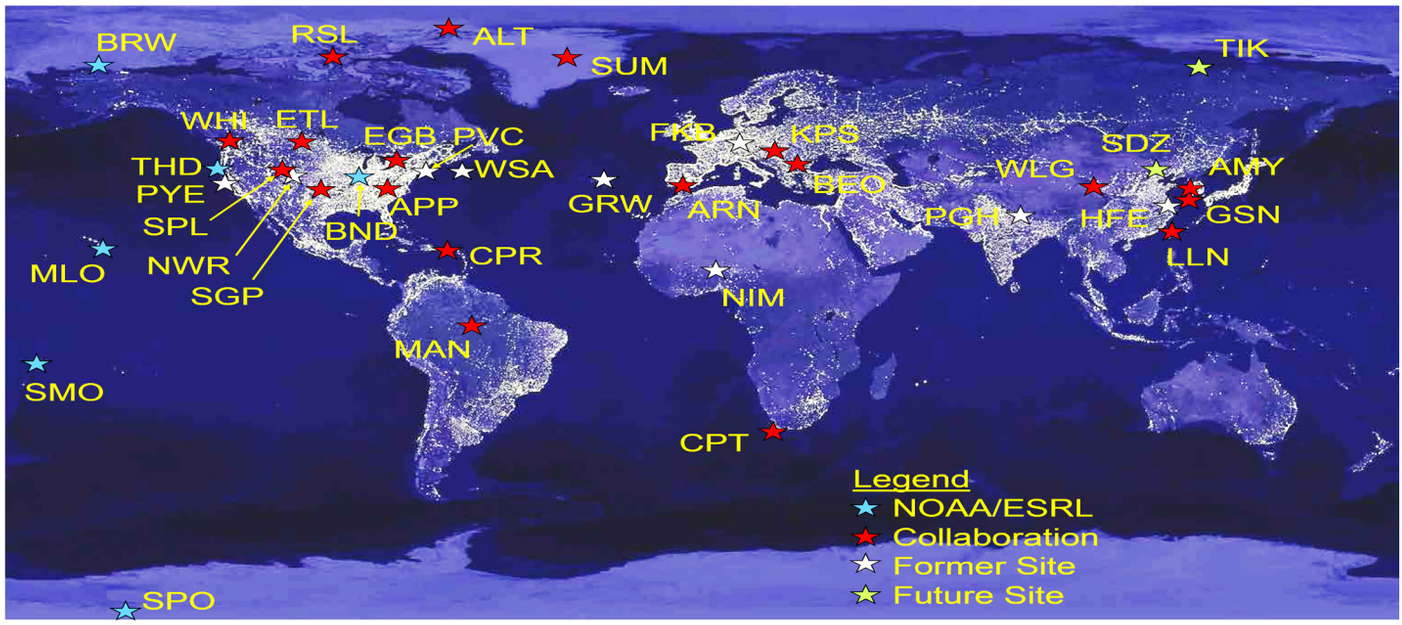


Fig. 3-2: The NOAA/ESRL GMD Global Federated Aerosol Network in December 2013.

MEASUREMENTS

As shown in Figure 3-2, the NOAA/ESRL Federated Aerosol Network had a total of 25 surface aerosol monitoring stations in operation at the end of 2013. Of these stations, six were operated fully by NOAA (blue stars) and 19 by collaborators with NOAA support (red stars). Of the six NOAA stations, five are Atmospheric Baseline Observatories and one (BND) is a station whose aerosol measurements are fully funded and operated by NOAA. The sixth NOAA Baseline Observatory, at Summit, Greenland (SUM), has aerosol measurements currently (in December 2013) taking place through collaboration with a U.S. university (Georgia Institute of Technology). Since they have the primary responsibility for operations, data collection, data quality control, etc., they have been listed in this report as a Collaborator Station.

In the following sections of this report, we discuss specific changes in aerosol operations over the last decade at the NOAA-controlled stations. The discussion is limited to the NOAA stations because those are the stations where NOAA maintains full control over all aspects of station operations, and detailed historical records of operations at these stations are available to us. Since the data from our Collaborator Stations are the property of our collaborators, they report the operational changes. For information on operational changes at Collaborator Stations, it is best to contact the collaborating Principal Investigator directly whose contact information is available on the Global Monitoring Division web page at http://www.esrl.noaa.gov/gmd/aero/net/index.html.

Aerosol measurements made at the six NOAA Federated Network stations and during the AAO aircraft project are listed in Table 3-3. Measure-

Table 3-3: Aerosol measurements made at the six NOAA Federated Network stations and during the AAO aircraft project.

Station ID	Aerosol Measurement	Start Date	End Date
MLO	Total particle number concentration	January 2004	December 2013
	Aerosol light scattering coefficient	January 2004	December 2013
	Aerosol hemispheric backscattering coefficient	January 2004	December 2013
	Aerosol light absorption coefficient	January 2004	December 2013
SPO	Total particle number concentration	January 2004	December 2013
	Aerosol light scattering coefficient	January 2004	December 2013
	Aerosol hemispheric backscattering coefficient	January 2004	December 2013
BRW	Total particle number concentration	January 2004	December 2013
	Aerosol light scattering coefficient	January 2004	December 2013
	Aerosol hemispheric backscattering coefficient	January 2004	December 2013
	Aerosol light absorption coefficient	January 2004	December 2013
	Aerosol size distribution	August 2006	December 2013
	Humidified aerosol light scattering coefficient	August 2006	October 2013
	Humidified aerosol hemispheric backscattering coefficient	August 2006	October 2013
	Cloud condensation nucleus number concentration	August 2006	December 2013
SMO	Total particle number concentration	January 2004	December 2013
BND	Total particle number concentration	January 2004	December 2013
	Aerosol light scattering coefficient	January 2004	December 2013
	Aerosol hemispheric backscattering coefficient	January 2004	December 2013
	Aerosol light absorption coefficient	January 2004	December 2013
THD	Total particle number concentration	January 2004	December 2013
	Aerosol light scattering coefficient	January 2004	December 2013
	Aerosol hemispheric backscattering coefficient	January 2004	December 2013
	Aerosol light absorption coefficient	January 2004	December 2013
	Humidified aerosol light scattering coefficient	January 2004	March 2006
	Humidified aerosol hemispheric backscattering coefficient	January 2004	March 2006
AAO	Total particle number concentration	June 2006	September 2009
	Aerosol light scattering coefficient	June 2006	September 2009
	Aerosol hemispheric backscattering coefficient	June 2006	September 2009
	Aerosol light absorption coefficient	June 2006	September 2009
	Aerosol size distribution	June 2006	September 2009
	Humidified aerosol light scattering coefficient	June 2006	September 2009

ments that spanned the entire decade show a start date of January 2004 and an end date of December 2013. This table shows the types of measurements that were made but provides few details; for specific information on these measurements and instruments (e.g., wavelengths, detection limits, particle sizes sampled and analyzed, etc.), see http://www.esrl.noaa.gov/gmd/aero/instrumentation/instrum.html.

AEROSOL INLET AND/OR SAMPLING CHANGES

The efficient sampling of aerosol particles through inlet systems relies on careful design to minimize particle losses in the lines. In all GMD aerosol systems, we perform calculations to match flow rates with appropriate tubing sizes to minimize losses to the extent possible. Over the years, we have made some changes to replace aging equipment, to accommodate additional system components, or to simply improve our sampling methods. Table 3-4 shows a comprehensive listing of all inlet and/or sampling changes at our NOAA stations over the last decade, and the effect(s) of the changes on the measurements. Most of the inlet and flow rate changes did not have obvious effects on the aerosol data based on comparison of pre- and post-change measurements. In most of the inlet changes, we did :not conduct parallel sampling through both inlet systems because removal of the old systems was required before the new inlets could be installed. An exception was at SPO where the addition of a single, higher-flow inlet line resulted in slightly higher particle concentrations being reported as compared with an identical particle counter on the old inlet line. For Particle Soot Absorption Photometer (PSAP) flow-rate changes that occurred after the installation of the new Continuous Light Absorption Photometer (CLAP) instruments, we were able to compare the pre- and post-change PSAP light absorption measurements with the CLAP data and determine that changes in flow rates over a fairly large range had little effect on the reported PSAP light absorption values. For details as to why specific changes were necessary or performed, contact the GMD Aerosols Group. Providing approx-

Table 3-4: Listing of all inlet and/or sampling changes at our NOAA stations over the last decade, and the effect(s) of these changes on the measurements.

Station ID	System Configuration Change	Date of Change	Effect of Change on Aerosol Measurements
MLO	Flow rate of light absorption instrument (PSAP) lowered to 1 lpm	1 November 2004	No obvious effect
	Flow rate of light absorption instrument (PSAP) lowered to 0.65 lpm	7 February 2012	No obvious effect
SPO	Added high-speed sampling line for CPC instruments	11 November 2007	Slight increase in CPC count rates
BRW	Installation of new instrument rack with different sample lines	12 August 2006	No obvious effect
SMO	Installation of new inlet system	10 February 2010	No obvious effect
BND	Installation of new instrument rack with different sample lines	19 November 2004	No obvious effect
	New stack rain cap	1 November 2008	No obvious effect
	Flow rate of light absorption instrument (PSAP) dropped tounacceptably low values	10 July 2006	Light absorption data are compromised and invalidated
	Flow rate of light absorption instrument (PSAP) increased to normal	27 October 2007	Data acceptable again
THD	Change impactor size cut and RH scan sequence for humidified nephelometer.	10 May 2004	No obvious effect
	Switch CPC inlet from high-speed line to pickoff of main aerosol line	17 February 2005	No obvious effect
	Installation of new instrument rack with different sample lines	14 October 2009	No obvious effect
	New stack rain cap	4 March 2010	No obvious effect
AAO	No configuration changes during the program		

imate dates with these system modifications should help users interpret any subtle step changes in the aerosol data, although we have evaluated the effect(s) of these changes and, if an obvious artifact was observed (e.g., from a flow rate that drifted low), data typically were invalidated during this period.

One of the major changes over time in our Network sampling methods was a downward adjustment of the flow rates of our PSAP light absorption instruments. The PSAPs were initially operated at clean sites at the highest flow rates achievable (> 2 standard liters per minute, slpm) because the aerosol light absorption coefficients there are typically so low, and this provides a stronger signal to the instrument. After discussions with colleagues on the possible effects of different flow rates on the comparability of Network light absorption data, we decided to lower the PSAP flows at clean sites to ~1 slpm to make them consistent with PSAPs measuring at other sites. PSAP flows were further lowered at some sites to a volumetric flow rate of 1 lpm (1 vlpm) to match the flow rate of the new CLAP instruments, which were deployed at sites in 2011–2013. This corresponds to a typical mass flow rate (standard conditions = 273.15 K and 1013.25 hPa) at MLO (elevation = 3397 m asl) of ~0.65 slpm. We have not observed any obvious effects of flow-rate changes of this magnitude, although temporary larger flow-rate reductions at some other stations have caused the light absorption data to become compromised and invalidated in the quality control editing process.

We made another system change; giving the condensation particle counters (CPCs) their own inlet lines at most stations rather than picking off the samples from the main inlet lines. Dedicated CPC inlet lines require higher flow rates than the nominal flow rates through the instruments because diffusional losses of very small particles in the lines could occur. Flows were increased to 5–6 lpm in ¼-inch outer diameter (OD) lines from the inlets to the instrument benches, and the CPC flows were taken from that excess flow. At one station (SMO), we use a larger, ½-inch OD inlet line so we sample at 15 lpm through that line and pick off the ~1 lpm CPC flow from that. At SPO, a high-speed inlet line was added in November 2007 to the existing low-speed line and we measured particle concentrations for an extended period of time (~13 months) using identical CPCs on both lines. An analysis of the data indicates that at times the CPC on the high-speed line reported slightly higher (by 5-10%) particle concentrations than the CPC on the low-speed line. We assume this was due to lower diffusional losses in this line. We do not perform particle size distribution measurements at SPO, so differences in diffusional losses are difficult to confirm. The particle concentrations at SPO are very low so concentration differences between the two counters are difficult to observe in any case, and probably fall within the overall uncertainty in the measurement. An exception to this dedicated CPC line strategy was at the THD station, where, due to the larger marine aerosol particles being sampled, the inlet line was switched to a pickoff from the main sampling line.

At THD, we modified the RH scan sequence for our hygroscopic growth measurements in May 2004. This involved changing the RH cycling for the humidified nephelometer and also the particle cut size switching. The original RH scan sequence provided for a gently increasing RH in the humidified nephelometer over the course of almost one hour before dropping back down to the low-RH start point again. We switched the system size cuts every six minutes over the hour. We employed this new strategy in May 2004 to maintain sampling on alternate particle size fractions for 30 minutes. During each 30 minute period, the RH in the humidified nephelometer was scanned alternately upward and then downward. This provided for an improved evaluation of particle size effects on the hygroscopic growth and also permitted the determination of any differences in the upward vs. downward RH scans.

We found that the original rain caps covering the top of many of the NOAA sampling stacks were not adequately waterproof. Their small size allowed rain to enter during windy, stormy conditions when the rain was not falling vertically. We replaced these with larger stainless steel pots that extend down the stack a few inches so water can only enter it if it travels up and over the top of the stack tube. These larger rain caps are clearly an improvement in keeping water out of the stack. Figures 3-3a and 3-3b show examples of both the old and new rain caps. We are uncertain to what extent the new rain caps affect the aerosol sampling, but the effect is thought to be minimal.

On 29 September 2009, a major earthquake and resulting tsunami hit American Samoa, and the NOAA Baseline Observatory (SMO) sustained some

Fig. 3-3a: (a) Old-design sampling stack rain cap.

Fig. 3-3b: (b) New-design sampling stack rain cap.

damage. We observed no significant data gap in the aerosol measurements, as the observatory building was one of the few that kept power. The old inlet system was damaged and leaning with one broken guy wire, but it was still functional. We took down the old inlet on 8 February 2010 and installed a new inlet system that became operational on 10 February 2010.

The new SMO aerosol inlet system is different from the old inlet system in several respects. The old inlet was a guyed, vertical stainless steel (SS) tube of ~4.1 cm internal diameter (ID). Replacing that design was deemed costly, difficult to maintain, and unnecessary, so we developed a new inlet design that uses a smaller diameter (~1.1 cm ID) SS tube that runs across from the roof of the Hudson Building to the large communications (Blue Sky) tower and then up to the approximate height of the old inlet. This new inlet has one roughly horizontal run and two gentle ~90-degree bends.

The passing efficiency for aerosol particles through a tube depends on many things, including their size, density, and the flow rate. For the calculations of particle passing efficiency, we assumed a particle density of 1.20 g cm-3 (appropriate for a H_2SO_4 and sea salt aerosol mixture at 80% RH). Figure 3-4 shows how the passing efficiency as a function of particle size compares between the old inlet, operated at its standard flow rate, and the new inlet, operated at different flow rates. Using these calculations, we decided to run the new inlet at a flow rate of ~15 lpm. The differences between old and new inlets for particles up to ~2 µm in diameter are very small. There are some significant losses

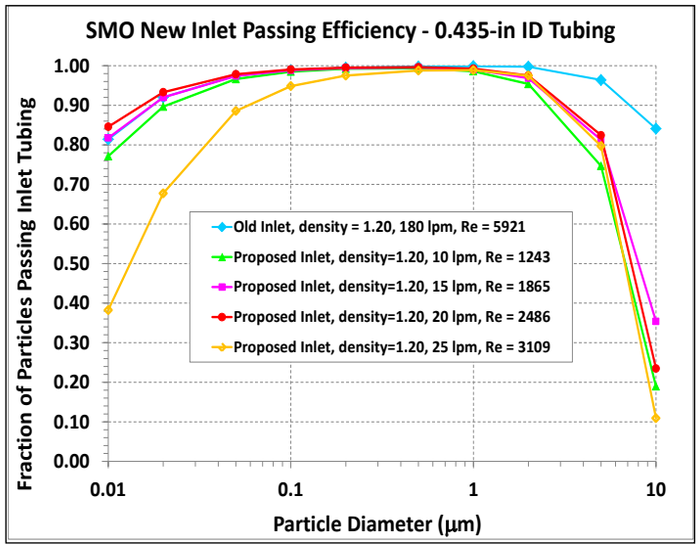


Fig. 3-4: Particle passing efficiency curves for the old SMO inlet compared with several flow rates through the new inlet.

for particles above ~5 µm in diameter, but particles in this size range are thought to make up a small fraction of the particles measured by the particle counter at SMO.

BEGINNING AND END OF SPECIFIC MEASUREMENTS

Table 3-5 shows when specific measurements were added or removed from the aerosol systems at the NOAA stations. This includes the addition or removal of an instrument from a specific measurement class (e.g., particle size distribution or humidified nephelometry), or the replacement of one instrument with another in the same class that had different operating specifications (e.g., a CPC

with a different lower size limit of detection). This table does not show the times for replacement of instruments with identical instruments, since both units should produce identical data if calibrated and working properly. This assumption was substantiated with side-by-side tests in the laboratory and, in some cases, in the field, with reference instruments.

The most common changes to the NOAA aerosol systems made over the last decade were 1) the replacement of single-wavelength PSAP instruments with three-wavelength models, 2) the addition of CLAP light absorption instruments, 3) the addition and removal of humidified nephelometry measurements, and 4) the addition of new condensation particle counters with a lower particle size limit

Table 3-5: Dates when specific measurements were added or removed from the aerosol systems at the NOAA stations.

Station ID	Instrument Change	Date of Change
MLO	Replace 1W-PSAP with 3W-PSAP	5 September 2006
	Installed CLAP	12 December 2011
	Installed MCPC	26 November 2012
	Removed 3W-PSAP	18 July 2013
SPO	Installed TSI Model 3760 CPC on high-speed inlet line	11 November 2007
	Installed WCPC on high-speed inlet line	11 November 2007
	Removed WCPC	19 December 2009
	Removed TSI Model 3760 CPC on low-speed inlet line	2 February 2009
	Installed WCPC on high-speed inlet line	26 January 2011
	Removed WCPC	18 January 2013
	Installed MCPC	22 January 2013
BRW	Replace 1W-PSAP with 3W-PSAP	12 August 2006
	Install SMPS	12 August 2006
	Install CCN	12 August 2006
	Installed humidified nephelometer	14 August 2006
	Remove TSI Model 3760 CPC	9 March 2007
	Installed TSI Model 3010 CPC	29 March 2007
	Installed CLAP	30 August 2011
	Removed humidified nephelometer	3 October 2013
SMO	TSI Model 3760 CPC replaces TSI Model 3010 CPC (temporary repair scenario)	19 March 2010
	TSI Model 3010 CPC replaces TSI Model 3760 CPC (original returned after repair)	23 December 2010
BND	Replace 1W-PSAP with 3W-PSAP	27 February 2006
	Installed CLAP	2 December 2010
	Removed 3W-PSAP	25 March 2012
	Installed MCPC	12 October 2012
THD	Replace 1W-PSAP with 3W-PSAP	5 October 2005
	Removed humidified nephelometer	30 March 2006
	Installed CLAP	25 November 2011
	Installed MCPC	7 December 2012
	Removed MCPC	30 August 2013
AAO	No instrument changes during the program	

of detection. In cases where an instrument was replaced with another instrument with different operating specifications, the measured parameter values will be affected because of the instrument. Typically when an instrument was replaced with another instrument with slightly different operating characteristics, the instruments were run in parallel for an extended period of time (often in excess of a year) so that any differences in the measurements are understood and documented. Most of the differences in instrument operating specifications are minor so we believe the effect on the measurements overall to be small.

The acronyms in Table 3-5 are as listed below.

- CPC – condensation particle counter
- MCPC – mixing condensation particle counter
- WCPC – water-based condensation particle counter
- 1W-PSAP – single wavelength Particle Soot Absorption Photometer
- 3W-PSAP – three wavelength Particle Soot Absorption Photometer
- CLAP – continuous light absorption photometer
- SMPS – scanning mobility particle spectrometer
- CCN – cloud condensation nucleus counter

Regarding instrument replacement differences, please note that the light absorption measurements are all made at slightly different wavelengths and then adjusted to common wavelengths. The uncertainty in the wavelength adjustment for each instrument may be slightly different depending on the wavelength range required for the adjustment. Another notable difference in aerosol instrument specifications that could affect the long-term data record is the lower size limit of detection for the particle counters. The TSI Model 3760 CPCs have a manufacturer-quoted 50% detection efficiency at a particle diameter of 14-nm, whereas the Thermo Systems, Incorporated (TSI) Model 3010 CPCs can detect particles at 50% efficiency down to 10 nm in diameter. The newer WCPC and the MCPCs are stated to measure particles down to 6 nm in diameter.

The upper-limit cutoffs for all of these instruments are all about 3 μm in diameter, so the upper limit of detection has little effect on any measurement differences between particle counters. During periods of high concentrations of very small particles, (e.g., new particle formation events), there could be large differences in the reported total particle concentration as a result of these lower detection limits. We observed that at most other times, the measurements from the different types of particle counters have been very close.

CHANGES IN DEFINITION OF CLEAN SECTOR FOR AEROSOL MEASUREMENTS

The four NOAA Baseline Observatories BRW, MLO, SMO, and SPO all have defined clean and contaminated sectors, which are used to discriminate when air is representative of background conditions or is contaminated by local sources (e.g., aerosol generated by the station, other local activities, a nearby town). The NOAA station at Bondville (BND) has no clean or contaminated sectors defined, as a wide variety of aerosol sources lie in all directions from the station. The NOAA THD Observatory was originally set up with defined clean and contaminated sectors; with clean broadly defined as air coming in off the open ocean and contaminated coming from the land and/or the town of Trinidad. Because of recirculation of air around the Head, however, contamination episodes were commonly observed coming in from the 'clean' sector. This caused difficulties in quality assurance procedures since questions would commonly arise as to whether a particular aerosol event should be considered contaminated. On 12 October 2003, the flagging of 'contaminated' sector data was discontinued. As at BND, there is a trailer at THD directly beneath the sampling stack that houses the aerosol system, so there is no obvious station-influenced wind direction to avoid. Similar to the BND data processing scheme, no THD aerosol data are marked now as contaminated, and data from all wind directions are considered potentially representative of mixed regional background aerosols.

At the beginning of 2004, the GMD aerosol systems at these stations all included dedicated aerosol wind vanes and anemometers. During the last decade, we decommissioned these redundant standalone wind systems, with the exception of the one at BND, to save resources (i.e., money) and labor (maintenance and calibrations). Since the BND station is not a NOAA Observatory, the GMD Ob-

servatory Group does not operate a meteorological system there so the Aerosol Group wind sensors were maintained. The GMD Aerosol Group now imports into their aerosol database the data files from the GMD Observatory Group meteorological instruments. These files have wind data along with many other atmospheric state measurements including ambient temperature, pressure, relative humidity, etc., at different heights above the surface. We have compared the Aerosol and Observatory Group wind vanes and anemometers at each station over time and the agreement was generally very good, so we have no reason to believe the change in sensors has caused a discontinuity in the historical wind records.

CHANGES IN THE LOCAL STATION ENVIRONMENT

In this section, we discuss any major temporary or permanent changes in the local station environment that may have influenced the aerosol data over the last decade. Large environmental changes are fortunately not common around the NOAA observatories and regional stations. We discuss below the few modifications that did, however, cause detectable changes in the aerosol record.

Bondville, Illinois (BND)

Major aerosol sources near the BND station include the agricultural fields in all directions, and the highway and CMI airport to the east (typically downwind of the site). Major changes in field usage or vehicular or aircraft transportation patterns in the area could affect the sampled aerosols at BND, but at this time we are not aware of any such changes.

Barrow Observatory, Alaska (BRW)

A main camp was built at the start of the DEW (Distant Early Warning) line road about 1 km from the site in 2012. During the summer of 2012, Shell Oil Co. began offshore exploration of oil and gas. Operations stopped in 2013, but presumably will begin again in the summer of 2014. The extent to which aerosol measurements were affected is unknown, but it is conceivable that some of the contamination spikes in clean sector data originated with these activities.

Mauna Loa Observatory, Hawaii (MLO)

Activity at MLO has increased over the decade due to more science projects being conducted on the mountain. Consequently, there is a little more traffic to and from the site and more human activity around the observatory. We have conscientiously limited activity and new projects in the uphill direction from the station, where the clean downslope winds flow over. No obvious changes in aerosol properties that could be attributed to this increased activity around the site have been observed over the last decade at MLO.

American Samoa Observatory (SMO)

Following the earthquake/tsunami in October 2009, Tula village residents began clearing the jungle off the side of the observatory access road and living in FEMA tents while subsequently building homes. This encampment is in the general direction of the nearby town, so aerosols from this wind direction should have been flagged as 'contaminated' (i.e., falling outside of the SMO clean sector). Given the proximity of the increased residences to the station, it is possible that some particulate emissions were inadvertently sampled. Major events would have been excluded from the clean dataset, but some minor episodes may have slipped through.

South Pole Observatory (SPO)

In 2010, the old South Pole Station was destroyed in a series of three explosions to make way for new construction. The blasts occurred on 1 December (0300 UTC), 4 December (0300 UTC), and 7 December (0200 UTC). Unfortunately, on all three days, the winds were blowing from the wrong direction and carrying explosion debris into the ARO Clean Sector. Figure 3-5 shows a photograph of the debris cloud from the dome blast on 4 December 2010 entering the ARO Clean Sector. This greatly influenced and compromised our aerosol measurements at the site for the next few days as winds from the Plateau brought the aerosols back to the station. Additionally, we observed what appeared to be contamination episodes from the direction of the Clean Air Sector occasionally over the next 6 to 12 months. It is possible that during high winds episodes, particulate debris was picked up from the snow and sampled by our instruments. These data are marked as contamination events in our clean data record, showing a slight increase in usual contamination events at SPO after the blasts.

In addition to the temporary environmental changes caused by the dome explosions, we have initiated long-term changes at the South Pole station over the last decade. Total particle number concentra-

Fig. 3-5: A photograph of the debris cloud from the 4 December 2010 blast entering the ARO Clean Sector.

tions have increased over time at SPO, possibly due to increased human population and activities at the station. The new South Pole station was constructed from 2001 to 2009 and both the winter and summer populations increased dramatically. In addition, the construction of the IceCube neutrino detector from December 2005 to December 2010 and the construction of the South Pole Telescope in 2005 and 2006 further increased the population and construction activities. Population numbers grew from 50-winter/150-summer staff to 86-winter/320-summer staff at the peak of construction in 2005 with over 300 C-130 flights. Population numbers did begin to fall, and by 2013 they were down to pre-2000 levels of 45-winter/180-summer and 100 C-130 flights.

Trinidad Head Atmospheric Observatory (THD)

The Trinidad Pier Reconstruction project commenced during August of 2011 and it was completed during September 2012. Probably the most significant artifact would be related to the use of a pile driver, which was operated by a diesel-powered crane. The pile driver was on the site from late September 2011 through December 2011. That time frame would have contained the heaviest equipment use for that project. Actual demolition began in September 2011, and was completed in July 2012. Given the unpredictable wind fields around the Head, it is likely that at times we sampled anthropogenic aerosols related to this project. We removed obvious aerosol spikes from the clean dataset that could be attributed to local sources.

Airborne Atmospheric Observatory (AAO)

The local environment for the AAO project (discussed below) is essentially the same as for BND. There were no known major changes to the local environment at AAO over the flight project years 2006–2009. Major changes in field usage or vehicular or aircraft transportation patterns in the area could have affected the sampled aerosols at AAO, but we are not aware of any such changes.

3.2 AEROSOL AIRCRAFT PROJECTS

To answer questions of how often and under what conditions aerosol properties aloft could be represented by surface measurements, GMD started two aircraft projects to conduct routine vertical profile aerosol measurements over network stations. The first was the In situ Aerosol Profiling, or IAP, project. We conducted this project in partnership with

the ARM program over the ARM Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site near Lamont, Oklahoma. We initiated IAP sampling in March 2000 and continued until December 2007; and conducted 597 research flights during this period. For more information on the IAP project, see http://www.esrl.noaa.gov/gmd/aero/net/iap/index.html.

The second aircraft project was the Airborne Aerosol Observatory, or AAO. GMD scientists conceived, developed, and conducted this program that was fully funded through NOAA. It had a similar set of objectives as the IAP program. The base of operations was near Champaign, Illinois, and we conducted flights over NOAA's BND regional aerosol monitoring station near Bondville, Illinois. AAO measurements started in June of 2006 and terminated in September 2009, encompassing 401 research profiles. Additional information on the AAO program can be found at http://www.esrl.noaa.gov/gmd/aero/net/aao/index.html.

3.3 SPECIAL PROJECTS

Chebogue Point Field Study (Yarmouth, Nova Scotia, Canada; June to July 2004): A component of International Consortium for Atmospheric Research on Transport and Transformation (ICARTT).

ICARTT was a series of coordinated experiments to study the emissions of aerosol and ozone precursors and their chemical transformations and removal during transport to and over the North Atlantic. This multinational research effort conducted in the programs that comprised ICARTT, focused on three main areas: regional air quality, intercontinental transport, and radiation balance in the atmosphere. The GMD Aerosols Group deployed a surface aerosol monitoring system to the western tip of Nova Scotia to support these efforts, with the goal of identifying emissions coming from major human population centers of the United States and Canada. For a description of the ICARTT project, see http://www.esrl.noaa.gov/csd/projects/icartt/.

SECTION 4 – CARBON CYCLE AND GREENHOUSE GASES (CCGG) RESEARCH GROUP

RESEARCH OVERVIEW

The Geophysical Monitoring for Climatic Change laboratory, the forerunner of what is now the Global Monitoring Division, made the first measurements of CO_2 in 1968 using air samples collected at Niwot Ridge, Colorado. In the next few years the measurements expanded to four baseline stations and several flask-sampling sites with access to clean well-mixed air. The primary purpose was to create an accurate and well-documented record of the changing CO_2 concentration in the atmosphere. The main principles of the measurement technique were frequent calibration of all instruments with reference gas mixtures, and ongoing comparison of continuous in situ measurements with discrete air samples obtained in flasks at the same location and sent to Boulder for analysis.

In the late 1980s, we realized that we could do more with the data than creating a record of the CO_2 increase. There was a clear, seasonally dependent and changing north-south gradient, which could be used to quantify emissions and removals ("sources and sinks") of CO_2 as a function of latitude when applying an atmospheric transport model to the data. This led to the discovery of unexpected and large net annual uptake of CO_2 by terrestrial ecosystems at temperate latitudes in the Northern Hemisphere. New measurements were gradually added to the analysis of the flask samples, first methane, then isotopic ratios of CO_2 (in collaboration with INSTAAR at the University of Colorado) as well as CO and H_2. The observed spatial and temporal distribution of the $^{13}C/^{12}C$ ratio of CO_2 confirmed the existence of a large terrestrial sink in the Northern Hemisphere, and also demonstrated that the seasonal cycle of CO_2 as well as inter-annual variations of the CO_2 growth rate are almost entirely caused by terrestrial ecosystems.

In the late 1990s, measurements of N_2O, SF_6, and isotopic ratios of CH4 were added to the flasks, see Figure 4-1. A large intensification of the network took place in the early 2000s, especially in North America. The expansion was NOAA's contribution to the inter-agency North American Carbon Program, with instruments installed on very tall communications towers and automated flask samples on small private aircraft. The main purpose is to study the large CO_2 sink on the continents at mid-latitudes. We also deployed the automated flask sampling packages on the tall towers. The number of chemical species analyzed in the flask samples increased enormously, with low-C hydrocarbons (with INSTAAR), CFCs and HCFCs (with the HATS group), and carbon-14 of CO_2, the latter also with INSTAAR.

In 2007, we launched CarbonTracker, a data assimilation system for CO_2. It combines atmospheric CO_2 data with existing mapped estimates of seasonal terrestrial photosynthesis and respiration, and maps of estimated net uptake/release of CO_2 by the oceans. An atmospheric transport model takes all of these surface fluxes, adds known fossil fuel emissions and estimated fire fluxes, to predict resulting CO_2 patterns in the atmosphere. When these modeled patterns are compared with observed CO_2, the initial (also called "prior") terrestrial and oceanic fluxes are adjusted to produce optimal statistical agreement with the CO_2 observations. CarbonTracker is updated annually as new measurements come in, and the assimilation methods are improved each time.

There are three crucial features of our measurements. They are all frequently and very carefully calibrated. In addition, we maintain the World Meteorological Organization (WMO) calibration scales for the most important greenhouse gases, and distribute calibrated mixtures of CO_2, CH_4, N_2O, CO and SF_6 in dry natural air to our international partners in the WMO GAW (Global Atmosphere Watch) program. This is the foundation for international quality control of the GAW measurements. Calibration by itself is not enough for full quality control. Errors can still occur during atmospheric sampling and sample handling, such as drying. This is addressed by the second crucial feature of the measurements, frequent ongoing comparisons of actual atmospheric air sampled and measured by different methods, and by different laboratories. The third crucial feature is data management and operations management systems. They enable quality control, efficient operation, and easy availability of the data. All data, accompanied by quality control flags and documentation, are freely available on the web, and several data products are kept up to date, such as GlobalView, CO_2 trends, CarbonTracker-inferred fluxes and atmospheric CO_2 fields, and the Annual GHG Index (AGGI).

Since our data are almost universally used in stud-

ies of the carbon cycle that use atmospheric data, and because of our central role in quality control of international measurements, we call our measurement system the Global Greenhouse Gas Reference Network (GGGRN).

During the last decade, remote sensing measurements of CO_2 and CH_4 have started to become available, with ground-based solar absorption spectrometers (TCCON), and from satellite platforms. We cannot calibrate remote sensing methods because what is in the optical path cannot be controlled. The remote sensing methods need extensive and ongoing comparisons (validation) with in situ chemical measurements to discover, diagnose, and remedy systematic biases down to levels that are unprecedented. Without a vigorous, extensive, and ongoing in situ measurement program, any meaningful and credible quantification of sources and sinks based on remote sensing data is impossible.

The emissions of CO_2 from the burning of coal, oil, and natural gas accelerated over the last decade, and now dominate the annual global carbon budget. Their uncertainty, although relatively small compared to total fossil fuel emissions, has become an important contributor to the uncertainties of the global carbon budget. Thus it has become necessary that we develop atmospheric observation based methods for quantifying fossil fuel emissions independently from inventories. In addition we have been very active in developing methods to objectively quantify regional emissions using high quality measurements of greenhouse gases and meteorology. There is a need for the objective estimation of leaks of methane and other hydrocarbons from oil/gas production regions, independent of inventories which are lists of activities and equipment, multiplied by assumed "emissions factors". The inventory estimates often appear to be too low. There is a similar need for objective and transparent estimates of emissions from nations and urban areas to create the necessary trust in stated emissions. They are now essentially self-reported, and therefore subject to political pressures and financial/economic interests.

NORTH AMERICAN CARBON PROGRAM ENHANCEMENTS

The North American Carbon Program (NACP) is a coordinated effort across U.S. government agencies to advance scientific understanding of sources and sinks for the carbon-containing gases CO_2, CH_4, and CO and of changes to carbon stocks, to provide information supporting decision-making and the development of carbon management strategies. NOAA's contribution to the NACP is the extension of surface and aircraft monitoring over North America described below.

NACP plans call for a long-term observing network to enable ongoing carbon flux estimates with coast-to-coast coverage at the regional scale. The plan calls for 30 sites with surface monitoring from tall towers and bi-weekly aircraft sampling. The proposed network would resolve spatial differences among regions roughly the size of, New England, the Midwest Corn Belt, or the southeast U.S. at temporal scales of months to seasons. We would need a substantially larger network to monitor carbon emissions on a state-by-state or city-by-city basis.

GMD's measurements in combination with data from other laboratories now provide regional-scale monitoring for North America. We need to work further to ensure compatibility across networks, to maintain and improve existing sites, and to establish additional sites for improved coverage. The frequency of aircraft sampling is particularly critical but funding shortfalls in recent years have drastically reduced sampling. A dozen studies that rely heavily on GMD's North American dataset have already been published; many more studies are underway.

4.1 FLASK AND IN SITU PROGRAMS

FLASK MEASUREMENTS - CCGG

NOAA's global measurements include data from discrete samples collected as part of our global cooperative air sampling network and continuous measurements at NOAA observatories. Both are part of our Global Greenhouse Gas Reference Network (GGGRN). These measurements provide important constraints on the emissions and sinks of long-lived GHGs, including the total atmospheric burden, rate of increase, and spatial gradients. Most of what is known with certainty about the budgets of these gases over large spatial scales is based on NOAA observations. The data are used within 3-D global chemical transport models to infer emissions at continental scales, as boundary conditions for regional-scale estimates of emissions using back-trajectory models, and to validate satellite

retrievals of column-averaged GHG abundance.

Discrete air samples are collected at 58 surface sites (as of 2013; see: (http://www.esrl.noaa.gov/gmd/ccgg/ggrn.php) with one of two portable sampling systems (one manual, and one partly automated with partial sample drying) and returned to ESRL in Boulder for analysis of CO_2, CH_4, N_2O, SF_6, CO, and H_2 at NOAA, and a suite of isotopic ($\delta^{13}C$ in CO_2 and CH_4, $\delta^{18}O$ in CO_2, and δD in CH_4, and $^{14}CO_2$ for a subset of samples) and non-methane hydrocarbon measurements (the latter since 2005) at INSTAAR. We have made no significant changes in sampling methods in the past decade.

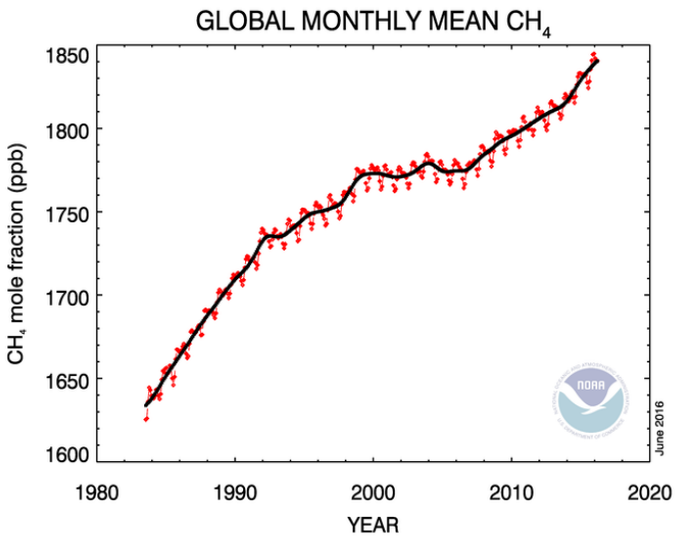


Fig. 4-1: Globally averaged monthly averages (red) and long term trend (black) of methane. The global average is based on the Marine Boundary Layer sites, a subset of the global cooperative flask air sampling network consisting of sites with access to well mixed surface air that has been over the oceans for weeks (http://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/ or see section 4.3 Data Products).

The number of sampling sites in the global network increased to a maximum of 68 in 2009 and has since decreased to 58 in 2013. We suffered one major loss to our network, the Pacific Ocean shipboard sampling at 5° latitude intervals from 35°N to 35°S. Lack of resources since 2007 has impacted the sampling frequency; the lack of spare samplers has caused data gaps at several sites, for example. All discrete air samples collected in the GGGRN, including those at global network sites, tall tower sites, and from vertical profiles, are analyzed at NOAA on one of two nearly identical systems using standards on the WMO mole fraction scales (except H_2, which is on the NOAA scale).

Prior to mid-2004, we used a single analytical system, but added a second to keep up with an increasing analysis load and provide analytical redundancy in case one system was not working to acceptable levels of performance. Important changes to the analytical systems since 2004 include replacement of reduction gas analyzers, which measured CO and H_2, with vacuum UV resonance fluorescence analyzers for CO (2008) and He-ionization, pulsed discharge detectors for H_2 (2009), a switch from a two-column separation of CH_4 (silica gel and molecular sieve) to a single-column system (Hayesep-Q; 2009), a switch in calibration of SF_6 measurements from a single standard extrapolated through zero to an off-line, multipoint calibration of ECD response, and a new species-specific sample flushing scheme to conserve sample air. During 2004, the number of analyses strongly increased, due to the introduction of Programmable Flask Packages, see Figure 4-2 (PFPs, see above, Aircraft Measurements).

We have enhanced our existing quality control strategy, which included daily measurements of test flasks and monthly measurements of test PFPs, with routine measurements of long-term (semi-annual measurement) and short-term (semi-monthly measurement) target tanks that cover a wide range of GHG mole fractions, and also with measurements of actual samples obtained at Cape Kumukahi on both analytical systems. We scrutinize comparisons frequently to ensure compatibility between systems.

Fig. 4-2: Progammable Flask Package. It has two layers of six glass flasks with motorized valves, a stainless steel gas manifold, a pressure sensor and a control and interface unit.

Our analytical load peaked in 2009 at 17,587 discrete network air samples, (global network + PFP) but has since declined 22% to 13,689 samples in 2013. These totals exclude measurements made as tests, which add 15–25% to the totals. Data from the global cooperative air-sampling network are available from: ftp://aftp.cmdl.noaa.gov/data/trace_gases/<gas>. Our goal is to provide uncertainties with all measurements, but, so far, only CH_4, CO, and isotopic ratios of CO_2 include uncertainties. Additionally, zonal averages of CO_2 and CH_4 are available with estimates of uncertainties from: http://www.esrl.noaa.gov/gmd/ccgg/mbl/.

Nearly every study of the large-scale budgets of CO_2, CH_4, N_2O, SF_6, CO, and H_2 use NOAA measurements as their main constraint, and some important conclusions have been reached from these studies. Some examples: A detailed analysis of NOAA (and Scripps Institution of Oceanography) CO_2 data shows that net global redistribution of carbon from the atmosphere to the oceans and terrestrial ecosystems has increased by ~0.05 PgC yr^{-2}, causing a doubling from 2.4±0.8 to 5.0±0.9 PgC yr^{-1} between 1960 and 2010.

Comparing SF_6 emissions calculated from the observations with emissions reported by Annex I countries to the United Nations Framework Convention on Climate Change clearly shows that the bottom-up inventories for SF_6 grossly underestimate emissions. For CH_4, changes in the difference between zonal averages calculated for northern and southern Polar regions indicate that warming in the Arctic has not yet resulted in a sustained detectable increase in emissions. Finally, for CO, which is relatively short-lived in the atmosphere (mean life time of ~3 months), a small negative trend over the past two decades in the Northern Hemisphere (-0.64±0.05 ppb yr^{-1}) and no trend in the Southern Hemisphere (0.03±0.03 ppb yr^{-1}) indicate a decrease in emissions in the Northern Hemisphere.

IN SITU MEASUREMENTS - CCGG

We make continuous measurements at BRW and MLO for CO_2, CH_4, CO, at SMO and SPO for CO_2. We also started continuous measurements of CH_4 at Cherskii, Russia (NE Siberia) in 2008. Our CO_2 measurement technique has remained the same, a non-dispersive infrared (NDIR) analyzer. To save the expense of shipping cylinders (carrier gas, oxidizer, and H_2) to BRW, we stopped continuous measurements made there by GC in June 2012 for CH_4 and April 2011 for CO, when existing supplies of gases at BRW were exhausted. CH_4 measurements resumed in April 2013 with an optical analyzer based on off-axis integrated output spectroscopy. Comparison of measurements from discrete samples collected at the observatories with continuous measurements provides useful quality control for both measurements.

QUALITY CONTROL TESTS OF SAMPLING PROCEDURES - CCGG

On a regular basis, PFPs along with control flasks are filled in the laboratory from high-pressure cylinders of dry, whole air and are subsequently compared using the same analytical systems that measure all of our regular field site samples. In addition to these ongoing routine tests, we have carried out several field experiments atop nearby Mount Evans (elevation ~4350 m; located ~80 km west of Denver, Colorado) where we have collected series of concurrent control samples, PFP air samples, and continuous in situ measurements, including a field test of two of our aircraft in situ systems. We were able to compare the PFP samples with control samples for ~50 trace compounds of interest. This mountaintop location was chosen to sample atmospheric air largely free of influence from nearby sources and sinks and with low variability over the sampling timescale, to provide for an optimal, real-air sampling comparison. The location avoids possible laboratory-induced artifacts from using high-pressure cylinders as the sample air source.

Specific experiments were also conducted both atop Mount Evans and in the laboratory to investigate possible biases related to materials used for sample inlet lines. We observed significant production of carbon monoxide in one type of tubing (Bev-A-Line) when it was exposed to sufficient sunlight. Another type of tubing (Kynar), which we use extensively in the aircraft network, is free of this effect.

We also observed the release of carbon dioxide from another common tubing type (Synflex) during a large pressure drop created when our pump system kicks on for sampling, in the long inlet lines typically used on the tall towers. We measured pressure transient-induced carbon dioxide enhancements of up to 0.7 ppm in samples taken through a typical length of ~500 m of this tubing, and therefore are careful to fully flush these lines

and allow the line pressure to stabilize prior to filling our sample PFP flasks at the tall tower field sites.

From laboratory experiments, we have discovered that many of our PFP flasks can produce spurious carbon dioxide enhancements of the air samples that tend to grow in magnitude over time due to an effect related to the presence of unknown (not visible) contaminants on the flask wall and the presence of water vapor in real sample air. We have measured enhancements up to ~2 ppm in the laboratory and through these tests developed a simple sampling strategy (flasks are sampled, vented quickly, and then sampled again), which effectively negates this sample bias. We have implemented this "pre-filling" strategy for all of our PFP sampling.

4.2 CARBONTRACKER – CO_2 AND CH_4

Models of atmospheric transport are extensively used to interpret observational records of trace gas concentrations. Since models are imperfect and observations are limited, in practice, this analysis requires significant expertise not only in atmospheric modeling, but also in understanding signals and their uncertainty in the measurements themselves. In 2006, GMD began a modeling project with the goals of improving techniques for simulating trace gas measurements in global models, of presenting up-to-date analyses of atmospheric carbon dioxide, and of evaluating the suitability of the global observational network for answering important questions in carbon cycle science. This project eventually became known as CarbonTracker, which now produces regular analyses of global surface sources and sinks of carbon dioxide and the resulting CO_2 distributions in the atmosphere, see Figure 4-3.

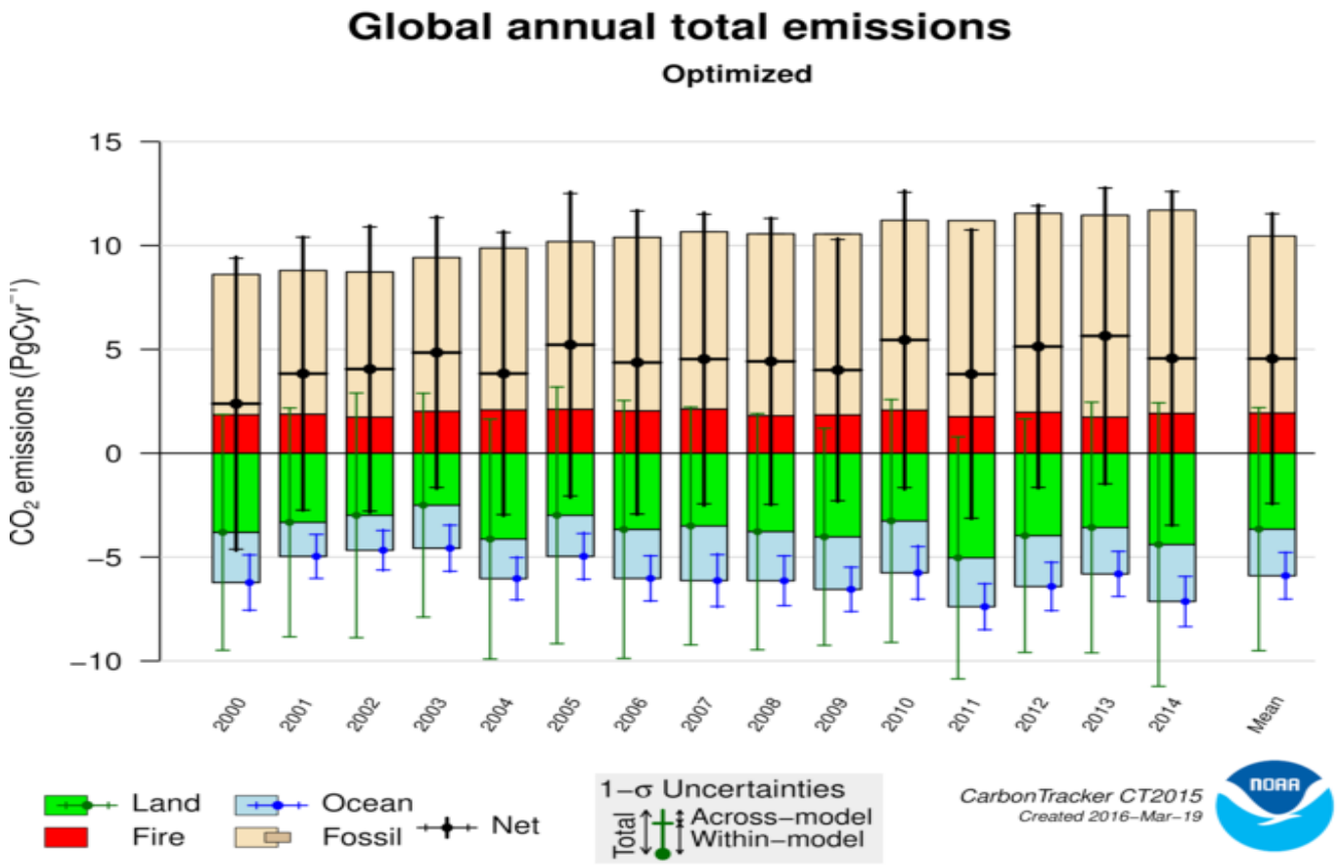


Fig. 4-3: Estimated global emissions by the CarbonTracker data assimilation system by source category. Fire and fossil fuel plus cement emissions are specified by inventories, while ocean and land sources are solved for by Carbontracker, based on atmospheric CO_2 observations. The total net annual source to the atmosphere (thick black lines) corresponds very closely to the observed global annual averages that we derive from Marine Boundary Layer sampling sites (http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html).

The first release of CarbonTracker was in February 2007. It presented results from the beginning of 2000 through the end of 2005, and assimilated about 24,000 CO_2 observations from 63 distinct data records. We used the TM5 (Transport Model version 5) off-line atmospheric tracer transport model driven by European Centre for Medium-range Weather Forecasts (ECMWF) forecast model winds running at a global resolution of 6° longitude by 4° latitude. Two nested "zoom" regions were employed over North America to provide enhanced model resolution of 1° x 1° in this area. This nested zoom meteorology was intended to improve the representation of transport over North America and thus improve the extraction of flux information from the relatively denser observational network over that continent. We developed an extensive web site for CarbonTracker, and made all model results available at http://carbontracker.noaa.gov. We designed CarbonTracker from the beginning to be as open as possible, so that independent researchers can evaluate for themselves the validity of the product and help us identify potential improvements.

We released the first update to CarbonTracker in December 2007. This version extended the results through the end of 2006, added several new data records, and introduced improved prior flux models for the ocean and fossil fuel emissions. In the intervening years, we released updates on an approximately annual basis, making improvements in each revision and increasing the length of the analyzed record.

The CarbonTracker project has proven to be a valuable resource for the carbon cycle science research community. It is widely used as a tool for evaluating new observational products such as the Total Column Carbon Observing Network (TCCON) and satellite platforms such as the Tropospheric Emission Spectrometer (TES) and Greenhouse Gases Observing Satellite (GOSAT). The CO_2 fields are often used as boundary conditions for regional simulations, and its optimized fluxes are taken as priors for refinement using independent datasets and in regional inverse modeling exercises.

CarbonTracker has attracted significant interest for collaborative research. Projects completed thus far include exploration of how best to represent observations in complex topography, investigation of combined sea-surface and ocean interior constraints on air-sea CO_2 exchange, and the development of NOAA's CarbonTracker-Methane. The regional zoom capabilities of TM5 have attracted researchers interested in Eastern Asia, South America, Europe, and Australia/New Zealand. Funded projects currently underway are exploring advanced models of wildfire emissions and of air-sea CO_2 flux, improving the representation of planetary boundary-layer dynamics, using Lagrangian particle dispersion models (LPDMs) to explore regional inverse methods, establishing techniques for assimilating upper-air observations like those from aircraft and satellites, developing $^{14}CO_2$ constraints on fossil-fuel exchange, using carbonyl sulfide observations to constrain terrestrial productivity, and developing accelerated "near real-time" simulations to improve the timeliness of CarbonTracker results.

4.3 DATA PRODUCTS

GLOBAL GREENHOUSE GAS REFERENCE NETWORK DATA

Our most important data product is the data itself. In the mid-1980s, we adopted an open data policy, which means we make our data freely available to the public (updated annually) and directly to collaborators when more near real-time data are requested. We continually develop methods and tools to improve the timeliness of our data distributions and our ability to include critical metadata with every distribution. In 2007, we developed tools to ensure all data across all projects distributed by the GGGRN are packaged using a standard protocol, which includes extensive documentation, metadata, proper attribution, and identical data format. In 2010, we began including estimates of measurement uncertainty with surface network flask data (CH_4, CO, and $\delta^{13}C$, $\delta^{18}O$ in CO_2) and all quasi-continuous tall tower data distributions. We will continue to work until we have included measurement uncertainty with all of our data distributions.

We have introduced several regularly updated, value-added data products that highlight important features from our reference network. Some products are intended as research tools while others are relevant to society as a whole. For the latter, we attempt to present these products and their relevance in a manner that can be easily understood and followed by policymakers, educators, and the general public. In 2006, GMD introduced the NOAA Annual Greenhouse Gas Index (AGGI). Using

measurements from GGGRN and the HATS group, the AGGI is a measure of the warming influence of long-lived trace gases and how that influence is increasing each year. In 2007, we introduced "Trends in Atmospheric CO_2", which provides near real-time updates of trends in atmospheric CO_2 determined from the long-term Mauna Loa record, updated weekly, and a global average from the Marine Boundary Layer (MBL) sites (see below), updated monthly. During May 2013, the site documented the first daily mean atmospheric CO_2 concentration at Mauna Loa exceeding 400 parts per million (ppm).

For nearly 20 years, we have regularly constructed MBL reference surfaces using measurements of weekly air samples from the marine surface air component of the GGGRN. They can be computed for nearly all long-lived trace gas species and isotopes routinely measured by NOAA and the University of Colorado Stable Isotope Laboratory. The MBL reference is a frequently requested data product because of its value in providing initial boundary conditions for global and regional modeling studies. In 2011, we began making the CO_2 and CH_4 MBL references with uncertainty estimates freely available using an interactive web application.

Many value-added products are developed with the aim to improve data coverage, accessibility, and usability. GLOBALVIEW-CO_2, first introduced in 1996 and updated annually, is one example of a multi-laboratory product coordinated by NOAA and designed to provide uniform spatial and temporal distribution of atmospheric observations for use in global carbon cycle modeling studies at a time when assimilation systems could not yet accommodate irregularly spaced data sets. Today, many data assimilation systems can directly ingest irregularly spaced atmospheric observations. While interest in GLOBALVIEW products persisted, demand peaked in 2007.

In 2011, we introduced ObsPack (Observation Package), a new generation of annually updated data products, as well as application-specific, customized products designed to meet the changing needs of both data users and providers, see Figure 4-4. Unlike GLOBALVIEW, ObsPack products can include actual data depending on intended use. Each ObsPack data file is self-documenting, which means that the format and content are fully described. Metadata includes provider contact information, location and sampling details, selection criteria, calibration history, comparison activity, and citation requirements.

ObsPack products are freely available. However, we have introduced a unique data usage policy and distribution strategy designed to improve communication between product user and data provider and to help ensure proper acknowledgement. The ObsPack Fair Use Statement requires users to contact each data provider contributing to the downloaded product to discuss, in advance, intended use and appropriate acknowledgment. To facilitate this requirement, users receive an automated e-mail (when a product is downloaded), which includes the Fair Use Statement, required citation, and the e-mail list of all contributing providers. Each contributing provider also receives an automated e-mail that includes users' contact information.

Beginning November 2013, all ObsPack products are assigned a Digital Object Identifier (DOI), which is included in the required citation. The DOI provides an unambiguous reference to the specific data product used in published work and improves our ability to track product usage.

Today's assimilation models, like CarbonTracker, are designed to use measurements from flasks and in situ analyzers directly. Data products suitable for this purpose have been carefully assembled using preprocessing procedures adapted to each record. These procedures start with identifying datasets that are carefully calibrated and can be successfully simulated by coarse-resolution global models. For some records, a selection of subsets suitable for assimilation is made, and high-frequency measurements and duplicate flask samples are averaged. Observations of CO_2, CO, CH_4, and SF_6 from GMD and collaborating laboratories have been gathered and processed for inclusion in modeling efforts using these methods. All data products are freely available at http://www.esrl.noaa.gov/gmd/ccgg/.

4.4 AIRCRAFT PROGRAMS

CCGG VERTICAL FLASK PROFILES

Vertical profiling from aircraft began in 1992. See: http://www.esrl.noaa.gov/gmd/ccgg/aircraft/. We designed the sampling strategy to capture seasonal and inter-annual changes in trace gas-mixing ratios throughout the boundary layer and free troposphere (typically up to ~8000 m/ 26,000 ft, but some as high as 13,280 m). Most flights collect 12 flask samples at different altitudes with the Pro-

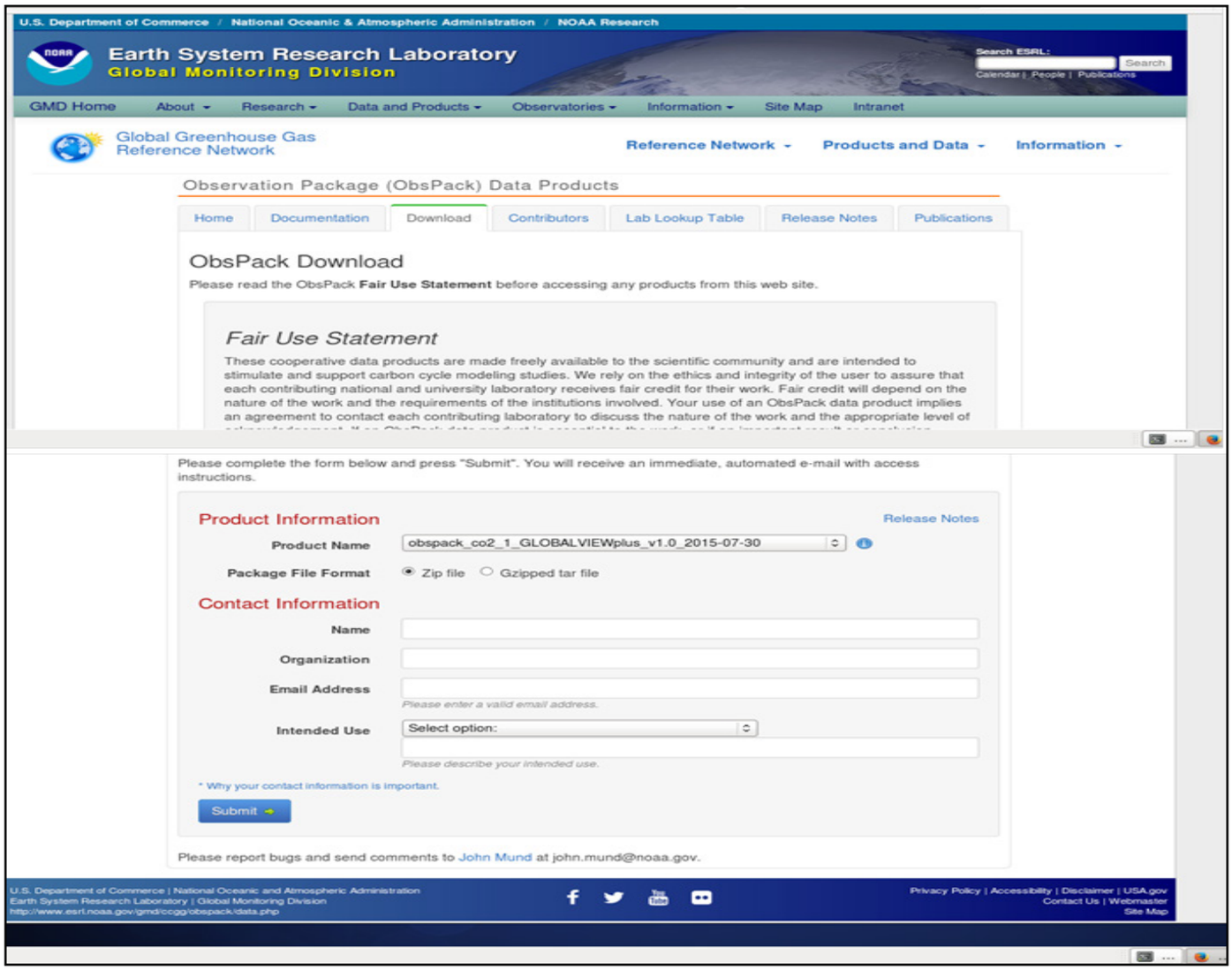


Fig. 4-4: Web page for downloading ObsPack products.

grammable Flask Package (PFP) automated sampling system. The packages can be quickly shipped back to NOAA/ESRL for carefully calibrated and quality-controlled measurements. At a predetermined altitude, the sampling system is automatically activated or activated by a toggle switch that is easily accessible to the pilot. Time, location, and auxiliary variables such as temperature and relative humidity are logged with each sample and downloaded to the NOAA/ESRL database when the samples are returned to the laboratory. The samples can be analyzed for CO_2, CO, N_2O, CH_4, H_2, and SF_6, as well as isotopic ratios of CO_2 and CH_4, ~30 halogenated compounds and ~10 hydrocarbons. Aircraft data provide a view of how the large-scale horizontal and vertical distribution of the measured trace gases change throughout a given year over the continent. The large-scale, three-dimensional picture of how trace gas-mixing ratios change throughout the year provides a means to estimate the contribution of the North American continent to the atmospheric concentration of long-lived gases like CH_4, N_2O, CO_2, and $^{14}CO_2$, carbonyl sulfide and other trace gases; it provides an essential benchmark for forward and inverse modeling and a critical validation tool for satellite measurements of CO_2, CO, and CH_4. The aircraft data are not yet posted on the ftp pages, but are freely available on request from the principal invstigator (PI).

CCGG INTENSIVE SAMPLING CAMPAIGNS

The aircraft program is actively pursuing alternative sampling strategies focused on regional processes in the North American carbon budget. Intensive sampling campaigns have been used for Lagrangian ("Where did the air come from a few days ago?") flux experiments to estimate natural uptake of CO_2 such as during the Mid Continent Intensive (2006–2008). More recently, the aircraft

program has used simple mass balance techniques to quantify CO_2 emissions from Sacramento, Indianapolis, and CH_4 emissions from oil and gas operations in Utah, Colorado, and Texas, see Figure 4.5. Our "top-down" estimates of methane emissions from oil and gas operations, in particular, have provided very valuable comparisons with the inventory-based ("bottom-up") emissions estimates. Joint development with Picarro Inc. of off-the-shelf, in situ systems have allowed a single aircraft to do regular sampling of large areas such as the boreal and tundra regions of Alaska in collaboration with the U.S. Coast Guard, and with NASA's Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE). These types of flights have allowed multiple profiles and boundary layer traverses aimed at better understanding spatial variability and temporal changes over large regions. The development of in situ measurements has progressed in anticipation of a commercial aircraft network, which would require completely unattended operation of similar in situ instrumentation to measure CO_2, CO, and CH_4. The all-weather and very frequent vertical profiles potentially obtainable on commercial aircraft would greatly enhance the quantification of CH_4, CO_2, and CO monthly average emissions over North America on regional scales, while also providing new constraints on modeled atmospheric transport.

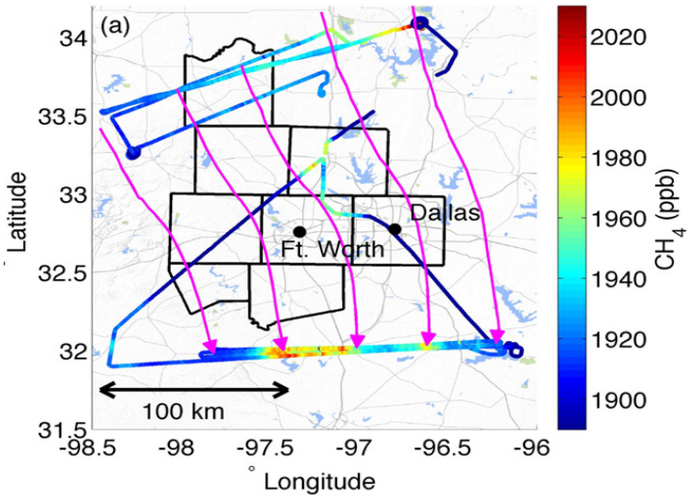


Fig. 4-5: Flight pattern on 19 October 2013 over the Barnett Shale oil and gas field for "mass balance" estimation of total methane leaks from the area. The downwind enhancement of the CH_4 mole fraction and the wind speed and direction (pink arrows from northwest veering toward south), as well as the boundary layer height are used. There were multiple transects downwind at different altitudes.

4.5 TOWER MEASUREMENTS

GREENHOUSE GASES MEASUREMENTS FROM TALL TOWERS

GMD began making measurements from tall towers in the 1990s to extend long-term carbon cycle gas monitoring to continental areas. We developed a new in situ CO_2/CO analysis system under the NACP for unattended sites, and the ground-based measurement network has expanded substantially since 2004 with extensive contributions from partners. See: http://www.esrl.noaa.gov/gmd/ccgg/insitu/.

When practical, we collect samples from television or FM radio transmitter towers > 300 m in height to enable trace gas measurements that are representative of the planetary boundary layer. Sampling footprints calculated from atmospheric transport models indicate that tall tower measurements are sensitive to fluxes hundreds of kilometers upwind, see figure.

We obtain measurements at different elevations, from 30 m to 300–500 m. Sampling levels above ~100 m are minimally impacted by nearby vegetation and other local emissions. Tall towers frequently penetrate the shallow nighttime boundary

Fig. 4-6: Tall tower at Beech Island, South Carolina. Air sampling intakes at 30, 61, and 305 m above ground.

layer, in which case measurements from the highest levels are decoupled from the surface. Seasonal, day-to-day, and diurnal variability of CO_2 observed at a tall tower site can be very large which provides valuable information about the role that local and regional transport and sources and sinks of CO_2 ambient boundary layer mole fractions play.

We have added short-tower, mountaintop and ridgeline sites to fill gaps in the monitoring network over mountainous regions, where tall broadcast towers are uncommon. However, the representativeness of such sites can be difficult to determine due to complicated meteorological conditions. We installed short-tower sites in Maine and Alaska for intensive measurement campaigns, and these are expected to continue indefinitely. Other short-tower sites pre-date the NACP network expansion or are platforms of opportunity, such as the Martha's Vineyard offshore tower.

The laboratory maintains strong partnerships with other researchers making surface measurements across North America. Environment Canada operates twelve greenhouse gas monitoring sites with towers that range in height from 20 to 105 m, and NOAA has co-located samples at several of these sites to ensure compatibility across the networks. Several Department of Energy-supported Ameriflux sites have instituted calibrated CO_2 measurements using reference gases that are traceable to the WMO scale. Researchers at NCAR, Oregon State University, Penn State University, Lawrence Berkeley National Laboratory, the California Air Resources Board, and other institutions have begun regional CO_2 and/or CH_4 measurement programs. A promising and unexpected development is the emergence of a private-sector greenhouse gas-monitoring network installed by Earth Networks. We need to continue working to establish ongoing comparisons with all of these groups.

4.6 SPECIAL PROJECTS

AIRCORE

The GGGRN has developed and demonstrated the new AirCore system for sampling a vertical profile from the surface to the middle stratosphere. The AirCore is an innovative atmospheric sampling system that consists of a long tube, coiled up inside a light and compact Styrofoam container that is easily lifted by balloon to altitudes of 30,000 m above sea level, see Figure 4-7. We designed the AirCore with a narrow diameter and long length to minimize the diffusive mixing occurring inside the tubing during sampling, storage, and analysis. With one end of the AirCore opened, the air in the tube is vented as the AirCore ascends and ambient air flows back into the tube as it descends. Aircore not only provides a low cost approach to sampling the lower/middle stratosphere but also provides an essential tool for the direct evaluation of remote sensing spectroscopic measurements, either from the ground or from satellites, of vertical column-averaged greenhouse gas concentrations, see Figure 4-8.

Fig. 4-7: Launch of AirCore.

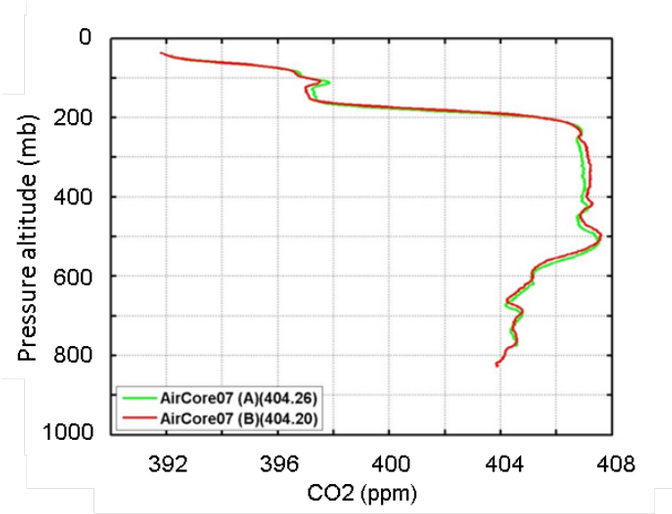


Fig. 4-8: Vertical profiles of CO_2 in two different AirCores flown simultaneously to an altitude of 28 km.

ISOTOPIC RATIOS OF CO_2 AND CH_4

While atmospheric mole fractions of CO_2 and CH_4 are linked to their total fluxes, isotopic ratios of these gases can provide valuable information on how different processes contribute to sources and sinks. In the last decade, the GGGRN, in cooperation with CU/INSTAAR, has expanded both the number and type of isotopic ratio measurements made. Since the early 1990s, the Stable Isotope Laboratory (SIL) at INSTAAR has made measurements of the $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios of carbon dioxide ($\delta^{13}C$ and $\delta^{18}O$) from air samples collected in flasks in the GGGRN network of sites. Since 1998, they also measured the $\delta^{13}C$ of CH_4 in a subset of network sites. The number of $\delta^{13}C$ of CO_2 measurements made by the SIL increased proportionately with the network expansion into tower and aircraft sites in North America. We originally intended to use measurements of $\delta^{13}C$ of CO_2 in the GGGRN as a way to separate the land- and ocean-flux components of CO_2. While this application is still possible, we have evolved our use of these data in the past decade to focus on using $\delta^{13}C$ of CO_2 as a tracer of ecosystem function and health.

In 2003 the GGGRN began actively collaborating with the CU Laboratory for AMS Radiocarbon Preparation and Research (NSRL) to measure the $^{14}C/C$ ratios of carbon dioxide ($\Delta^{14}C$) in a limited subset of North American and global samples. Measurements of $^{14}CO_2$ are the best possible constraint of CO_2 emissions from fossil fuel combustion, because fossil fuels contain no ^{14}C. Our long-term objective is to develop a North American-focused global network of ^{14}C observations that will allow for independent atmosphere-based (i.e., "top-down") verification of fossil fuel emissions. Progress in the last decade is based on the development of state-of-the art measurement precision and stability and the initiation of sampling at more than 12 sites in North America and Asia. Until our network is dense enough to independently constrain fossil fuel emissions, we have leveraged the close relationship between ^{14}C of CO_2 and fossil fuel-CO_2 emissions (which is well known) to improve emissions estimates of gases with poorly known emission inventories, like carbon monoxide (CO), and many high-GWP (global warming potential) halogenated compounds.

Starting in 2012, we also developed the capability to measure the $\Delta^{14}C$ of CH_4. Measurements of ^{14}C of CH_4 (and CO_2) have focused on two sites in interior and North Slope Alaska. With these measurements, we plan to assess the degree to which old (and thus ^{14}C-depleted) carbon buried in permafrost may be emerging into the atmosphere.

MOPITT VALIDATION

The aircraft-based vertical profiling air-sampling programs over Alaska (PFA), Hawaii (HAA), Massachusetts (HFM) and the Cook Islands (RTA) continued biweekly air sampling under NASA funding for the Measurement Of Pollution in The Troposphere (MOPITT) validation program. The MOPITT instrument is situated on the NASA Earth Enterprise System satellite TERRA and measures CO in the lower to mid troposphere. As part of the level-3-retrieval validation, we chartered small aircraft to collect samples of air from 8 to 0.5 km (PFA, HAA, HFM) and 6 to 0.5 km over the RTA. We collected air approximately every 0.3–0.5 km using a portable, computer-driven package holding 20 glass flasks. Flight schedules and sampling times were coordinated with the satellite overpass. We measured the samples in Boulder for CO, CO_2, CH_4, N_2O, and SF_6. When NOAA assumed the aircraft program in 2008, flights at HAA and HFM ended due to funding constraints.

SECTION 5 – HALOCARBONS AND OTHER TRACE ATMOSPHERIC SPECIES (HATS) RESEARCH GROUP

RESEARCH OVERVIEW

The GMD Halocarbons and Other Trace Atmospheric Species (HATS) Research Group and its predecessors began making measurements of atmospheric trace gases that influence stratospheric ozone and climate, such as halogenated gases and nitrous oxide, in the late 1970s. What began as a program to measure a handful of trace gases at three NOAA observatories (section 2) has grown into one in which more than 40 trace gases are measured. NOAA and cooperative organizations (starting with the Institute of Arctic and Alpine Research (INSTAAR); Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia; and Environment Canada) make measurements routinely at surface sites, from aircraft platforms, and periodically as part of focused field campaigns, employing both flask sample and in situ methods. Many of these measurements complement those obtained by other GMD research efforts, such as those made by the Carbon Cycle and Greenhouse Gases and Ozone and Water Vapor groups.

The HATS group's primary objective is the study of trends and distributions of atmospheric trace gases that influence stratospheric ozone, climate, and air quality. Key outcomes include: a) monitoring changes in halogenated compounds controlled by the Montreal Protocol on Substances that Deplete the Ozone Layer and its amendments and adjustments to provide feedback on the effectiveness of various control measures, b) characterizing sources and sinks of ozone-depleting substances (ODS) and radiatively important gases, c) using information on trends and distributions of trace gases to improve our knowledge of atmospheric chemistry and transport, and d) development of gas standards and calibration methods (see section 8).

We perform sample analyses with various instruments; including gas chromatography with electron capture detection (GC-EC), gas chromatography with mass spectrometric selective detection (GC-MS), tunable diode laser absorption spectroscopy (airborne water vapor), and UV absorption spectroscopy (airborne ozone). We describe changes and improvements in sampling, analysis, and data processing in the subsections below.

5.1 FLASK AND IN SITU PROGRAMS

The flask program is one of the cornerstones of the HATS sampling efforts. We obtain routine surface measurements at sites across much of the Western Hemisphere and through much of the troposphere above North America by sampling using flasks. Samples are analyzed on dedicated instruments under controlled conditions, thus limiting calibration and inter-instrument issues that can influence in situ measurements made under field conditions. By combining efforts with other research groups in GMD, approximately 50 compounds are measured on some flask samples. Flask samples have also been collected during special projects such as HIPPO, involving the NCAR Gulfstream V aircraft (see section 5.2, Table 5-4).

We started the in situ program in the late 1980s to complement the flask program by providing high-frequency measurements of fewer compounds at a relatively small number of sites. We upgraded the original in situ Radiatively Important Trace Species (RITS) program in the late 1990s with custom-built gas chromatographs with electron capture detectors.

We can obtain a comprehensive view of atmospheric trace gas mole fractions and distributions, and insight into the natural and anthropogenic processes controlling changes in the chemical composition of the atmosphere over seasonal to decadal periods, with a combination of surface in situ measurements and flask sampling from a variety of platforms. GMD creates and uses combined data in indices such as the NOAA Annual Greenhouse Gas Index (AGGI) and Ozone Depleting Gas Index (ODGI), as well as international assessments and reports.

FLASK MEASUREMENTS - HATS

Current operations

We made a number of improvements to the flask program during 2004–2013. These improvements allow better characterization of concentrations and emissions of ozone depleting substances and non-CO_2 greenhouse gases throughout the globe and in particular over the U.S. The HATS global flask sampling network consists of sixteen ground-based sites, with two new sites added since 2004 and continuing at present. Paired flask samples are collected weekly or biweekly at these sites. The total number of flask sample pairs collected per year has

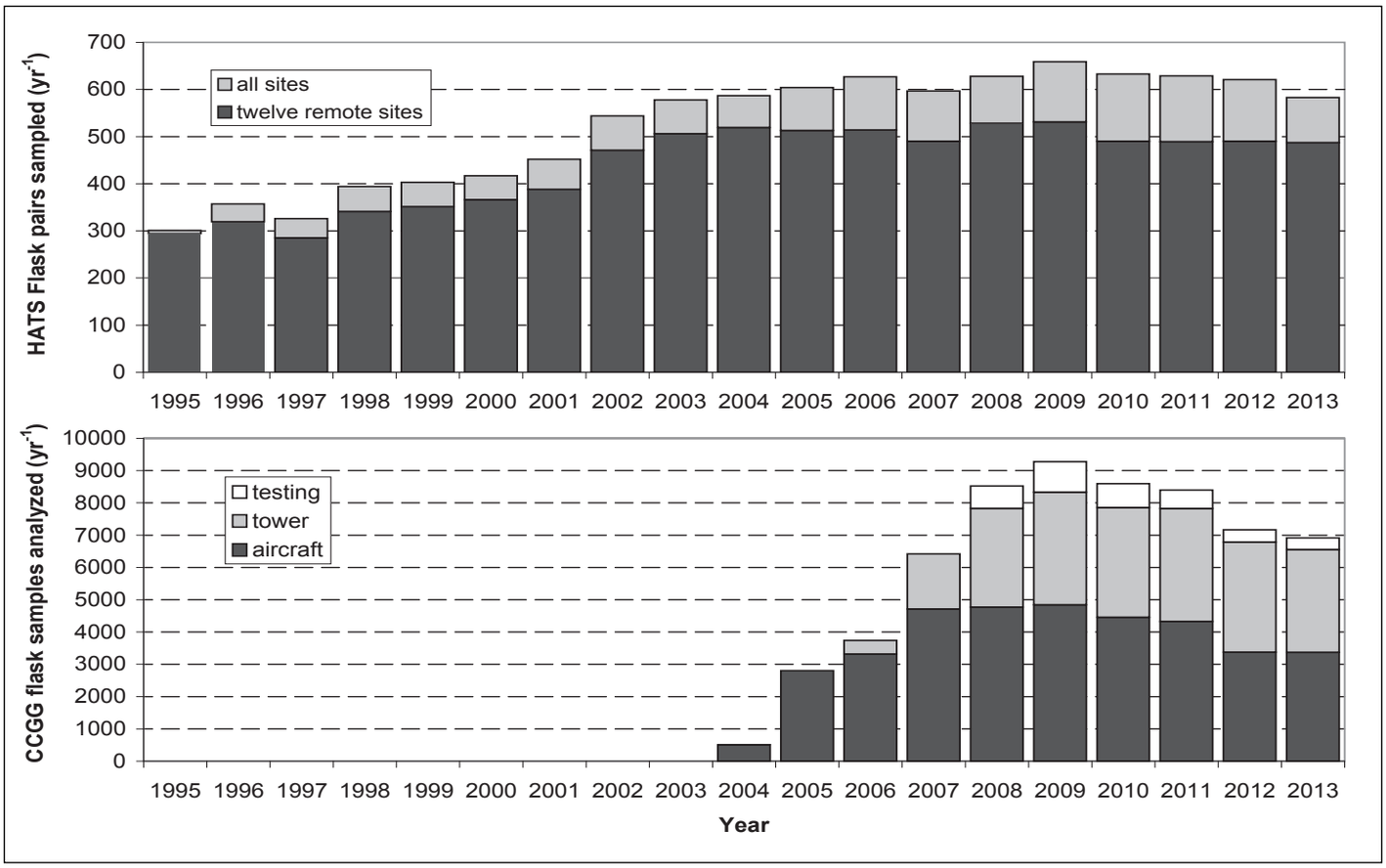


Fig. 5-1: The number of flasks collected annually in the HATS or CCGG sampling networks that were analyzed by GCMS instrumentation. Top panel: Paired flask samples collected from the HATS group's ground-based sampling network (at all sites and 12 remote background sites). Bottom panel: The number of flasks collected by the CCGG group that were analyzed on GC-MS instrumentation. The CCGG samples are collected at tower and aircraft platforms in North America and over the Pacific Ocean, typically as single flasks

ranged between 583 and 659 since 2004 (Figure 5-1); the sampling pair frequency at the 12 baseline sites has ranged between 487 and 531, which amounts to 0.78–0.85 pairs per week. Sampling frequencies are sometimes below one per week at the remote baseline sites because of out-of-sector wind conditions, flask shortages, and pump malfunctions. We routinely analyze HATS-paired flasks with two aliquots per flask surrounded by reference gas injections.

For this program, we update data that have been documented in peer-reviewed publications approximately once every two weeks on the web at ftp://ftp.cmdl.noaa.gov/hats/. These compounds include: CFC-113, CH_3CCl_3, HCFC-22, HCFC-142b, HCFC-141b, H-1211, H-2402, HFC-134a, HFC-152a, CH_3Cl, CH_3Br, COS, CH_2Cl_2, and C_2Cl_4.

We also began to make higher frequency flask measurements (~daily) at 13 additional U.S. sites in collaboration with the CCGG tall tower network and semimonthly to monthly at 19 additional sites with 12-flask aircraft profiles as part of the CCGG aircraft network (Table 5-1a & b). We collect these samples as single flasks and analyze them on the GC-MS with a single injection based on flask and air availability and instrument time constraints. On average, from 2008 to 2013, we analyzed 9400 flasks of all types each year on GC-MS instruments. We update these data regularly on internal GMD databases, and some are available on request.

Instrumentation modifications and upgrades

In 2009, we replaced the original HP 5971A GC-MS analyzer (M1), used since 1991, with an Agilent 5973 GC-MS (M3). This change was necessary, as the performance of the original instrument had deteriorated. The instrument upgrade notably improved precision for nearly all gases (Figure 5-2). We built a second GC-MS instrument (M2) in 2007 to handle the additional samples collected from the CCGG's tower and aircraft network. Currently all ground-based, non-tower network flasks are analyzed on the M3 GC-MS. We analyze only some of

Table 5-1a: New sites at which flask collection and analysis by GC-MS was initiated during 2004-2013 either as part of the HATS or CCGG networks. Note that previously ongoing sites are not listed.

A) Ground-based tower network (CCGG) sites with flasks analyzed by GC-MS

Site	Lat	Long	Alt. (m)	Start - End
LEF	45.93	90.27	716	Oct. 2006
INX	39.8	86.02	406	Oct. 2010
LEW	40.94	76.88	256	Jun. 2013
MBO	43.98	121.7	2742	Apr. 2010
MWO	34.22	118.1	1774	Feb. 2006
NWF	40.03	105.55	3052 or 3073	Feb. 2006 – Nov. 2009
STR	37.75	122.45	486	Oct. 2007
SCT	33.41	81.83	420	Aug. 2008
WBI	41.72	91.35	620	Jun. 2007
WGC	38.26	121.49	91 or 483	Sep. 2007
WKT	31.32	97.33	708	Aug. 2006

B) Profiling aircraft network (CCGG) sites with flasks analyzed by GC-MS

Site	Lat	Long	Start - End
AAO*	40.1	88.56	Jun. 2006 – Sep. 2009
ACG**	87 to 86	130 to 170	Apr. 2009 (no winter samples)
BGI	42.82	94.41	Sep. 2004 – Nov. 2005
BNE	40.8	97.18	Sep. 2004
CAR	40.37	104.3	Jan. 2005
CMA	38.83	74.32	Sep. 2005
CRV**	60 to 71	144 to 164	Mar. 2011
DND	48.14	97.99	Sep. 2004
ESP	49.58	126.37	Mar. 2005
ETL	54.34	104.99	Oct. 2005
FWI	44.66	90.96	Sep. 2004 – Nov. 2005
HAA	21.23	158.95	Aug. 2006 – Apr. 2008
HIL	40.07	87.91	Sep. 2004
INX	39.59	86.4	Oct. 2010
LEF*	45.93	90.27	Jun. 2005
NHA	42.95	70.63	Oct. 2005
OIL	41.28	88.94	Sep. 2004 – Nov. 2005
PFA	65.07	147.29	Apr. 2009
RIA	42.4	91.84	Sep. 2004
RTA	20.96 S	159.78	Sep. 2007
SCA	32.77	79.55	Oct. 2005
SGP*	36.8	97.5	Mar. 2006
TGC	27.73	96.86	Feb. 2005
THD	41.05	124.15	Nov. 2004
ULB*	47.4	106 E	Nov. 2004 – Nov. 2005

* maximum altitude routinely < 25000 ft

** sites where the flask sampling plan includes spatial surveys in addition to vertical profiling.

Table 5-1b: Newly added ground and aircraft sites where halocarbon measurements are made from flasks (CCGG Network). (All latitudes are °N unless indicated; All longitudes: °W)

Site	Flask Type	Frequency	Start Date	End Date
ALT	SS	1/wk	pre-1991	Ongoing
BRW	SS	1/wk	pre-1991	Ongoing
SUM	glass	0.5 to 1/wk	Jun 2004	Ongoing
MHD	SS	1/wk	Oct 1998	Ongoing
LEF	SS	1/wk	Oct 1996	Ongoing
HFM	SS	1/wk	Nov 1995	Ongoing
THD	SS	1/wk	Feb 2002	Ongoing
NWR	SS	1/wk	pre-1991	Ongoing
WLG	glass	0.5 to 1/wk	Sep 2009	Feb 2014
WIS	glass	0.5/wk	Jan 2007	Ongoing
KUM	SS	1/wk	Nov 1995	Ongoing
MLO	SS	1/wk	pre-1991	Ongoing
SMO	SS & glass	1/wk	pre-1991	Ongoing
CGO	SS & glass	1/wk	pre-1991	Ongoing
TDF	SS	1/wk	May 2004	May 2010
PSA	glass	1/wk	Dec 1997	Ongoing
SPO	SS & glass	1-2/month	pre-1991	Ongoing

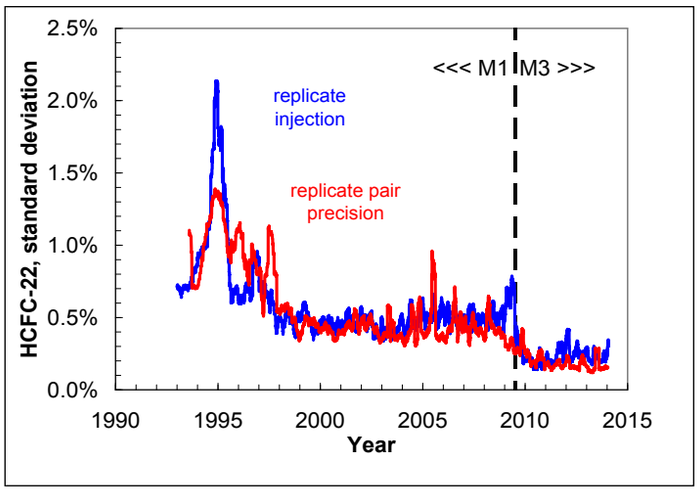


Fig. 5-2: Instrument performance in the analysis of HCFC-22 from flask air. Shown are running mean replicate injection precisions from ~18,500 flasks analyzed since 1992 as part of the HATS sampling network on M1 and on M3 (100-point running means of the individual replicate injection precisions, which aren't displayed; blue line). Also shown are the differences between the individual flasks filled simultaneously as a pair (~9000 pairs, 100-point running means of these individual pair differences are shown as red lines).

these flasks on M2 to provide global distributions of the subset of gases uniquely measured on M2 (see Table 5-2). We analyze on M2 the majority of samples collected by the CCGG group using automated flask packages fromtowers and aircraft

In the transition from instrument M1 to M3 in mid-2009, nearly all the plumbing for sample handling, valves, and sensors remained unchanged with one exception: we replaced the 25-year old capillary column (60-m, 0.25-mm I.D., 1-micron film DB-5) with a newer one. We made small adjustments to the oven temperature program to maintain optimal separation for chemicals of interest with the new column. An unanticipated result of this column change was the chromatographic behavior of residual water. Residual water on the new DB-5 column periodically interferes with the quantification of HCFC-142b and sample-to-sample variability for this chemical has worsened. As of late 2013, we have been looking into a solution to this problem. A 30-m, 0.32-mm I.D. PLOT column provides separation on M2. This column enables separation and quantification of a number of additional gases not readily measured on the DB-5 column used on M3. Though this instrument provides excellent results for most gases (Figure 5-3) and residual water elutes in an idle part of the chromatogram, we found that measurement precisions for some low concentration chemicals are not as tight as they are on M3, in part due to peak broadening on the more highly-retentive PLOT column. We are currently

Table 5-2: GC-MS Compounds: Chemical measured in flask air by GC-MS.

Chemical	Instrument	New Compounds Since 2004 Analysis Start Date
N_2O	Otto	
SF_6	Otto	
CFC-11	M1&M2&M3 & Otto	
CFC-12	M1&M2&M3 & Otto	
CFC-113	M1&M2&M3 & Otto	
CFC-115	M2	2007
HCFC-22	M1&M2&M3	
HCFC-141b	M1&M2&M3	
HCFC-142b	M1&M2&M3	
HCFC-21***		
HFC-134a	M1&M2&M3	
HFC-152a	M1&M2&M3	
HFC-32	M2	2007
HFC-125	M2	2007
HFC-143a	M2	2007
HFC-365mfc	M2&M3	2007
HFC-227ea	M2&M3	2007
H-1211	M1&M2&M3	
H-1301	M1&M2	2004
H-2402	M1&M2&M3	2004
CCl_4	M1&M2&M3 & Otto	
CH_3CCl_3	M1&M2&M3 & Otto	
CH_3Br	M1&M2&M3	
CH_3I	M1&M2&M3	
CH_2Cl_2	M1&M2&M3	
$CHCl_3$	M1&M2&M3	
C_2Cl_4	M1&M2&M3	
CH_2Br_2	M1&M2&M3	
$CHBr_3$	M1&M2&M3	
COS	M1&M2&M3	
CS_2**	M2&M3	2005
C_2H_2	M2	2007
C_3H_6	M3	2011
C_3H_8	M2&M3*	2007
n-C_4H_{10}	M2&M3*	2007
i-C_4H_{10}	M3*	
n-C_5H_{12}	M2&M3	2007
i-C_5H_{12}	M2&M3*	2007
n-C_6H_{14}	M2&M3	2007
C_6H_6	M1&M2&M3	
$CHBrCl_2$****	M3	2009
CFC-13****	M2	
HFC-23****	M2	

Notes:

* Only measured on a subset of CCGG flasks analyzed on M3

** Only reliably measured at some sites

*** Robust calibration scale not yet developed

**** No longer measured regularly

M1, M2, and M3 are different GCMS instruments (see text); Otto is a GC-ECD instrument. Measurements of Halon-1211 and Halon 1301 on LEAPS are discontinued.

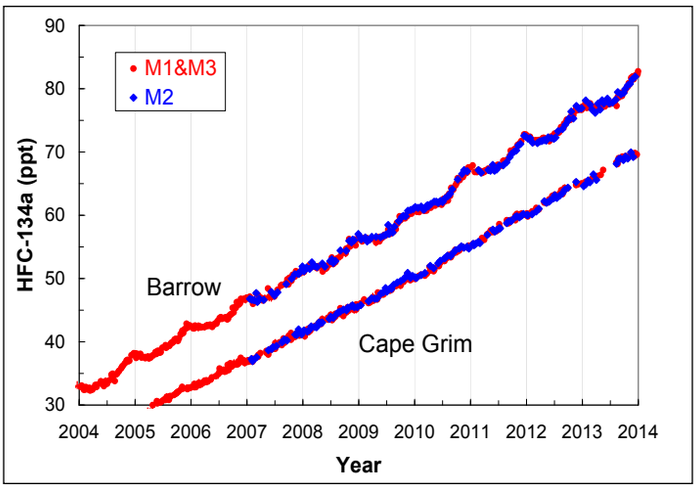


Fig. 5-3: Results for HFC-134a from flasks collected at Barrow, Alaska and Cape Grim, Tasmania since 2004. Points represent the measured mean mixing ratio in each sampled flask pair from an analysis on the different GC-MS instruments. Results from M1 and M3 (red points) are compared to the subset of flasks analyzed on M2 (blue points; ~2 flask pair/month) since 2007. The difference in mean annual mixing ratios determined from the flasks analyzed on these different instruments is -0.1 ± 0.2% at CGO and -0.1 ± 0.3% at BRW (±1 s.d., n = 7 years).

developing an additional instrument to provide highly precise measurements of all these gases and additional chemicals in a single injection. We anticipate that this instrument will provide higher precision, accuracy, and reliability at reduced analysis costs.

Compounds analyzed

In addition to the suite of chemicals measured from flasks before 2004 on GC-ECD and GC-MS (CFC-11, CFC-12, CFC-113, N_20, SF_6, HCFC-22, HCFC-141b, HCFC-142b, Halon-1211, CH_3CCl_3, CCl_4, CH_2Cl_2, $CHCl_3$, C_2Cl_4, HFC-134a, HFC-152a, CH_3Br, CH_3Cl, CH_3I, CH_2Br_2, $CHBr_3$, COS, and Benzene), we have added a number of new chemicals to the list of those regularly measured in flasks. In particular, the M2 GC-MS allows a broader suite of HFCs to be measured (Figure 5-4).

Although most trace gas measurement records have been derived from measurements on a single instrument with minimal modifications over time, there are some exceptions. We obtained results for halons (H), H-2402 and H-1301, from GC-MS during 2004 to 2006 (and a portion of 2007) with

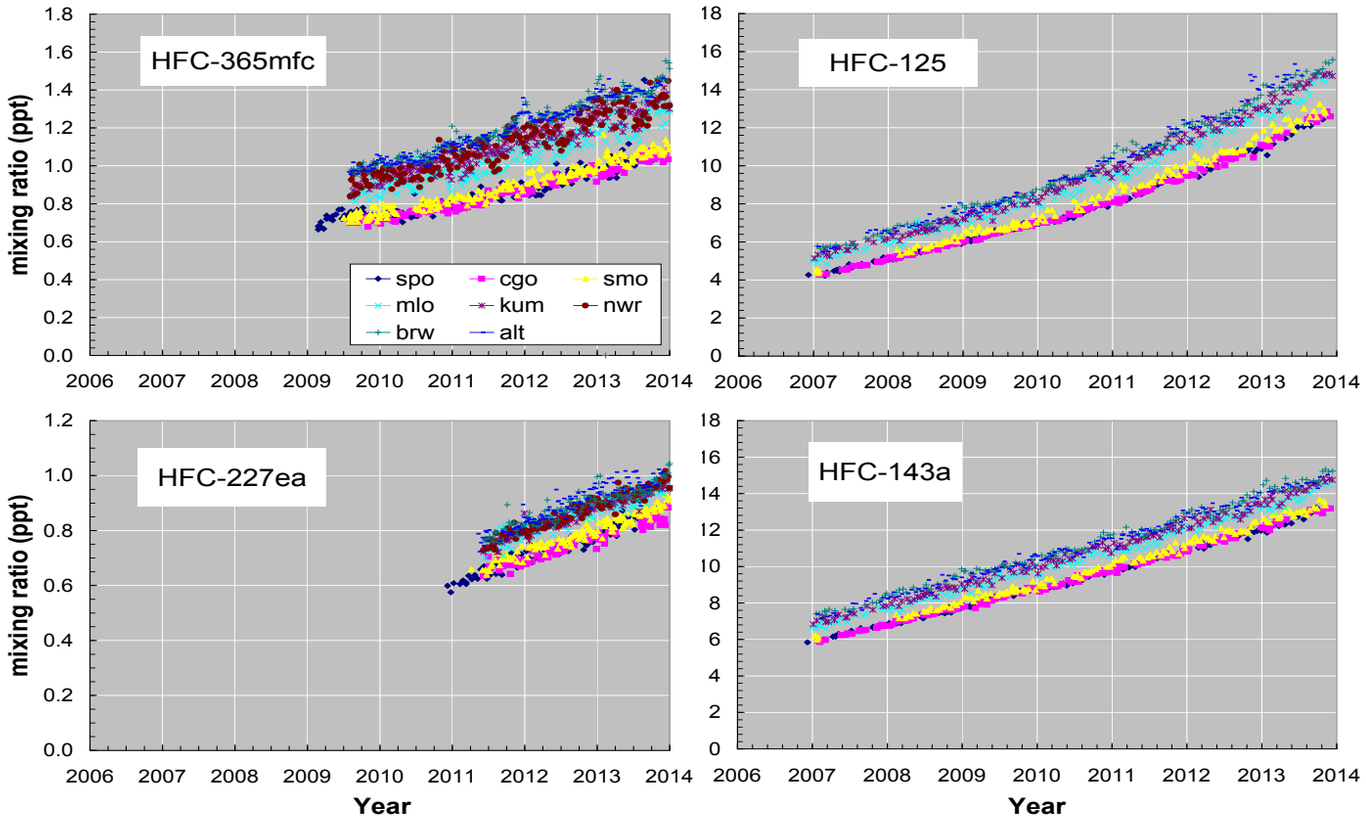


Fig. 5-4: Results for select HFC's added to the list of gases analyzed by HATS during the 2004-2013 period. Results are from HATS flasks analyzed on M3 (left-hand panels and M2 (right-hand panels).

Ascarite scrubbing as air was transferred from the flask to the cryogenic trap. This enabled sample volumes approximately double the normal size (500 vs. 250 sccm) without peak splitting of early-eluting gases owing to co-trapping of CO_2. Results for H-1301 after 2007 are from analysis of a subset of remote-site flasks on M2, while results for H-2402 after 2007 are from analysis on M3.

We made additional improvements with the introduction of M3, including the removal of a co-eluting chemical in the analysis of H-1211. We corrected data obtained from M1 to account for this artifact, providing a consistent measurement record beginning in the early 1990s through to the present.

Flask sampling

We conduct measurements at most HATS sites solely from either stainless steel (SS) or glass flasks. Since the early 2000s, we have used both glass and SS flasks at SPO; SMO; Cape Grim, Tasmania (CGO); and Park Falls, Wisconsin (LEF). At the Southern Hemisphere sites, they fill the different flask types using the same pumping apparatus. These procedures have allowed us to identify flask artifacts associated with sampling containers for some sensitive chemicals in dry air, and they have prompted the use of glass flasks exclusively at low humidity sites associated with long storage times (e.g., Summit, Greenland (SUM), Negev Desert in Israel (WIS), Mt. Waliguan in China (WLG)).

Personnel at LEF fill samples in flask types with different pumps and pumping systems (45.9°N, 90.3°W), including HATS pumps and the automated CCGG programmable compressor packages. Results for nearly all measured gases are independent of the pumps used and flask types in which samples are collected and transported to Boulder, even fairly reactive compounds such as COS and $CHBr_3$ (Figure 5-5). Results from this site demonstrate good comparability with results from the different sampling apparatus and different instruments.

While flask sampling in the HATS network continues as paired samples filled in parallel or series, samples collected in the CCGG tower and aircraft network are typically single flasks. We collect only a small fraction of the CCGG samples as paired flasks, and the air in these pairs is often used for co-measurements of $^{14}CO_2$ at INSTAAR.

Flask Analysis by GC-ECD ("Otto") DataProcesing

We use an electron-capture gas chromatograph (GC-ECD) to analyze flask samples with an instrument nicknamed "Otto". Otto has been in operation since 1995, and is capable of measuring N_2O, SF_6, CFC-11, CFC-12, CFC-113, CH_3CCl_3 and CCl_4 in stainless steel and glass flasks. We compare flask samples to two calibration standards, one with ambient mole fractions and one diluted 10% with zero-grade air. We use a linear approximation (two-point method) to determine mole fractions. The linear approximation works well as long as the ECD response is reasonably linear and the mole fraction of the sample is within the range spanned by the calibration standards.

In practice, the sample mole fractions may be outside the range covered by the two calibrations standards, and this can lead to errors in the linear approximation. This is particularly true for compounds whose atmospheric mole fractions have changed rapidly (e.g., CH_3CCl_3). To overcome these potential errors, we introduced a new data processing method in 2008. The new method takes advantage of the fact that calibration standards used over time span a range of mole fractions (they are installed on the system within a few months of being filled, and are replaced about every three

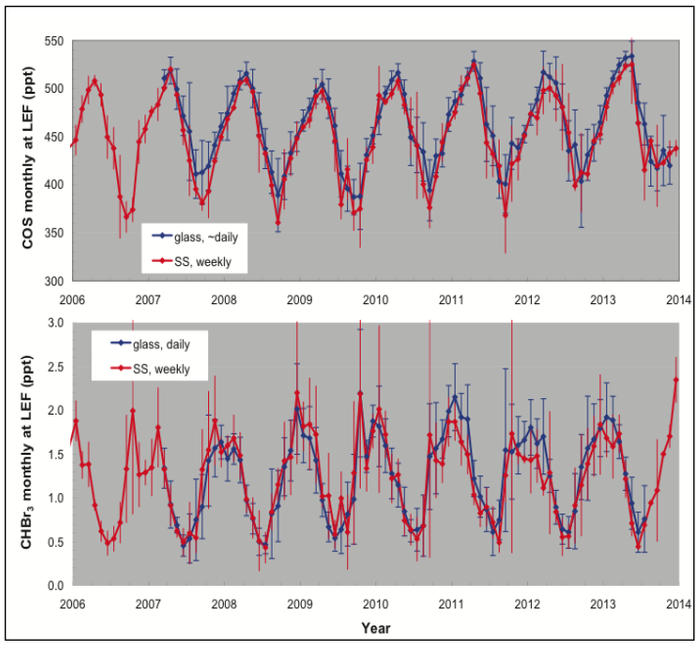


Fig. 5-5: Monthly mean mixing ratios for carbonyl sulfide (COS) and bromoform ($CHBr_3$) at LEF as determined from two different instruments, flask sampling apparati, and flask types. Results from M2 (blue line) are from 10 to 50 glass flasks sampled per month with the automated CCGG programmable compressor package; results from M1&M3 (red line) are derived from paired SS flasks sampled once per week. Error bars represent one standard deviation of the results obtained during each month.

years) and that both calibration standards used on the system are typically not changed simultaneously. Periods of overlap among existing and replacement standards provide more information about ECD non-linear response than is obtained from two standards alone. In the new method, we combine bilateral comparisons of standards over many years to estimate a non-linearity factor, which is then used to adjust the linear method to be consistent with the long-term calibration data across changes in calibration gas. This method has led to improvements in long-term consistency as mole fractions of various trace gases have changed with time. See a detailed explanation at ftp://ftp.cmdl.noaa.gov/hats/doc/HATSflaskECDanalysis.docx.

IN SITU MEASUREMENTS - HATS

We deployed six custom built gas chromatographs (GCs) at remote NOAA and cooperative institute facilities where continuous background air measurements are conducted nearly every hour. These instruments make up the HATS ground-based in situ program. We installed the current set of instruments (known as CATS: Chromatograph for Atmospheric Trace Species) in 1998 (at BRW, MLO, SMO and SPO), 2000 (at NWR) and 2007 (at SUM) and replaced the RITS instruments. The CATS GCs are composed of four chromatographic channels, each equipped with gas sample valves, flow controllers, packed columns, and an electron capture detector (ECD). NOAA built the GCs in the 1990s and they have undergone field maintenance, repairs and upgrades. We documented many of the significant changes to each CATS instrument in Table 5-3.

The CATS instrumentation measures mole fractions of N_2O, SF_6, CFC-11, CFC-12, CFC-113, CCl_4, CH_3CCl_3, and halon-1211. CH_3Cl, HCFC-22 and HCFC-142b are also measured, but the chromatography for these gases can be affected by a whole host of problems leading to poor accuracy and/or precision. Measurement of CH_3Cl, HCFC-22 and HCFC-142b requires pre-concentrating a large air sample (80 mL) onto a cold trap (a packed column from Restek: Hayesep-D, 80/100 mesh, three inches of column material in the center of a one ft, 1.0 mm ID tube), and then flash-heating the sample onto a megabore capillary column (25 ft, Chrom-

Table 5-3: Significant events and changes to CATS instruments.

Location	Date	Comment
BRW	6/15/98	Installation of CATS instrument.
BRW	Dec 2006 - May 2007	N_2O/SF_6 ECD temperature control problems.
BRW	3/13/08	WMO N_2O audit.
BRW	9/5/08	Installed new carrier gas flow controllers.
BRW	9/7/08	Installed Nafion dryer on sample lines.
BRW	5/30/13	Significant improvements to ECD temp controll-affecting N_2O/SF_6.
MLO	10/11/98	Installation of CATS instrument.
MLO	Nov 2001 - May 2003	Very nosy ECD affecting N_2O/SF_6 precision.
MLO	9/23/03	N_2O/SF_6 ECD replaced.
MLO	9/27/07	ECD replaced. CFC-11, CFC-12, and CFC-113 precision affected.
MLO	2/25/08	Installed new carrier gas flow controllers.
MLO	6/19/09	Installed Nafion dryer on sample lines.
NWR	11/9/00	Installation of CATS instrument.
NWR	7/1/06	Rainwater severely damanged GC, removed and refurbished.
NWR	10/31/07	Changed N_2O/SF_6 Chromotography to use N_2 carrier gas and CO_2 doping.
NWR	10/31/07	CG rebuit and reinstalled.
NWR	10/28/08	Installed Nafion dryer on sample lines.
SMO	12/2/98	Installation of CATS instrument.
SMO	6/12/09	Installed new carrier gas flow controllers.
SMO	9/11/09	Installed Nafion dryer on sample lines.
SMO	9/29/09	Observatory hit by 8.3 mag. Earthquake. GC sustained minor damage.
SPO	1/25/98	Installation of CATS instrument.
SPO	5/18/07	Replace N_2O/SF_6 ECD due to poor precision.
SPO	1/24/09	Installed new carrier gas flow controllers.
SUM	6/26/07	Installation of CATS instrument.
SUM	8/19/09	Installed Nafion dryer on sample lines.
SUM	6/6/10	Installed new carrier gas flow controllers (replaced Tylan MFC).
SUM	10/5/10	Building and tower moved to a new location.
SUM	7/30/13	Raised buiding and inlets about 10 ft.

pack Poraplot Q-HT). We encountered problems in the field including sample contamination, variability in sample volume, failure of chiller or flash heating electronics, and unstable calibration cylinders. Consequently, we have experienced many data gaps and accuracy issues for the CATS CH_3Cl, HCFC-22 and HCFC-142b measurements. For these gases, we should evaluate the long-term trends and tropospheric gradients from the HATS GC-MS flask program. However, we can estimate hourly and day-to-day variability for these gases from the CATS data.

You can access regularly updated CATS data online at http://www.esrl.noaa.gov/gmd/hats/insitu/cats/. The data are also used in several GMD data products including the combined N_2O, SF_6, CFC-11, CFC-12, CFC-113, and CCl_4 data sets, as well as the NOAA indices, the Annual Greenhouse Gas Index (AGGI) and Ozone Depleting Gas Index (ODGI). Several national and international assessments and publications have included these data.

Improvements to all CATS instruments

The HATS group constructed all of the CATS GCs in the 1990s with some custom designed parts, as well as commercially available power supplies, sensors, and controllers. We continue routine maintenance, including repairing and replacing components, however there have also been improvements made to the GCs during the last decade. Most significantly, we replaced all six of the carrier gas digital flow controllers (custom-built) with an off-the-shelf unit (Pneucleus Technologies LLC, 100 cc/min controller). The new controllers improved the stability of the gas flows and ultimately the precision of the GC measurements.

We dry air and calibration gas samples prior to injection via a custom-packed, inline magnesium perchlorate trap. The lifetime of these traps is much shorter at humid sampling locations. From 2008 to 2009 we installed Nafion membrane dryers (Perma Pura, ¼" OD S.S. tubing) upstream to the magnesium perchlorate trap. This improvement lengthened the duration a magnesium perchlorate trap could be used, thus simplifying field maintenance.

Instrument Changes at Niwot Ridge, Colorado

During the summer of 2006, strong winds blew off the protective cover over the air inlet at Niwot Ridge, Colorado (NWR). Subsequently, rainwater was drawn into the GC, severely damaging most of the valves, traps, columns, and flow controllers. We removed the GC from the field site and later refurbished it in Boulder. We disassembled and cleaned all of the valves, and installed new rotors. It was also an opportune time to replace the aging Tylan flow controllers with new, smaller, and more stable controllers from Pneucleus Technologies LLC. We also modified the N_2O/SF_6 chromatographic channel to improve measurement precision by changing the carrier gas, columns, and chromatography.

Installation at Summit, Greenland

We built two GCs in the mid-1990s and installed them at a pair of North American tall-tower sites (WITN in North Carolina and WLEF in Wisconsin). These GCs were very similar to the CATS instruments; custom-built, four channels equipped with electron capture detectors. Likewise, these instruments measured CFCs, N_2O, SF_6, and halon-1211; however, in place of the complicated CH_3Cl and HCFCs channel, we installed a doped ECD channel measuring H_2, CH_4 and CO. After many years of successful measurements and publications, we removed these instruments and returned them to Boulder. We refurbished one of them and deployed it at Summit, Greenland during the summer season of 2007 and incorporated it into the HATS CATS in situ program.

World Meteorological Organization N_2O audit

In March 2008 a representative of the World Meteorological Organization (WMO) World Calibration Centre (WCC) for Nitrous Oxide visited the Barrow, Alaska station. The representative conducted a site assessment and several blind audits of trace gas measurements including the CATS N_2O channel. We substituted a calibrated N_2O cylinder for an air sample on the CATS instrument. We sampled the tank eleven times over a course of 22 hours and processed the data with normal CATS algorithms as an air sample. Based on the NOAA-2006 N_2O scale, we obtained a value of 315.74 ± 0.30 ppb (1σ), which is in agreement (315.73 ppb) with the value assigned by the WCC-N_2O.

5.2 SPECIAL PROJECTS

SPECIAL HATS FLASK SAMPLING PROGRAMS

HATS-analyzed flasks associated with a number of special projects during 2004–2013 (Table 5-4). These projects focused on deriving long-term measurement histories of trace gases (firn-air

Table 5-4: Special Projects Involving Halocarbon Measurements from Flasks

Firn Air Sampling Analysis Instrument	Project
Antarctica:	
M1	Megadunes, 2004
M1	Wais Divide, 2006
M1&M2	South Pole, 2008
Greenland:	
M1	Summit shallow tubes: 2004, 2006, and 2008
M1	Summit deep hole: 2006
Other Analysis Instrument	**Project**
M2	HIPPO, tropospheric transect with profiles, 2009-2011
M2	CARVE, Arctic samples, 2001-ongoing
M1	ARCPAC, Arctic samples, 2008
M1	Harvard Forest Intensive, diurnal COS variability, 2006
M3	Boulder COS Intensive, comparisons in situ COS analyzer, 2011
M1	TROICA, Samples across Russia from a train, 2004
Additional Short-Term Projects in Collaboration with CCGG	
BARCA 2009 (Amazon)	
Sacramento [Turnbull et al.]	
Indianapolis	
Oil and Gas development investigations (Denver Julesberg, Utah, Texas, Pennsylvania)	

projects), characterizing the remote Pacific basin throughout the troposphere in all seasons (HIPPO), more focused regional aircraft studies particularly in the Arctic (CARVE and ARCPAC), regional studies to characterize trace gases associated with continental oil and gas drilling, and other short-term research investigations. The HIPPO deployments substantially augmented sampling coverage in the remote atmosphere during the five HIPPO deployments that we conducted in different months; NOAA flask programs provide long-term, ongoing atmospheric sampling throughout the year (Figure 5-6).

5.3 HATS STANDARDS PROJECT

The HATS Standards Project is an important part of the HATS overall program. We first developed gravimetric capabilities in the late 1980s and have progressed over the years. The HATS standards project supports the HATS and CCGG groups through preparation of gravimetric, compressed gas standards and whole air standards filled at the Niwot Ridge C-1 facility. You can find further details related to HATS standards and calibration activities in section 8.

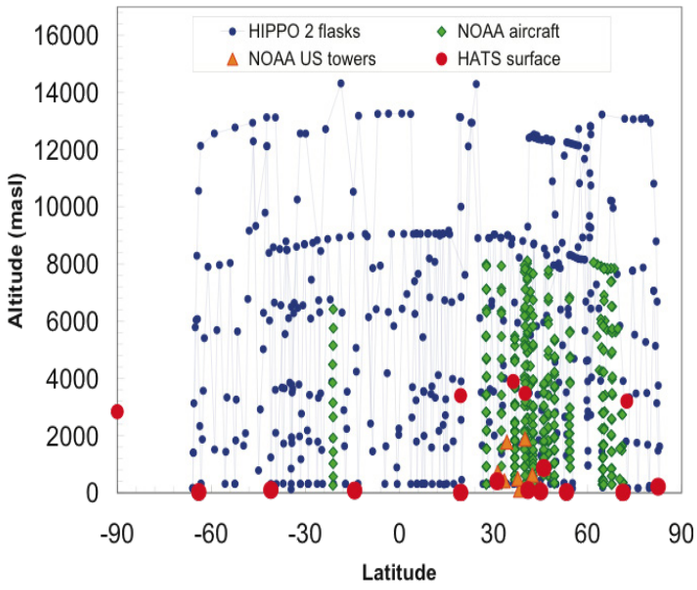


Fig. 5-6: Locations of samples collected during the month of November 2009 from HATS, CCGG, and special projects which were subsequently analyzed by GCMS: HATS paired surface flasks (red points); CCGG aircraft profiles (green points); CCGG tower network (orange points), and the second HIPPO deployment (blue points connected by lines).

5.4 AIRCRAFT

Measurements of trace gases in the free troposphere and lower stratosphere are an important part of our measurement program. We have developed several custom instruments to measure halo-

Table 5-5: Science missions involving HATS airborne instruments.

Date	Mission Name	Location	Platform	Instrument Used
2011-2014	ATTREX 1-3, Airborne Tropical Tropopause Experiment	NASA DFRC,CA; Guam	NASA Global Hawk	UCATS (O_3(2), H_2O)*
2013-2014	Sky Wisp - NOAA	Boulder, CO	Balloon, Sky Wisp	O_3, ground-based GC
2010	GloPac, Global Hawk Pacific	NASA DFRC, CA	NASA Global Hawk	UCATS (O_3, H_2O)
2009-2012	HIPPO 1-5, HIAPER Pole-to-Pole Observations (HIPPO) of Carbon Cycle and Greenhouse Gases	Pole-to-Pole open Pacific	NSF Gulfstream V	PANTHER (H_2O), UCATS (O_3, H_2O)
2008	Erie Tower	Erie, CO	Tall Tower	PANTHER
2008	START08, Stratosphere-Troposphere Analyses of Regional Transport (START) Experiment (2008)	Jeffco, North America	NSF Gulfstream V	PANTHER (H_2O), UCATS (O_3, H_2O)
2007	TC4, Tropical Composition, Cloud, and Climate Coupling	Costa Rica	NASA WB-57F	PANTHER
2006	NASA/USDA-Forest Service Fire Mission, Altair UAS	Gray Butte, CA	NASA Altair	UCATS (O_3, H_2O)
2005-2006	CR-AVE, Aura Validation Experiment (Costa Rica)	Costa Rica	NASA WB-57F	PANTHER
2005	The NOAA UAS Demonstration Project, Altair UAS	Gray Butte, CA	NASA Altair	UCATS (O_3, H_2O)
2005	ACE (WIIF), Aura Validation Experiment - Water Isotope Intercomparison Flights	NASA JSC, Houston, TX	NASA WB-57F	PANTHER (H_2O)
2005	AVE (2005), Aura Validation Experiment	NASA JSC, Houston, TX	NASA WB-57F	PANTHER
2004	Pre-AVE, Pre Aura Validation Experiment	NASA JSC, Houston, TX; Costa Rica	NASA WB-57F	PANTHER
2004	TROICA-8	Moscow to Vladivostok, Russia	Trans-Siberian Railway	ACATS-IV
2002-2004	BOS, Balloon Observations of the Stratosphere	Fort Sumner, NM	Balloon	LACE

* Second O_3 instrument added during ATTREX-2, second mission

carbons, nitrous oxide, sulfur hexafluoride, ozone, water vapor, and peroxyacetyl nitrate (PAN). We have deployed these instruments on various platforms associated with numerous campaigns (Table 5-5). The instrument PANTHER was originally designed to measure PAN, select halogenated gases, and nitrous oxide in the lower stratosphere (NASA WB-57). We then used it to determine the vertical and latitudinal distributions of a number of trace gases in the troposphere. The original design of Unmanned aircraft systems Chromatograph for Atmospheric Trace Species (UCATS) was intended for use on unmanned aerial vehicles (NASA Altair), but it has also been deployed alongside PANTHER on the NCAR Gulfstream V (GV). We developed a flask collection package called the NOAA Whole Air Sampler (NWAS) for use on larger aircraft such as the NCAR Gulfstream V. The Lightweight Airborne Chromatograph Experiment (LACE), last deployed in 2004, was designed to measure select halogenated gases and N_2O in the lower stratosphere via a balloon-borne platform. We are also developing a remotely piloted glider aircraft that could be used to collect air samples and derive vertical profiles of select trace gases. Table 5-5 lists the various platforms, instruments, and missions we have been involved in from 2004 to 2013.

Over the period 2004 to 2013, we have transitioned our missions from those focused on understanding stratospheric ozone depletion (e.g., airborne chromatograph for atmospheric trace species (ACATS) and Lightweight Airborne Chromatograph Experiment (LACE) to missions focused on climate studies, with a coincident shift from stratospheric to tropospheric observations. This shift in focus has pushed us to expand both our instrumentation and the platforms used to obtain data.

INSTRUMENTATION

ACATS-IV

Airborne Chromatograph for Atmospheric Trace Species (ACATS-IV) is a high altitude, four-channel GC-EC capable of measuring CFC-11, CFC-12, CFC-113, CH_3CCl_3, CCl_4, CH_4, H_2, SF_6, and N_2O. It was our original airborne GC designed for stratospheric air sampled by the high-altitude aircraft, NASA ER-2, and used during this period on the Russian Trans-Siberian Railway for TROICA-8 from 19 March to 1 April 2004.

LACE

Lightweight Airborne Chromatograph Experiment (LACE) is a high-altitude, three-channel GC-EC capable of measuring halon-1211, CFCs, CCl_4, CH_3CCl_3, SF_6, N_2O, CH_4, CO, and H_2.

PANTHER

PAN and other Trace Hydrohalocarbon ExpeRiment (PANTHER) is a two-channel GC-MSD, 4-channel GC-EC, and water vapor TDL capable of measuring gases listed for LACE plus PAN, some HCFCs and HFCs, methyl halides, COS, and H_2O.

UCATS

Unmanned aircraft systems Chromatograph for Atmospheric Trace Species (UCATS) is a two-channel GC-EC, ozone photometer, and water vapor TDL capable of measuring SF_6, N_2O, CH_4, CO, H_2, O_3, and H_2O.

NWAS

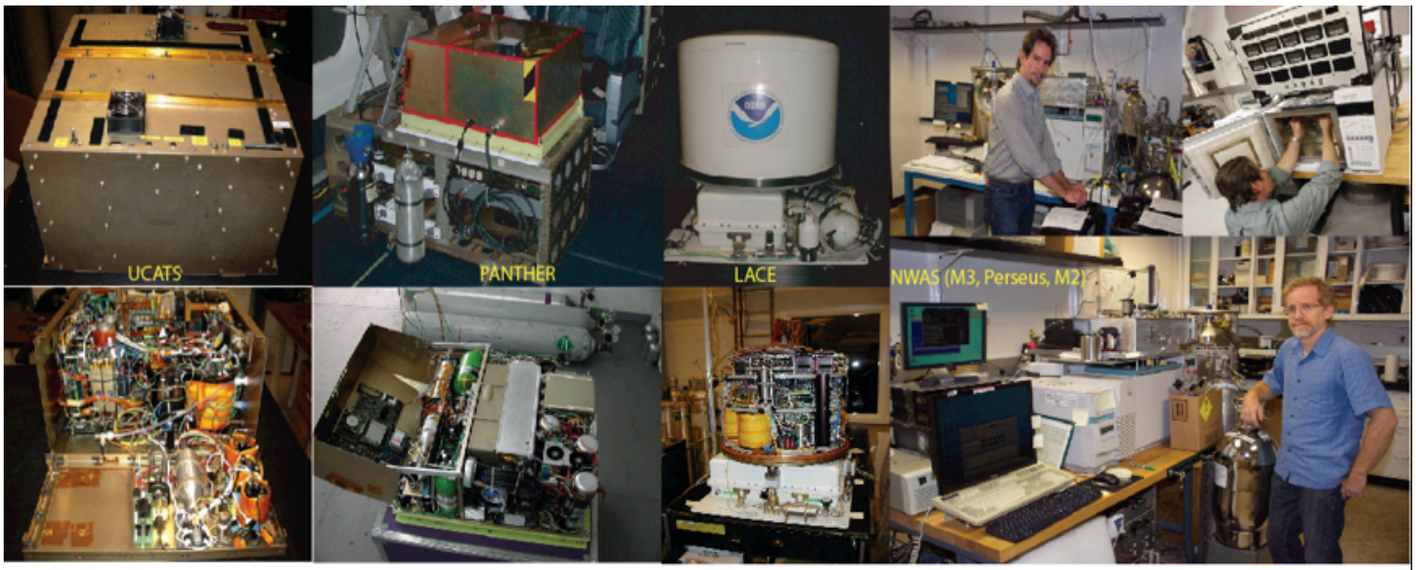
NOAA Whole Air Sampler (NWAS) is a flask-sampling system that uses the CCGG Programmable Flask Package (see section on flask special projects for more information).

StratCoreGC

This laboratory instrument is a two-channel GC-ECD capable of measuring halon-1211, CFCs, SF_6, and N_2O from AirCores collected primarily for stratospheric air.

Science themes

Convective population of the TTL region: The tropical tropopause layer (TTL) is the gateway to the



Instruments and Platforms used to generate the Global Data sets.

Fig. 5-7: Photos of instrumentation and platforms associated with airborne and special projects. Also included are small UAS platforms, SkyWisp and the 3DR Aero, that may play a role in the future.

stratosphere, and NASA missions Aura Validation Experiment (AVE), Tropical Composition, Cloud and Climate Coupling (TC4), and Airborne Tropical Tropopause Experiment (ATTREX) all focused on improving our understanding of this important region and the convective processes that define the TTL. Many short-lived and chemically-active species reach the TTL through convection from the planetary boundary layer on timescales of hours. They remain there for weeks, isolated from the free troposphere, ultimately moving up into the stratosphere where they break down and ODS release inorganic halogens, all of which affect ozone chemistry. Intense convection in the tropics also leads to low temperatures in the TTL that control the amount of water vapor that enters the stratosphere, impacting climate and ozone. The NOAA Unmanned Aircraft Systems (UAS) Demonstration Project and the NASA GloPac missions were used to demonstrate feasibility of the Altair and Global Hawk UAS, and included some flights in the TTL. Data from AVE, TC4, GloPac, and ATTREX are available on the NASA Earth Science Project Office site at https://espoarchive.nasa.gov.

Tropospheric Dynamics and Chemistry: This theme involved two NSF-based programs: Stratosphere-Troposphere Analyses of Regional Transport (START-08) and HIAPER Pole-to-Pole Observations (HIPPO). START-08 was focused on stratospheric-tropospheric exchange processes. Here we targeted the phenomenon known as tropospheric-folds, a major mechanism for bringing stratospheric air into the free troposphere. These folds can be responsible for high-ozone events at the surface that have ramifications for air quality policy. This exchange is also an alternate pathway for tropospheric air entering the lowermost stratosphere, competing with the standard tropical upwelling process. START-08 was the precursor to the global survey HIPPO campaign, which acquired data in the free troposphere at altitudes from 500 ft to above the tropopause, with seasonal coverage at nearly all latitudes in the Pacific region. Models used to predict climate and the chemical composition of the atmosphere, to a large degree, are primarily constrained by the tropospheric network of surface measurements. Satellite measurements often lack the spatial resolution and/or precision to address the vertical structure and processes occurring in the troposphere. The high degree of spatial resolution and precision, coupled with the seasonal coverage of the HIPPO data set, puts a much tighter constraint on these models, improving the accuracy of their representation of the current atmosphere. The modeling community widely requested the data set after the public release of the HIPPO data through the Carbon Dioxide Information Analysis Center (CDIAC) managed archive at http://hippo.ornl.gov/dataaccess. GMD personnel provided support and co-authorship on a large number of publications that resulted in peer-reviewed journals and presentations at international conferences. So far this work has quantified temporal and spatial structure in emissions of important greenhouse and ozone depleting gases, improved estimates of the tropospheric OH field that controls much of atmospheric chemistry, and led to improved estimates of tropospheric transport time scales. The data are also beneficial in process-oriented studies such as inter-hemispheric exchange, vertical transport in the tropics and extratropics, and the competition between bulk transport and mixing.

Stratospheric processing: The last LACE balloon flight to sample the lower- and middle-stratosphere occurred at the beginning of this report period. We now realize the importance of maintaining a continuous LACE-type stratospheric data set. Rapidly accumulating evidence shows climate-driven changes in stratospheric circulation which, in turn, induce strong feedbacks on tropospheric climate. There is a growing understanding that climate models will be limited if they do not incorporate a realistic representation of this changing stratospheric circulation. To this end, we have proposed an affordable and therefore sustainable long-term stratospheric circulation-monitoring program based on the new AirCoreTM technology. We constructed and tested the StratCore GC, which is central to the proposed program and is now operational. In addition, we have been developing new techniques to interpret stratospheric data that provide information on age-of-air and photolytic loss. We now have the ability to detangle the distributed Brewer-Dobson circulation from tropical entrainment, quasi-biennial oscillation (QBO), and other perturbations that imprint themselves on measured tracers in a dynamically evolving stratosphere. In this stratosphere-monitoring program, the AirCoreTM will be lofted to more than 30 km using a balloon. Recovery of the AirCoreTM will benefit from a steerable recovery vehicle. In preparation, we have been testing lightweight, auto-piloted gliders, such as the SkyWisp, dropped from 32 km.

SECTION 6 – OZONE AND WATER VAPOR (OZWV) RESEARCH GROUP

RESEARCH OVERVIEW

The Ozone and Water Vapor Research Group conducts long-term observations and intensive field programs using ground-based and balloon-borne instruments to measure:

- Total column ozone - (Dobson Spectrophotometer and ozonesondes)
- Ozone vertical profiles - (Balloon-borne ozonesonde and Dobson Umkehr)
- Water vapor vertical profiles - (Balloon-borne Frost Point Hygrometer)
- Ground-level ozone - (UV surface ozone monitor)
- Aircraft ozone – (UV surface ozone monitor)

We started routine measurements of the thickness of the ozone layer in the early 1960s with the establishment of the Dobson spectrophotometer global network. We maintain Instrument #83, which serves as the world standard for this network. Total column ozone measurements are made three times per day during weekdays at 16 locations around the globe with several records now surpassing 40 years. We measure Umkehr ozone profiles at six of the sites. The Umkehr profile layers fall broadly within 10 standard pressure levels.

Ozonesondes provide a high-resolution measurement of ozone and temperature from the surface to 30–35 km altitude. We started the ozone profile measurements intermittently in the 1960s using the Regener chemiluminescent balloon-borne ozonesondes which were eventually replaced by the now commonly used electrochemical concentration cell (ECC) ozonesondes. We began regular weekly ozonesonde measurements in the mid-1980s at Boulder (BLD), Amundsen Scott South Pole Station (SPO) and Hilo, HI (near MLO). The collocated Dobson instruments have been a valuable guide for comparison of total column ozone, and in turn, the ozonesonde vertical profiles complement the Dobson Umkehr profile sites. In 1995 we began ozonesonde measurements at Pago Pago, American Samoa (SMO), and since 1998 we expanded ozonesonde measurements to several tropical locations (i.e., Suva, Fiji; Watukosek-Java, Indonesia; Ha Noi, Vietnam; San Cristobal, Galapagos) through NOAA collaboration with the NASA SHADOZ program (http://croc.gsfc.nasa.gov/shadoz/). We began monitoring ozone at the Trinidad Head, CA site starting in 1997. We added weekly soundings at Huntsville, Alabama (since 1999) and at Narragansett, Rhode Island (since 2004). These sites provide data to help track polluted air masses and stratospheric folds across the continental U.S. The water vapor soundings we have taken over BLD since 1980 provide a unique long-term data record of water vapor-mixing ratio in the upper troposphere and lower stratosphere (to ~30 km) that may reveal changes in atmospheric dynamics and stratospheric ozone resulting from climate change. The cryogenic frost point hygrometer monthly launches later included two additional sites at Hilo, Hawaii (near MLO) and at Lauder, New Zealand (LDR) in collaboration with the National Institute of Water and Atmospheric Research (NIWA).

We currently monitor ground-level ozone using ultraviolet (UV) absorption photometers at eight sites that are generally representative of background conditions. These sites, four of which have records exceeding 25 years in length, provide information on long-term changes in tropospheric ozone near the surface. In addition, we have used UV ozone monitors onboard the CCGG sampling aircraft since 2004 with small, portable 2b Technologies ozone monitors. The instruments collect ozone, temperature, humidity, and GPS data during routine vertical profiling flights at nine locations. We also provide instrumentation and data analysis for a variety of special projects and campaigns.

6.1 AIRCRAFT

TROPOSPHERIC AIRCRAFT OZONE NETWORK

OVERVIEW

Since 2004, the Ozone and Water Vapor Research Group has conducted in situ measurements of atmospheric ozone-mixing ratios with small, portable 2b Technologies ozone monitors. The instruments collect ozone, temperature, humidity, and GPS data during routine vertical profiling flights around North America. As of 2013, we complete routine measurements at nine locations (see Table 6-1). However, the program also provides instrumentation and data analysis for a variety of special projects and campaigns. Due to the collaboration

Table 6-1: Aircraft Network.

Site	Location	Dates Active	Flight Frequency
ACG	Alaska Coast Guard	2011 - Current	Seasonal
CAR	Briggsdale, Colorado	March 2004 - Current	2/Month
CMA	Cape May, New Jersey	August 2005 - Current	2/Month
ESP	Estevan Point, British Columbia	March 2009 - Current	1/Month
HIL	Homer, Illinois	September 2009 - Current	1/Month
NHA	Worcester, Massachusetts	May 2005 - Current	1/Month
SCA	Charleston, South Carolina	October 2005 - Current	2/Month
SGP	South Great Plains, Oklahoma	June 2006 - Current	4/Month
THD	Trinidad Head, California	April 2005 - Current	2/Month
WBI	West Branch, Iowa	January 2005 - Current	1/Month

with the Carbon Cycle and Greenhouse Gases Aircraft Program, flask sampling packages and the ozone-monitoring equipment operate on the same flights. The flasks provide a complementary data set, including constituents such as carbon dioxide, carbon monoxide, nitrous oxide, methane, hydrogen, and sulfur hexafluoride as well as isotopes of carbon dioxide, methane, halocarbons, and hydrocarbons. These flights provide data that highlight pollution events, boundary layer stability, ozone trends, biomass burning and atmospheric mixing dynamics.

6.2 OZONESONDE VERTICAL PROFILES

OVERVIEW

The ECC ozonesonde long-term monitoring and short-term field campaign sites for 2004 to 2013 are listed in Table 6-2a & b. We provide a brief description of each campaign below. The high-resolution profiles provide data for monitoring stratospheric ozone trends and tracking the yearly Antarctic ozone hole over SPO within the main depletion layer from 14 to 21 km altitude.

Participation in intercomparison campaigns (e.g., Balloon Experiment on Standards for Ozone Sondes (BESOS) in Laramie, WY 2004) are important for addressing changes in ozonesonde models from the two manufacturers and changes in standard operating procedures that may have occurred throughout the ozonesonde records. These campaigns, including NOAA laboratory tests and dual ozonesonde flights, have shown that a change in ozonesonde model or sensing solution will require application of a correction algorithm to maintain a homogenous data record.

Recently, NOAA participated in campaigns focused on tropospheric ozone. We have analyzed tropospheric ozone variability from natural (seasonal, stratospheric intrusions, lightning) and anthropogenic sources (transported pollution) from regular sonde launches. For the first time in 2012, NOAA developed a tethered ozonesonde system with automation software for the Uintah Basin Campaign, for continuous profiling within the lower boundary layer to measure ozone production rates during local pollution events. Results were summarized in the report titled “2012 Uintah Basin Winter Ozone & Air Quality Study” at https://rd.usu.edu/files/uploads/ubos_2011-12_final_report.pdf.

The ozonesonde network in Tables 6-2a and 6-2b is a compilation of the GMD ozonesonde sites and water vapor frost point instrument sites. The first five sites listed in Table 6-2a are the GMD long-term observatories, which have 16 to more than 25 years of balloon profile measurements. The campaigns and long-term projects are also listed in the tables. We provide brief descriptions for each campaign below.

NOAA OBSERVATORY SITES

NOAA GMD observatories and cooperative sites have maintained a long-term weekly ozonesonde launch schedule to investigate tropospheric and stratospheric trends and participate in intensive ozonesonde campaigns. Website: http://www.esrl.noaa.gov/gmd/

SHADOZ

Southern Hemisphere Additional Ozonesondes (SHADOZ) is a project to augment balloon-borne ozonesonde launches and provide an archive of tropical and subtropical ozonesonde profile data.

Table 6-2a: Ozonesonde Network: Long-Term Sites

Site	Ozone	Water Vapor	NOAA Observatory	SHADOZ	Health of Atmos	IONS 2004	IONS 2006a	IONS 2006b	SEACIONS - 2013	NSF & MATCH	TICOSONDE	SOWER
Boulder, CO (BLD)	1985-2013	1980-2013	x			x	x	x	x			
Hilo, HI (MLO)	1982-2013	2010-2013	x	x								
American Samoa (SMO)	1995-2013		x	x								
South Pole (AMS)	1986-2013		x							x		
Trinidad Head, CA (THD)	1997-2013		x		x	x	x	x				
Huntsville, AL	1999-2013				x	x	x	x				
Summit, Greenland	2005-2013									x		
Narragansett, RI	2004-2011				x	x	x	x				
Suva, Fiji	1997-2013			x								
San Cristobal, Galapagos	1998-2013			x								x
Costa Rica	2005-2012			x							x	

Table 6-2b: Ozonesonde Network: Field Campaigns

Field Campaigns	Ozone	Water Vapor	Intercomparison	SHADOZ	IONS 2004	IONS 2006b	IONS 2010 (CALNEX)	Texas Tall Tower	BrO Fairbanks (NASA)	Uintah Basin-Oil & Gas	BESOS
Vernal, UT (3 tether sonde sites)	2012-2013									x	
Fairbanks, AK	2011								x		
Joshua Tree National Park, CA	2010						x				
Point Sur State Park, CA	2010						x				
Point Reyes State Park, CA	2010						x				
Shasta State Park, CA	2010						x				
San Nicolas Island, CA	2010						x				
Moody, TX	2010							x			
Table Mountain, CA	2006					x					
Pellston, MI	2004				x						
Barbados	2006-2009					x					
Lauder, New Zealand		2004-2013									
Watukosek, Indonesia (supplies)	1998-2013			x							
Ha Noi, Vietnam (supplies)	2004-2013			x							
La Reunion (supplies)	2003-2013			x							
Laramie, WY			2004								x

Beginning in 1998, the initial NASA Goddard-funded project resulted in the first profile climatology of tropical ozone in the equatorial region and provided information for satellite remote sensing methods for measuring tropical ozone. Currently, 13 sites operate in the SHADOZ network. Websites: http://croc.gsfc.nasa.gov/shadoz/ http://croc.gsfc.nasa.gov/shadoz/Sites2.html

http://croc.gsfc.nasa.gov/shadoz/Sites2.html

HEALTH OF THE ATMOSPHERE

NOAA's Health of the Atmosphere research is playing a key role in collaborative efforts that will lead to a better understanding of ozone and fine-particle pollution in the United States. Under the Health of the Atmosphere project ozonesondes are launched at four U.S. stations, including Trinidad Head, CA; Boulder, CO; Huntsville, AL; and Narragansett, Rhode Island, selected to cover air quality monitoring sites across the continental U.S. from west to east. These stations are used to track the evolution of polluted air masses that enter the U.S. on

the West coast, acquire pollution produced within the U.S. mainland, and assess levels of the pollution that leave the U.S. on the East coast. Data from these stations are often used in the Task Force on Hemispheric Transport of Air Pollution (TF HTAP). Established by the Executive Body of the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution, TF HTAP produces assessment reports on the hemispheric transport of air pollutants.

IONS - 2004, 2006A, AND 2006B

Coordinated INTEX Ozonesonde Network Study (IONS) ozonesonde launches over North America complemented the INTEX-NA and INTEX-B (https://cloud1.arc.nasa.gov/intex-b/) campaigns. We use the ozone data to complement aircraft data, validate satellite products from Aura, and to model the atmosphere. Website: http://croc.gsfc.nasa.gov/intexb/SONDES/ions06_augsept.html-http://croc.gsfc.nasa.gov/intexb/SONDES/ions06_augsept.html and http://croc.gsfc.nasa.gov/intexb/SONDES/ions06_augsept.html

IONS-2010 (CALNEX)

IONS-2010 took place for five weeks during May to June 2010. We made near-daily ozone profile measurements at six sites in California to investigate baseline ozone and transport from Asia. These sites span from northern to southern California, including Trinidad Head, Shasta State Park, Point Reyes, Point Sur, San Nicolas, and Joshua Tree.

SEACIONS

The SouthEast American Consortium for Intensive Ozonesonde Network Study (SEACIONS) project used NASA aircraft and supplemental ozonesondes across the southeastern U.S. along with daily ozonesondes from seven sites across the U.S. to aid in understanding how pollutant emissions are redistributed by deep convection throughout the troposphere. Website: http://croc.gsfc.nasa.gov/seacions/

MATCH

Match is a coordinated ozonesonde launch method under QUOBI (Quantitative Understanding of Ozone losses by Bipolar Investigations), funded by the European Commission. During the springtime, launches were coordinated at several Arctic ozonesonde sites, based on trajectory analysis, to sample air parcels at different times (up to 10 days) and determine actual chemical ozone loss rates. Website: http://www.nilu.no/quobi/

TICOSONDE

TICOSONDE projects involved collaborations between NASA (AURA), the North American Monsoon Experiment, the Instituto Meteorológico Nacional, and four other academic and scientific institutions in Costa Rica to characterize the vertical structure and temporal variability of the atmosphere over Central America during summer from 2004 to 2006. The GMD Water Vapor and Ozone Group and CIRES provided training and Frost Point instruments with ozonesondes during the projects. Website: http://acdb-ext.gsfc.nasa.gov/People/Selkirk/TICOSONDE/Ticosonde_index.html

SOWER

Soundings of Ozone and Water in the Equatorial Region/Pacific Mission (SOWER / Pacific) began in 1998 to improve our knowledge of the ozone and water vapor distributions in the tropical Pacific region by making coordinated radiosonde and ozonesonde observations at three equatorial places, the Galapagos Islands (Ecuador), Christmas Island (Kiribati), and Indonesia.

TEXAS TALL TOWER-OZONE STUDY

We measured ozone in central Texas in October 2010 to: 1) determine the influence of ozone levels in air that carry ozone and precursors from upwind sources, and 2) study frequency and influence of low-level jet stream. We launched ozonesondes near the KWKT tower in Moody, Texas to assess vertical ozone distribution throughout the planetary boundary layer and to validate in situ ozone measurements with readings continuously collected at several levels on the tower. We sent the report to the Texas Commission on Environmental Quality. Website: https://www.tceq.texas.gov/assets/public/implementation/air/am/contracts/reports/mm/5820886246FY1005-20100312-noaaesrl-nocturnal_jet_and_ozone.pdf

BRO-FAIRBANKS

BrO-Fairbanks was a two-week campaign during March and April 2011 in which we compared BrO measurement techniques and validated correlation with total ozone and ozonesonde profiles from Fairbanks, Alaska.

UINTAH BASIN – OZONE OIL & GAS FIELD STUDY

GMD participated in the Uintah Basin winter ozone study located southwest of Vernal, Utah in January and February of 2012 and 2013. Tethered ozonesondes measured profiles of ozone throughout daylight hours from the surface to ~250 m above the ground to investigate high wintertime ozone under inversions within the Uintah gas and oil fields. Website: http://www.esrl.noaa.gov/csd/groups/csd7/measurements/2012ubwos/. http://www.esrl.noaa.gov/csd/groups/csd7/measurements/2013ubwos/

BESOS

Global Atmosphere Watch (GAW) and the NOAA National Weather Service sponsored the Balloon Experiment on Standards for Ozone Sondes (BESOS). Several international organizations participated in the (BESOS) project at Laramie, Wyoming from 6–15 April 2004. A gondola carrying 18 ozonesondes (16 ECC and 2 Japanese KC96) and a reference UV ozone photometer was launched on 13 April 2004 to intercompare three different ozonesonde models and three ozonesonde-sensing solution compositions. Website: http://croc.gsfc.nasa.gov/besos/BESOS.html

OZONESONDE ECC SENSOR COMPOSITION

All of the sites and campaigns used electrochemical concentration cell (ECC) ozonesondes purchased from EN-SCI Corporation and Science Pump Corporation. The sensing solution used in each sonde consisted of 3 ml of cathode potassium iodide (KI) solutions. However, solution recipes have changed twice, once in 1998 and again in 2005. The solution recipes (compositions) used by all ozonesonde groups are shown in Table 6-3. GMD switched from the standard 1% KI buffered solution (1.0% KI-b) to an unbuffered 2% KI solution in 1998 after determining that secondary side reactions of the phosphate buffers give an enhanced ozone sensor response that is proportional to the buffer concentration. The 2% KI-u solution composition provided good results in ozonesonde intercomparisons and comparing with UV calibration sources. However, there was a higher rate of spiking (sudden one second jump in cell current followed by exponential decay) observed with the 2% KI solution, especially in the 90- to 30-hPa pressure altitude levels. The cause of spiking is random and has not been determined, but when we switched in 2005 to a modified version of the standard recipe that consists of 1% KI, 2.5% KBr with 1/10th dilution of the buffers (1.0% KI0.1b in Table 6-3) it reduced the spikes and nearly eliminated the secondary side reactions that enhance the ozone reading. Several dual ozonesonde flights and lab tests showed that ozone measured by the 2% KI-u and 1.0% KI-0.1b were within normal uncertainty range of approximately ± 5%.

NOAA Cathode Solution Switch Dates (from 1.0% KI-b to 2% KI-u).

Boulder: 21 August 1997 (BL413)

Samoa: 17 April 1998 (SA138)

South Pole: 4 March 1998 (AS557)

Fiji: 30 April 1998 (FJ045)

Hilo: 15 April 1998 (HI321)

NOAA Cathode Solution Switch Dates (from 2% KI-u to 1.0% KI-0.1b).

Boulder: 30 November 2005 (BL951)
Hilo: 20 December 2005 (HI727)

Samoa: 21 October 2005 (SA451)
South Pole: 5 June 2005 (SP147)

Trinidad Head: 15 November 2005 (TH461)
Huntsville: 1 March 2006 (HU353)

Narragansett: 22 October 2004 (RI072)
San Cristobal: ~April 2005

OZONESONDE DATA SERIES HOMOGENIZATION PROJECT

The electrochemical concentration cell (ECC) ozonesonde instruments have gone through various design improvements and standard operating procedures (SOP) have changed during the past 40 years since they were first developed. Approximately every three to four years intercomparison projects assess performance of various sonde types and procedures (e.g., Julich Ozone Sonde Intercomparison Experiment, JOSIE). Intercomparison projects have shown that SOP and instrument changes may contribute to an inhomogeneous ozonesonde record. Two examples are a switch from one ozonesonde type or manufacturer to another and the change in sensing solution composition used in ECC sondes. Other changes that may be important include: type or model of radiosonde, processing software, measurement of pump flow rate, mea-

sure of background current, total ozone normalization factors, and pump temperature (actual pump temperature or box temperature).

These intercomparison reports and independent studies (dual flights from several ozonesonde sites) have shown that a long-term data set for trend analysis requires a major data homogenization effort. This was outlined in the new SPARC-IG-ACO-IOC Initiative: Past Changes in the Vertical Distribution of Ozone (SI2N) found in the SPARC-News Article at http://igaco-o3.fmi.fi/VDO/files/Harris_ozone_trends_initiative.pdf.

For all ozonesonde sites, we initiated the intercomparison activity in 2011 with the following two major objectives:

1. Homogenization of selected ozonesonde data sets. The goal is to reduce uncertainty from 10–20% down to 5–10% primarily through a transfer function to correct older data before a switch to different model/manufacturer of ozonesondes and change in sensor solution compositions as shown in Table 6-3. We have known since 1997 and documented that the 1.0% KI-b sensor solution has a secondary reaction proportional to the amount of ozone that the solution has sampled, thus the correction factor had to account for a nonlinear artifact increase related to ozone amount.
2. Documentation of the homogenization process and the quality of ozonesonde measurements to allow the recent record to be linked to the older records.

For GMD, the homogenization project went beyond applying a transfer function correction factor, and involved a profile-by-profile review of the data and hard copy check sheets. This included adjusting for Vaisala RS-80 pressure offsets, sensor backgrounds, flow rate checks, and editing erroneous sensor spikes in the data before applying a transfer function correction. We derived the transfer function for the GMD ozonesonde data from analysis of scatterplots and best fit statistics when comparing ozonesonde measurements that used the two sensing solutions (1.0% KI-b and 1.0% KI-0.1b listed in Table 6-3). The GMD correction factor applied only for the 1.0% KI-b flights and is shown in the following equation:

$$CF = (1.0 - 0.4*\text{atm-cm}) * i$$

Table 6-3: Ozonesonde Solutions. Widely used ECC Ozonesonde Sensor Solution Compositions.

Sensor Solution	KI	Buffers: g/l and [M]		KBr
	(g/l)	$Na_2HPO_4 \cdot 12H_2O$	$NaH_2PO_4 \cdot H_2O$	(g/l)
1.5%KI-b [a]	15	7.5 (0.021)	1.88 (0.014)	37.5
1.0%KI-b [b]	10	5.0 (0.014)	1.25 (0.009)	25
1.0%KI-0.1b[c]	**10**	**0.5 (0.0014)**	**0.125 (0.0009)**	**25**
0.5%KI-b[d]	5	2.5 (0.007)	0.63 (0.005)	12.5
2%KI-u [e]	20	0	0	0

[a] Science Pump *ECC 1A Manual* [1968]; *Barnes et al.* [1985]

[b] Standard Recipe - *Komhyr* [1986]; Science Pump *ECC 6A Manual* [1996]

[c] currently used at all NOAA/GMD sites.

[d] EN-SCI *ECC 2Z Manual* [1996]; *Boyd et al. [*1998]

[e] previously used only at NOAA/CMDL sites

g/l = grams per liter; [M] = moles per liter

Where "i" is the sensor microamp current and atm-cm is the cumulative column ozone amount calculated during the flight in atmosphere-centimeters. The atm-cm data were smoothed in a one-minute running average. The typical correction factor ranged from 1.0 at the surface to approximately 0.89 (reduction of 11% in ozone reading) near burst altitude.

CHANGEOVER FROM VAISALA RS-80 TO INTERMET RADIOSONDES

Radiosondes provide vital measurements of pressure, temperature, and humidity (PTU) during balloon flights. The Vaisala RS-80 radiosonde became an integral part of GMD balloon, ozonesonde and frost point water vapor sounding payloads in 1991 that we used for the next 18 years. Even though Vaisala ceased its production in 2005, surplus RS-80s were available for purchase. By mid-2009 the GMD supply of RS-80 radiosondes was nearly exhausted. International Met Systems had just released a replacement radiosonde, the iMet-1-RSB. We conducted the first FPH sounding from Boulder with the iMet-1-RSB on 6 May 2009. In addition to PTU measurements, this new radiosonde provides a GPS-based position that enables payload tracking as well as wind speed and direction. Most importantly the iMet-1-RSB has a new open-source telemetry protocol (X-data) that allows multiple instruments to be "daisy-chained" to a single radiosonde that telemeters all of their data streams.

We had to make significant changes to the receiving software for balloon soundings to implement

the X-data protocol in the iMet-1-RSB and its capability to telemeter multiple data streams. GMD engineers developed "SkySonde", a software suite designed to receive and demodulate telemetered data streams, store raw data, display sounding data in real time, create human-readable output files at the conclusion of soundings, process and quality control sounding data after flights, and generate final data files in different formats. We replaced the DOS telemetry program (STRATO) with SkySonde at all GMD soundings sites where iMet-1-RSB radiosondes are used. However, South Pole station is the final site where we will continue using remaining surplus RS-80 radiosondes for the ozonesonde flights through 2014. Pressure and temperature data from the South Pole balloon flights are duplicated with the South Pole MET office adding their routine weather sounding RS92 radiosonde to the ozonesonde package.

6.3 SURFACE OZONE

OVERVIEW

Surface ozone (O_3) regulates the oxidation capacity of the troposphere, influencing background levels of trace chemicals. As a strong greenhouse gas, ozone is produced in the troposphere by photochemical oxidation of CO, CH_4, and non-methane volatile organic carbons in the presence of NO_x. Along with the chemical production of ozone, tropospheric ozone can be attributed to stratosphere-troposphere exchange. We monitor near ground-level ozone using ultraviolet absorption photometers at 17 sites. Eleven of these sites measure ozone conditions that are generally representative of background conditions. We use the other six sites to monitor air quality conditions in a local region. These sites provide information on possible long-term changes in tropospheric ozone near the surface.

GROUND LEVEL OZONE

GMD has been measuring surface-level ozone since 1973 at Barrow, Alaska and Mauna Loa, Hawaii. We have since expanded monitoring coverage to include 17 different sites, with the most recent beginning sampling in Weaverville, California in 2011. Table 6-4 lists all surface ozone measurement locations and dates of active measurements. We continuously measure surface level ozone with Thermo-Scientific 49i/c ozone monitors, measuring the degree to which sample air absorbs UV light at 254 nm.

UNIVERSITY OF COLORADO MOUNTAIN RESEARCH STATION COLLABORATION

In 2003, GMD installed a new instrument at the Tundra Lab at 3523 m above sea level with collaboration from the University of Colorado Mountain Research Station. This location is beneficial as a complementary data set to the Niwot Ridge-C1

Table 6-4: Ozonedsonde Network.

Site	Location	Dates Active	Calibration Date	Station Notes
ARH	Arrival Heights, Antarctica	1998 - Current	Nov-11	
PCO	Pico: Azores, Portugal	2011 - Current	Apr-01	
BAO	Erie, Colorado USA	2008 - Current	Oct-12	6m and 300m samples
BAR	Ragget Point, Barbados	1989 - Current	Sep-10	
BER	Tudor Hill, Bermuda	1988 - Current	Sep-10	Data gap: 1998-2003
BRW	Barrow, Alaska USA	1973 - Current	Jan-10	
ICE	Storhofdi, Iceland	1992 - 2010	Aug-05	Instrument failure, not replaced
LDR	Lauder, New Zealand	2003 - Current	Dec-11	
MLO	Mauna Loa, Hawaii	1973 - Current	Jan-10	
NWR-C1	Niwot Ridge, C1	1991 - Current	Jan-10	3035m elevation
NWR-TUN	Niwot Ridge, Tundra Lab	2003 - Current	Mar-13	3523m elevation; new instrument April 2013
SMO	Cape Matatula, American Samoa	1976 - Current	Oct-10	
SPO	South Pole, Antarctica	1975 - Current	Nov-11	
SUM	Summit, Greenland	2000 - Current	Jan-10	
THD	Trinidad Head, California USA	2002 - Current	Mar-09	
TIK	Tiksi, Russia	2009 - Current	Summer 2014	Arctic depletion monitoring
WKT	Moody, Texas USA	2006 - Current	Apr-09	
WVR	Weaverville, California USA	2011 - Current	Apr-11	Local seasonality

measurement site located at the same station, but 3035 m above sea level. These data are imperative for monitoring background ozone conditions as well as establishing a network of measurement locations at increasing elevations in the Rocky Mountain Region. The events of stratospheric air intrusions are detected in the unusually high ozone levels (above 70 ppbv) during spring and early summer months. The monitoring by the HATS group at a nearby location provides confirmation of extremely low levels in the measured halocarbons. We monitor both instruments on a daily basis through the AERO data program provided by the Aerosol group in GMD.

TIKSI, RUSSIA ARCTIC MONITORING

Starting in 2009, through the collaborative agreement with the Russian Roshydromet program, the NOAA Global Monitoring and Physical Sciences Divisions began to actively monitor processes in the near surface atmosphere at the Tiksi, Russia research station. We regularly report the data through the International Arctic Systems for Observing the Atmosphere (IASOA). In situ surface ozone sampling is taken continuously. Similar to the Barrow record, the low ozone events observed in the Tiksi ozone record in spring are related to the release of the bromines in the so-called "bromine explosion events" that have been related to the chemistry in the open ice leads. Observations in Tiksi are imperative for continuing research with spring Arctic ozone depletion events and providing background measurements for this region.

DATA PROCESSING, CALIBRATIONS, AND DIAGNOSTICS

The OZWV group collects surface ozone data every 10 seconds, and averages the data into one-minute, five-minute, and one-hour data files. We correct data using calibration factors calculated from the linear relationship between the field instrument and the NIST-Calibrated standard (2012 Calibration). The group monitors calibrations monthly by ozone level checks to ensure the instrument is measuring accurately. We report diagnostics each day and on a weekly basis. Parameters of temperature, pressure, flow, and intensity allow for early repair and prevention of instrument failure.

6.4 TOTAL COLUMN OZONE

OVERVIEW

We make total column ozone measurements as part of a global network to detect and understand atmospheric ozone change. At several locations, the measurement record is 40 years in length. The Dobson spectrophotometer that makes the total column measurements also measures ozone profiles using the Umkehr technique at six network locations.

DOBSON MEASUREMENTS

We continued making total ozone observations from 2004 to present at the stations that constitute the U.S. Dobson spectrophotometer network, as listed in Table 6-5. All instruments in the network are either fully automated or semi-automated, except for the one manual instrument at the Peruvian site.

NOAA and NASA personnel were unsuccessful in convincing the University administration at Florida State University (FSU) to restart the observing program, so observations there have been discontinued. The data series after 1999 is not very useful.

The instrument (D042) at SMO was damaged in the September 2009 earthquake and tsunami. SMO staff returned the instrument to Boulder and instrument D080 was sent as a replacement. We rebuilt D042 and it is currently used at SPO in rotation with D082.

We upgraded the automated systems at BLD, MLO, and Lauder, NZ (LDR) with automation designed by the Japan Meteorological Agency. The upgrade required the replacement of the instrument's internal electronics and computer interface. The automation included a software package with features allowing data analysis and quality control. The software can also be used to more efficiently process data from non-automated machines and create informative reports.

The three stations operating with the aging NOAA automation system are University of Alaska, Fairbanks (UAF); l'Observatoire de Haute Provence, France (OHP); and Perth Airport, Australia (PTH). We are making an effort to find the funding for the rebuilding of these instruments, with OHP planned for spring 2014 and UAF in spring 2015. Australian Bureau of Meteorology support for the instrument at PTH is uncertain.

Table 6-5: U.S. Dobson Ozone Spectrophotometer Station Network for 2004–2013

Station	Period of Record	Instrument No.	Agency	Automation Type
Bismark, North Dakota	1963 - 2013	33	NOAA	Semi-Auto
Caribou, Maine	1 Jan 1963 - Present	34	NOAA	Semi-Auto
Wallops Is., Virginia	1 Jul 1967 - Present	38	NOAA, NASA	Semi-Auto
American Samoa	19 Dec 1975 - Present	42	NOAA	Semi-Auto
Tallahassee, Florida	2 May 1964 - 30 Nov 1989, 1 Nov 1992 - Present	58	NOAA, Florida State University	
Boulder, Colorado	1 Sept 1966 - Present	61	NOAA	JMA automation in 2009, Unkehr
Fairbanks, Alaska	6 March 1984 - Present	63	NOAA University of Alaska	Umkehr
Lauder, New Zealand	29 Jan 1987 - Present	72	NOAA, NIWA	JMA automation in 2011, Umkehr
Mauna Loa, Hawaii	2 Jan 1964 - Present	76	NOAA	JMA automation in 2010, Umkehr
Nashville, Tennessee	2 Jan 1963 - Present	79	NOAA	
Perth, Australia	30 Jul 1984 - Present	81	NOAA, Australian Bureau of Meteorology	Umkehr
South Pole, Antarctica	17 Nov 1961 - Present	82	NOAA	
Haute Provence, France	2 Sept 1983 - Present	85	NOAA, Centre National de la Recherche Scientifique	Umkehr
Marcapomacocha, Peru	26 Feb 2001 - Present	87	NOAA, Servicio Nacional de Meteorologia d Hidologia	
Barrow, Alaska	6 Jun 1986 - Present	91	NOAA	
Fresno, California	22 June 1983 - 13 March 1995	94	NOAA	
Hanford, California	14 March 1995 - Present	95	NOAA	

Many of the operational sites transfer data electronically, once a day, allowing for access to preliminary ozone data in near real time. GMD processes all submitted data every six months and then archives it at the World Ozone and Ultraviolet Data Centre (WOUDC), Canada, in Ozone Data for the World (http://www.woudc.org).

UMKEHR OBSERVATIONS

Umkehr observations are routinely performed by automated Dobson instruments at BDR, MLO, UAF, OHP, PTH and LDR. These observations allow us to elucidate the vertical profile of the ozone layer. The algorithm used to process these measurements was refined to reduce the influence of a priori information and produce ozone profiles that can be used in long-term trend analysis, and has since been accepted as a method for reducing Umkehr data worldwide. GMD archives all NOAA Umkehr data (http://www.esrl.noaa.gov/gmd/ozwv/umkehr/) and routinely deposits it at the WOUDC (http://www.woudc.org/data_e.html) for further distribution. We are working to assess optical characteristics of each Dobson instrument (stray light contribution) to quantify long-standing differences between Dobson and other ozone measuring networks.

The NOAA EPA UV Brewer network (NEUBrew, http://www.esrl.noaa.gov/gmd/grad/neubrew/ was formed in 2006 and has six Brewer instruments installed at six NOAA stations across the continental U.S. In addition to measurements of the UV Solar spectrum, Brewer instruments have the ability to perform Umkehr-type measurements. In 2008, the retrieval algorithm and PC-based software were developed to derive ozone profiles in an approach similar to the method used in the Dobson Umkehr retrieval algorithm (http://www.esrl.noaa.gov/gmd/grad/neubrew/ProductDisplays.jsp#o3profiles). Umkehr data and retrieved ozone profiles are archived at the NOAA NEUBrew site and available at an ftp access website for free download.

CALIBRATION OF DOBSON SPECTROPHOTOMETERS

GMD maintains the World standard Dobson instrument (D083). Langley checks the calibration plot

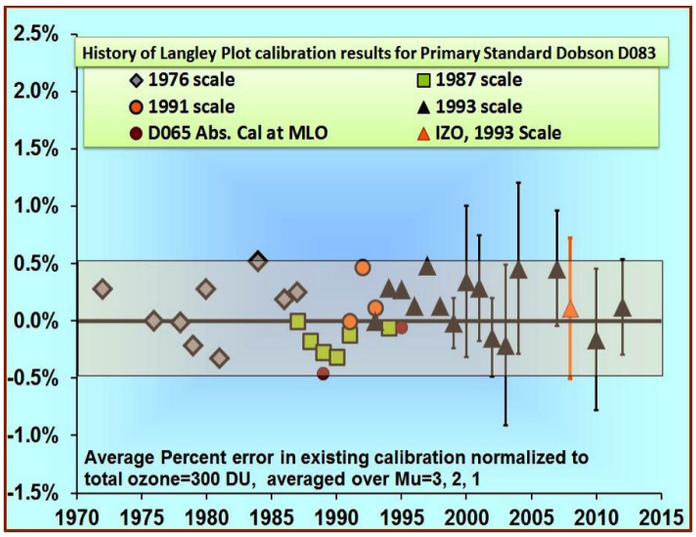


Fig. 6-1: Shows the results of Langley measurements made between 2003 and 2013. They are presented as the percent error introduced to a measurement of 300 Dobson units using the existing calibration.

campaigns at MLO approximately every other year, and results are displayed in Figure 6-1

A GMD staff member participated as the Scientific Director for the Asia Regional Intercomparison of Dobson Instruments meeting held in Tsukuba, Japan during March 2006, and in the South American Regional Intercomparison of Dobson Instruments meeting held in Buenos Aires, Argentina during November to December 2010.

The Boulder station instrument (D061) is normally compared with the primary standard (D083) whenever intercomparisons are made. The MLO station instrument (D076) is compared against the primary standard during its biannual Langley campaigns at MLO. The secondary standard (D065) is normally compared to the primary standard twice yearly. These instruments are maintained to within ±1% of the primary standard. Instrument D065 has maintained calibration to within ±0.5% since 1994.

6.5 TOWER MEASUREMENTS

TOWER- AND SURFACE- OZONE MEASUREMENTS CO-LOCATED IN ERIE, COLORADO

In 2008, GMD established a measurement location in Erie, Colorado. This location allows surface measurements to be used with the addition of tower measurements made at 300 m from a modified 2b technologies 205 ozone monitor. This combination of measurement heights allows for analysis of the vertical gradient in ozone as well as diurnal variation within and outside of the boundary layer. This location is beneficial for monitoring air quality changes from the local impact of increasing gas and oil extraction and production.

6.6 WATER VAPOR VERTICAL PROFILES

OVERVIEW

Water vapor vertical profiles are made by balloon-borne, cryogenic frost point hygrometers that we launch from Boulder, CO (BLD); Hilo, HI (near MLO); and Lauder, NZ (LDR) to obtain vertical profiles of water vapor in the upper troposphere and lower stratosphere (to ~30 km). Water vapor soundings over Boulder (since 1980) provide a unique, long-term data record that may reveal changes in atmospheric dynamics resulting from climate change. The BLD water vapor sounding program entered its 34th consecutive year of balloon-borne upper tropospheric and lower stratospheric (UTLS) water vapor measurements in 2014.

INSTRUMENT

We made only minor changes to the analog hygrometer until 2003 when substantial upgrades to electronics were required by component obsolescence. Since 2003 we have made improvements to the optical, electrical and mechanical assemblies of the FPH, including the development of a new digital hygrometer starting in 2005. We began collecting high-quality sounding data in 2008 with the new FPH after conducting extensive intercomparison flights alongside the old analog FPH and the cryogenic frost point hygrometer (CFH), developed at the University of Colorado. The new digital FPH not only realized significant improvements over the old analog hygrometer in terms of measurement reliability and quality, it also provided a number of improvements in frost point hygrometer technology, including:

- Minimized false, sunlight-driven measurement signals through rapid LED modulation and digital signal filtering, eliminating the need for a problematic sunshield
- Eradicated the fogging and icing of focusing lenses within clouds by heating

the optical components

- Improved frost layer stability from the surface to peak altitude by implementing a frost point-dependent proportional-integral-derivative (P-I-D) gain schedule for mirror temperature control
- Enabled a digital interface with ozonesondes and other instruments
- Lightened the hygrometer to <900g (including batteries and cryogen)
- Reduced the instrument size and volume of cryogen needed per flight
- Ruggedized the payload to increase the potential for hygrometer reuse
- Simplified hygrometer setup and field preparation for use by non-experts
- Enhanced real-time engineering data feedback for quality control and troubleshooting
- Improved the consistency, quality and capacity of in-house instrument production
- Expanded the FPH capability to measure the integrated precipitable water column

The digital FPH design became stable in mid-2011 after several years of minor adjustments. The current instrument incorporates a continuous copper cold finger and mirror piece that protrudes from the cryogen-filled dewar into the air flow path of the hygrometer. Air is channeled past the temperature-controlled mirror by 2.2 cm diameter x 17 cm long intake tubes shaped from thin sheets of stainless steel. When installed on the top and bottom of the mirror housing these tubes serve as entry and exit air ducts during ascent and descent of the FPH. A dynamic schedule of P-I-D values based on the measured frost point temperature enhances the ability of the FPH to stably control the frost layer over an extremely wide range (105) of water vapor number densities in the atmosphere. Styrofoam packaging provides thermal insulation to keep the FPH circuit board warm from ambient air (-80°C to 30°C) and minimizes payload damage when it lands.

NETWORK ADDITIONS (LAUDER, NZ & HILO, HI)

Since 2003, GMD added two new water vapor sites to the original BLD site. A program of monthly FPH soundings began at Lauder, NZ (45°S) in August 2004; by late 2013 the length of this data record had surpassed 9 years. Staff of the National Institute of Water and Atmospheric Research (NIWA) perform the pre-flight FPH preparations and launch the balloons at Lauder. In December 2010, GMD Mauna Loa Observatory staff initiated monthly FPH soundings from Hilo, HI (20°N).

We have been involved with numerous water vapor campaigns over the 34 years of the program. Details are located in the special projects section.

6.7 SPECIAL PROJECTS

OTHER AIRCRAFT CAMPAIGNS

Uintah Basin:
Uintah 2011–2013: We flew aircraft ozone monitors in the Uintah Basin during an intensive campaign regarding oil and gas production and high winter ozone episodes in this Basin. Due to high volatile organic carbon (VOC) content in this region in 2012, we took measurements with a 211 2b Technologies Scrubberless Ozone monitor to help eliminate contamination. We used nitrous oxide to remove ozone from the zero air, which allowed for accurate measurements.

ATTREX/UCATS/NASA Global Hawk:
Between 2011 and 2013, GMD contributed two modified 2b Technologies 205 Ozone monitors for the Airborne Tropical Tropopause Experiment along with many collaborating scientific communities. These monitors provide an accurate measurement of ozone levels in the tropical tropopause on board the unmanned NASA Global Hawk.

STRATOSPHERIC WATER VAPOR SOUNDING CAMPAIGNS AND INTERCOMPARISONS

Over the past decade GMD has contributed to many scientific field campaigns by launching balloon-borne frost point hygrometers and ozonesondes in conjunction with flights of instrumented aircraft and large payload balloons. We used GMD frost point hygrometers during several water vapor measurement intercomparisons with other aircraft-, balloon- and laboratory-based in situ and remote water vapor sensors. Note that the CFH was considered to be a GMD frost point hygrometer

Table 6-6: Water Vapor Sounding Campaigns and Inter-comparison Experiments: 2004–2013.

Site Location	Date	Number of Soundings	Campaign	Instruments
Fort Sumner, New Mexico	Sep 2004	3	BOS	FPH, ECC, RS-80
Alajuela, Costa Rica	Jul 2005	24	AVE	CFH, ECC, RS-80
Summit, Greenland	Nov 2005 - Feb 2006	4	Arctic Polar Vortex Study	FPH, ECC, RS-80
Alajuela, Costa Rica	Jan 2006 - Mar 2006	29	CR-AVE	CFH, ECC, RS-80
Table Mountain, California	Oct 2006	10	MOHAVE	CFH, ECC, RS-80
Alajuela, Costa Rica	Jul 2007 - Aug 2007	17	TC-4	CFH, ECC, RS-80
San Cristobal, Ecuador	Jul 2007 - Aug 2007	10	TC-4	CFH, ECC, RS-80
Karlsruhe, Germany	Oct 2007	2 week study	AquaVIT (AIDA chamber)	CFH
Lauder, New Zealand	Sep 2009 - May 2010	7	COMBALD Aerosol Expt.	FPH, COBALD, ECC, iMet
Table Mountain, California	Oct 2009	4	MOHAVE 2009	FPH, ECC, iMet
Table Mountain, California	Apr 2010	1	GloPac	FPH, ECC, iMet
Boulder, Colorado	Apr 2010	2	Marshall Field Inter-comparison	FPH, CFH, SWS TDL, RS-92, RR01, iMet, ECC
Houston, Texas	Apr 2011	6	MACPEX	FPH, CFH, ECC, iMet
Lauder, New Zealand	Apr 2012	3	Lidar/Balloon Inter-comparison	FPH, COBALD, ECC, iMet, RS-92
Boulder, Colorado	Jun 2012	2	Univ. of Cambridge Instrument Inter-comparison	FPH, ECC, iMet, RS-92, RR01, RS-41, SAW, UCEC, NDIR
Kunming, China	Aug 2012	38	Asian Monsoon Study	FPH, CFH, COBALD, ECC, iMet
Hilo, Hawaii	Feb 2013	2	ATTRES	FPH, ECC, iMet
Karlsruhe, Germany	Apr 2013	2 week study	AquaVIT-2 (AIDA chamber)	FPH

until 2008 when instrument fabrication was privatized and our control over design and manufacture ceased. The airborne platforms (and science projects) supported during 2004–2013 include the NASA WB-57F (AVE, CR-AVE, TC-4, MACPEX), the unmanned NASA Global Hawk (GloPac, ATTREX) and the National Scientific Balloon Facility balloon-borne in situ gondola (BOS). Intercomparison specific campaigns include AquaVIT and AquaVIT-2 at the AIDA Chamber in Karlsruhe, Germany; MOHAVE and MOHAVE 2009 at the Table Mountain Facility, California; and MACPEX at Ellington Field, Texas. See a summary of our participation in water vapor sounding campaigns and intercomparison experiments during the past decade in Table 6-6.

Instruments: Electrochemical Concentration Cell Ozonesonde (ECC); Vaisala RS-80 Radiosonde (RS-80); Cryogenic Frostpoint Hygrometer (CFH); ETH Compact Optical Backscatter Aerosol Detector (COBALD); iMet-1-RSB Radiosonde (iMet); Southwest Sciences Tunable Diode Laser Hygrometer (SWS TDL); Vaisala RS-92 Radiosonde (RS-92); Vaisala DRYCAP Sensor (RR01); Vaisala RS-41 Radiosonde (RS-41); University of Cambridge Sound Acoustic Wave Hygrometer (SAW); University of Cambridge Electrochemical Sensors for O_3, SO_2 and NO_2 (UCEC); University of Cambridge Non-dispersive Infrared Carbon Dioxide Sensor (NDIR)

OTHER SPECIAL CAMPAIGNS & MEETINGS

During April 2004, GMD participated in the Balloon Experiment on Standards for Ozone Sondes (BESOS - http://croc.gsfc.nasa.gov/besos/BESOS.html) at the University of Wyoming, supplying a Dobson D080 and an operator for both total ozone and Umkehr measurements.

The WMO/GAW Scientific Advisory Group on Ozone (SAG-O_3) held a meeting at the GMD Boulder headquarters in October 2004.

We participated in the Sodankylä Total Column Ozone Intercomparison (SAUNA - http://fmiarc.fmi.fi/SAUNA/) at the Finnish Meteorological Institute's Arctic Center during March 2006, supplying a Dobson D065 and an operator for total ozone and zenith measurements.

GMD participated in a Langley Plot Campaign at the Izaña Atmospheric Observatory (IZO), Tenerife Island (The Canary Islands), Spain during September 2008.

SECTION 7 – GLOBAL RADIATION (GRAD) RESEARCH GROUP

RESEARCH OVERVIEW

The Global Radiation (GRAD) Research Group is involved in observational and theoretical research of the Earth's surface and atmospheric radiation budgets. The group specializes in the investigation of climatically significant variations in long-term radiation and meteorological measurements made at diverse globally remote and continental U.S. sites (SURFRAD and ISIS). We are also involved in absolute measurement of spectral solar UV for the investigation of the interaction of ozone and solar radiation across the continental U.S. (NEUBrew) and in Antarctica (Antarctic UV Monitoring Network). In addition, we make observations of spectral solar radiation for the purpose of remote sensing of certain atmospheric constituents. Our research interests include the extent and cause of observed radiation and climate variations. Understanding factors affecting changes in surface radiation such as aerosol column properties, cloud macro-physical properties from surface-based measurements, and cloud forcing and feedbacks with surface radiation are important and inclusive components. Our group collaborates with other research groups making satellite observations, air quality, climate model calculations, and weather forecasts.

7.1 BASELINE AND REGIONAL RADIATION OBSERVATORIES

HISTORY AND MISSION

The Radiation Group conducts surface irradiance and optical depth measurements that provide supporting information for baseline climate monitoring activities. The group also investigates causes and consequences of trends and variations in components of the observed surface radiation at globally remote locations. GRAD Baseline and Regional Observatories' major goal is to obtain a record of surface radiation parameters that is as long and complete as possible and can be examined for all scales of natural and modified variability.

SITE LOCATION AND DATA PRODUCTS

In Table 7-1 we list the current NOAA GRAD radiation sites, location, and topography for both the

NOAA Baseline Observatories and the Baseline Surface Radiation Network (BSRN) regional observatories maintained by NOAA GRAD. Table 7-2 shows the current list of measurements and data products performed at each site. Five of the above sites are also BSRN stations. They are Barrow (BRW), Boulder Atmospheric Observatory (BAO), Bermuda (BERM), Kwajalein (KWAJ), and South Pole (SPO). You can obtain the BSRN data from the BSRN archive at http://bsrn.awi.de/. Edited, one-min (three-min prior to 1998) averages for the irradiance data are available at the GMD FTP site: ftp://

Table 7-1: The current GRAD NOAA Baseline and Regional Observatories, location, and topography.

Baseline and Regional Observatories					
Station	**Latitude**	**Longitude**	**Elevation**	**Topography**	**Inception**
Alert (ALT)	82.45	-62.51	200	Tundra	Aug-14
Eureka (EUR)	80.22	-86.18	138	Tundra	Aug-14
Summit (SUM)	72.58	-38.48	3238	Snow	Aug-14
Tiksi (TIK)	71.6	128.89	5	Tundra	Jun-14
Barrow (BRW)	71.32	-156.6	8	Tundra	Jan-76
Trinidad Head (THD)	41.05	-124.15	104	Forest	Apr-02
Boulder Atmos Obs (BAO)	40.05	-105.08	1584	Plains	Sep-89
Bermuda (BERM)	32.3	-64.77	60	Island	Apr-91
Mauna Loa (MLO)	19.54	-155.58	3400	Mountain	Jan-76
Kwajalein (KWAJ)	8.72	167.72	10	Island	Apr-92
American Samoa (SMO)	-14.25	-170.56	82	Island	Jan-76
South Pole (SPO)	-90	-102	2841	Snow	Jan-76

Table 7-2: Measurements made at each GRAD Baseline and Regional Observatory. http://www.esrl.noaa.gov/gmd/grad/instruments.html.

Measurements Made at Each Station												
Broadband Irradiance (unless otherwise noted)												
	ALT	**EUR**	**SUM**	**TIK**	**BRW**	**THD**	**BAO**	**BER**	**MLO**	**KWJ**	**SMO**	**SPO**
Direct solar beam	X	X		X	X	X	X	X	X	X	X	X
Diffuse solar	X	X		X	X	X	X	X	X	X	X	X
Total downward solar	X	X	X	X	X	X	X	X	X	X	X	X
Reflected solar	X	X	X	X	X		X					X
Downward IR	X	X	X	X	X	X	X	X	X	X	X	X
Upward IR	X	X	X	X	X		X					X
Other Measurements												
Spectral optical depth	X				X	X	X	X	X	X		X
All-sky digital imagery	X[1]				X[2]		X[3]	X[4]				
Wideband direct solar irradiance					X[5]				X[5]		X[5]	X[5]
Soil temperatures*	X[6]	X[7]		X[8]	X[9]							
Apparent transmission									X			

Discontinued: 1 - May-2012, 2 - August-2012, 3 - July-2013, 4 - June-2008
Discontinued: 5 - 2012
*Ten measurements are made from depths of 5 cm to 120 cm.
Started: 6 - September-2005, 7 - June-2008, 8 - April-2011, 9 - November-2011

ftp.cmdl.noaa.gov/data/radiation/baseline. There is a directory for each site at this location. You can find descriptions of the routine operations, standard activities, and calibration efforts at http://www.esrl.noaa.gov/gmd/grad/srf.html. There is also a timeline for each data type for all stations. All other data are available upon request at http://cmdl1.cmdl.noaa.gov:8000/ftp/timeline.html.

SITE, INSTRUMENT, OR DATA MODIFICATIONS

We were informed that the ARM site located near the GMD Barrow Observatory was operating a TSI all-sky imager, so we decided to decommission the TSI all-sky imager at BRW due to extensive rust and lack of funding to keep the imager in good operating condition.

We added SP02 spectrophotometers at SPO, BRW, and MLO for calculating aerosol optical depth. South Pole and Barrow's instruments require rotation through the Mauna Loa Observatory for annual calibration due to the inability to perform in situ calibrations at high latitude sites. We can take Barrow's instruments off line in the winter and return before sunrise. However, shipping to South Pole requires that we have a second instrument so that we can alternate between calibration and measurements.

GMD added an internet (web) camera at SPO and BRW to provide a live feed of images. Barrow's camera is also used to monitor and troubleshoot instrumentation issues and calculate snow depth.

The corrosive environment at Barrow was causing the sonic snow depth sensor to fail every other year. Funding was not sufficient to support the maintenance required so we removed the sensor.

GMD built and installed a sensor at Barrow to monitor the permafrost active layer thickness to a depth of 120 cm. The data are used to augment the BSRN and energy budget studies as part of the Study of Environmental ARctic CHange (SEARCH).

7.2 INTEGRATED SURFACE IRRADIANCE STUDY (ISIS)

HISTORY OF ISIS AND STATION INFORMATION

The Integrated Surface Irradiance Study (ISIS) solar radiation network is the result of an Environmental Services Data and Information Management (ESDIM) grant to the NOAA Air Resources Laboratory (ARL) to save about one-third of the solar radiation stations of the defunct U.S. SOLRAD network. The SOLRAD network began in the 1970s with approximately 30 U.S. stations that were located primarily at NWS offices. After several buildups and failures, SOLRAD was abandoned in 1993. Ten of those stations were preserved as ISIS. The Atmospheric Turbulence and Diffusion Division (ATDD) of ARL in Oak Ridge, Tennessee refurbished six SOLRAD stations in 1995, and four in the subsequent year. Station location, elevation, and other relevant information are listed in Table 7-3 for the 10 original ISIS stations as of 2013. The local hosts abandoned two of the original stations, Oak Ridge, Tennessee and Tallahassee, Florida, and in 1998 the ISIS station at Desert Rock, Nevada was converted to a SURFRAD station. Although ESDIM funding expired in 1997, the ARL ATDD continued to operate ISIS with base funds through January 2002. In February of that year responsibility for ISIS was transferred to the ARL Surface Radiation Research Branch (SRRB) in Boulder, Colorado. In 2005, ARL SRRB merged with ESRL/GMD, and we assumed responsibility for ISIS.

ISIS STATION INFRASTRUCTURE

ISIS stations measure only downwelling solar radiation. You can see a typical station in Figure 7-1. We listed ISIS instrumentation and their characteristics in Table 7-4. The direct-normal and diffuse components of downwelling solar are measured by instruments mounted on a solar tracker, which are combined for the best estimate of downwelling solar radiation. We also deployed a single-detector pyranometer as a backup in case the solar tracker fails. After ARL SRRB took over management of ISIS, several improvements were made. Originally Eppley PSP pyranometers were shaded for the diffuse solar measurement, but in 2002 we replaced them with Eppley model 8-48 pyranometers for reasons given in the SURFRAD section. Ultraviolet B radiation (UVB) is the only other measurement we make at ISIS stations. Originally, we deployed the Solar Light UVB radiometer, model 501A, but as those instruments deteriorated we replaced them with Yankee Environmental Systems, model UVB1 radiometers. SRRB also discontinued the use of homemade ventilators and housed the global and diffuse pyranometers in commercial ventilators as further improvements. In June 2009, we replaced the UVB radiometer at Madison, Wisconsin with a

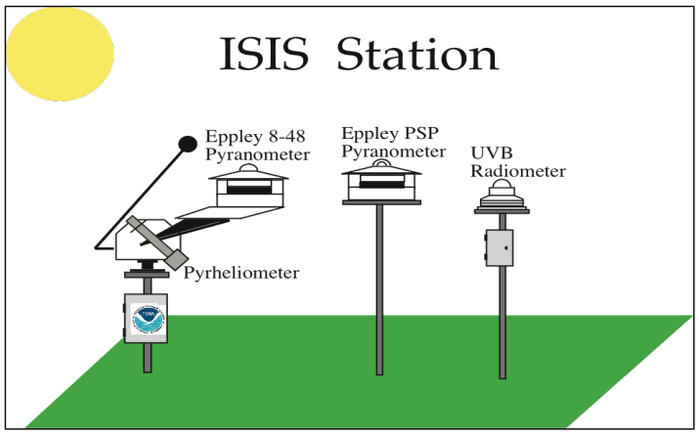


Fig. 7-1: Complement of instruments at each ISIS network station. Downwelling radiation only is measured at these sites.

Table 7-3: Locations and operating periods of the ten original ISIS stations.

Station name	Latitude	Longitude	Elevation (m)	Start date	End date	Nearest city	Station ID
Albuquerque	35.04	-106.62	1617	3 Mar 1995	N/A	Albuquerque, NM	ABQ
Bismarck	46.77	-100.77	503	9 Jul 1996	N/A	Bismarck, ND	BIS
Hanford	36.31	-119.63	73	25 Apr 1996	N/A	Hanford, CA	HNX
Madison	43.13	-89.33	271	12 Jun 1996	N/A	Madison,WI	MSN
Oak Ridge	35.96	-84.29	334	20 Oct 1995	8 Jun 2007	Oak Ridge, TN	ORT
Seattle	47.68	-122.25	20	23 Mar 1995	N/A	Seattle, WA	SEA
Salt Lake City	40.77	-111.97	1288	29 Aug 1996	N/A	Salt Lake City, UT	SLC
Sterling	38.98	-77.47	85	25 Aug 1995	N/A	Herndon, VA	STE
Tallahassee	30.38	-84.37	18	15 Jan 1995	30 Oct 2002	Tallahassee, FL	TLH
Desert Rock	36.62	-116.02	1007	30 Jun 1995	28 Jun 1998	Mercury, NV	DRA

Table 7-4: Instruments and measurements employed at the ISIS sites.

Instrument	Manufacturer	Wavelength range	Dome/diffuser	Detector	Parameter measured
Pyranometer, model PSP	Eppley Laboratory	280-2800nm	Two WG295 Schott filter domes	Thermopile	Global solar irradiance
Pyranometer model 8-48	Eppley Laboratory	280-2800 nm	One WG295 Schott filter dome	Thermopile	Diffuse solar irradiance
Pyrheliometer, model NIP	Eppley Laboratory	280-2800 nm	WG295 window	Thermopile	Direct-normal solar irradiance
UVB Radiometer, model UVB-1	Yankee Enviromental Systems	280-320 nm	Schott WG280 quartz dome and UG11 filter	GaAsP photodiode	Erythemal UVB irradiance
Solar Light UVB radiometer, model 501A	Solar Light	280-320 nm	Fused silica (quartz)	GaAsP photodiode	Erythemal UVB irradiance
Pyrgeometer, model PIR (Madison only)	Eppley Laboratory	4000-50,000 nm	Silicon dome with interference filter coating	Thermopile	Upwelling and downwelling thermal infrared irradiance

pyrgeometer at the request of the local host.

We have attempted to visit ISIS stations on an annual basis, however, without funding, that is practically unachievable. We made several site visits on trips of opportunity, e.g., nearby conferences and side trips from SURFRAD visits.

DATA PRODUCTS & QUALITY ASSURANCE

From 1995 through January 2002, we recorded 15-min averages of 1-sec samples at ISIS stations. When ARL SRRB took over in 1 February 2002, they increased the temporal resolution to three min. They also began to distribute daily files of ISIS data from the anonymous FTP site at: ftp://aftp.cmdl.noaa.gov/data/radiation/isis/. Daily ISIS files for individual stations are organized temporally in UTC. They are available in station and year subdirectories and made available on a next workday basis. You can access graphic displays of daily time series of measured quantities on the interactive web site: http://www.esrl.noaa.gov/gmd/grad/isis/isispick.html.

The ISIS FTP site listed above has a folder labeled "1995–2001" that contains data before SRRB took over the network in 2002. Those data are only available in the form that they were submitted to the National Climatic Data Center (now the National Centers for Environmental Information (NCEI)), i.e., hourly averages organized in monthly files in local standard time: ftp://aftp.cmdl.noaa.gov/data/radiation/isis/1995-2001/ISISNCDC/.

On a regular schedule, we replace batteries, fans, and other equipment that naturally deteriorate, and exchange instruments on a quasi-annual basis for two reasons: 1) to keep calibrations current and 2) to eliminate sensor drift in long-term trend analysis. Pyranometer and pyrheliometer calibrations are directly traceable to the World Radiometric Reference (WRR), which is located at the World Radiation Center in Davos, Switzerland. Before 2005, ISIS solar radiometers were calibrated at the National Renewable Energy Laboratory in Golden, Colorado, and from 2005, they have been calibrated by the World Meteorological Organization Region 4 Regional Solar Calibration Center in Boulder. Both centers employ essentially the same method and WRR-traceable reference instruments. To ensure a reputable product, an analyst checks all ISIS data before being released.

7.3 SURFRAD NETWORK

MISSION AND RATIONALE

GMD established the U.S. Surface Radiation Budget Network (SURFRAD) in 1993 through the support of NOAA's Office of Global Programs. We began to distribute data in January 1995. SURFRAD is the first and only operational national-scale network of its kind. Its primarily supports global change research, NOAA and NASA satellite programs, renewable energy activities, and numerical modeling for weather and climate, with continuous measurements of the surface net radiation budget. Considering that upward radiation is negative by convention, the surface net radiation is the sum

of four primary measurements: broadband downwelling and upwelling (reflected) solar (280–3500 nm), and broadband downwelling and upwelling thermal infrared (3500–10,0000 nm). It represents the available energy at the surface for atmospheric heating and evaporation, which are the primary energy sources for weather and climate. Accurate model synthesis and satellite-based estimates of surface net radiation are essential for credible climate studies and assessments.

We make ancillary measurements of cloud cover, aerosol optical depth, atmospheric state variables, direct and diffuse solar irradiance, UVB radiation, and photosynthetically active radiation to increase the versatility of SURFRAD data for research. We also produce twice-per-day interpolated atmospheric soundings and equivalent clear sky irradiance products.

You can see sixteen years of continuous Surface Radiation (SRB) measurements from SURFRAD in Figure 7-2. There has been an extraordinary increase of surface net radiation over the U.S. from 1996 to 2011. Analysis of the individual SRB components show that a systematic increase in downwelling solar at the surface due to decreasing clouds contributed most to the net radiation increase.

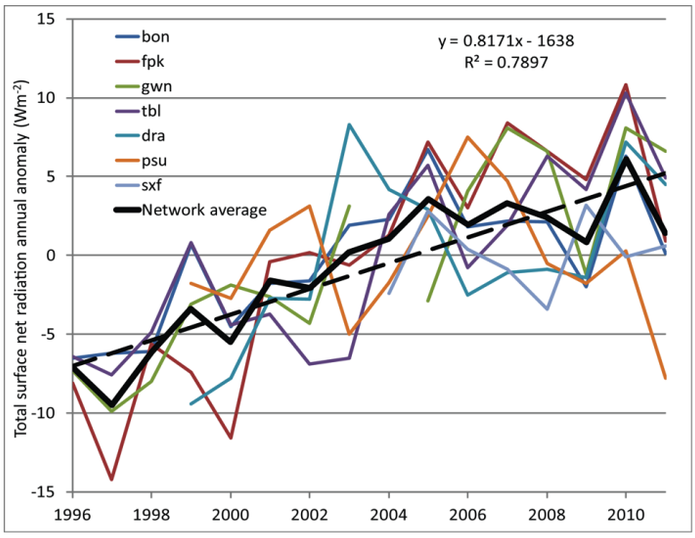


Fig. 7-2: Time series of total surface net radiation annual anomalies at the SURFRAD Network sites. Color curves represent the individual stations, and the heavy black curve is the network mean. The dashed line is a least-squares linear fit to the network mean for which the best-fit equation and coefficient of determination R^2 are given at upper right.

SURFRAD STATIONS

The SURFRAD network is shown in Figure 7-3. We began to operate four stations in 1995. Stations at Desert Rock, Nevada and Penn State were added in 1998 and Sioux Falls, South Dakota was installed in June 2003. Location, elevation, and representative surface type for each station is listed in Table 7-5. The spatial distribution of SURFRAD stations well represents the north-south and east-west cross section of the U.S. climate. Pictures of SURFRAD stations and their surroundings are available at http://www.esrl.noaa.gov/gmd/grad/surfrad/sitepage.html.

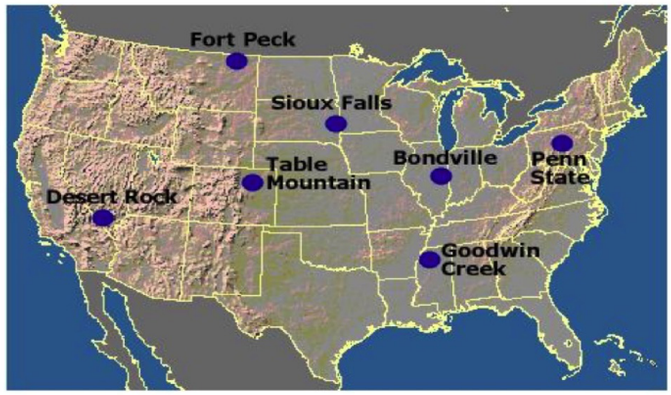


Fig. 7-3: The seven SURFRAD site locations, distributed to represent distinct climatological regimes across the continental U.S.

INSTRUMENTATION AND INFRASTRUCTURE

Instruments and support equipment at SURFRAD stations reside on three platforms that are generally aligned north to south. That orientation ensures that the station's physical structures do not interfere with the measurements. Upward-viewing radiometers rest on a rectangular fiberglass grating (~0.3 m by 3 m) and a solar tracker. The rectangular grating, hereafter referred to as the main platform, is elevated about 2 m above ground level. The solar tracker is on a separate post that is typically about 3 m south of the main platform. Initially, Eppley solar trackers were deployed but they were replaced in 1999 by SCI-TEC (now Kipp & Zonen) solar trackers. The solar tracker hosts a pyrgeometer that measures downwelling thermal infrared irradiance, a shaded Eppley 8-48 pyranometer for diffuse solar irradiance, and a pyrheliometer that is kept trained on the solar disk

Table 7-5: Location of the SURFRAD Network sites.

Station name	Latitude	Longitude	Elevation (m)	Start date	Nearest city	Station ID	Surface type
Bondville	40.052	-88.373	213	1 Jan. 1995	Bondville, IL	BON	Prairie grass
Fort Peck	48.308	-105.102	634	28 Jan. 1995	Poplar, MT	FPK	Prairie grass
Goodwin Creek	34.255	-89.873	98	1 Jan. 1995	Batesville, MS	GWN	Pasture
Table Mountain	40.125	-105.237	1689	19 Jun. 1995	Boulder, CO	TBL	Sand, rock, scattered desert shrubs, sparse grasses
Desert Rock	36.626	-116.019	1007	16 Mar. 1998	Mercury, NV	DRA	Fine rock and gravel, scattered desert shrubs
Penn State	40.72	-77.931	376	29 Jun. 1998	Pine Grove Mills, PA	PSU	Grass and crops
Sioux Falls	43.734	-96.623	473	15 Jun. 2003	Sioux Falls, SD	SXF	Prairie grass

to measure direct-normal solar irradiance, or the solar beam. You can find instrument descriptions at http://www.esrl.noaa.gov/gmd/grad/instruments.html. A 10-m tower located 25 m or more north of the main platform supports downward viewing radiometers that measure reflected solar and upwelling IR irradiance, and most meteorological instruments. The only exception is that the barometer is located under the main platform. Because of local constraints, the tower at Desert Rock is located south of the main platform and the solar tracker is furthest north, but they are far enough away from each other that interference is not an issue. A cross arm at the 8-m level of the tower supports the down-looking radiometers and is also aligned north to south. You can find a listing of the instruments and their characteristics in Table 7-6.

We made changes to the instrument strategy as the network matured. Diffuse solar was not a part of the original suite of measurements in 1995, but by 1996 all four existing stations included a diffuse solar measurement. Originally, a single-detector

Table 7-6: Instruments and measurements employed at the SURFRAD sites.

Instrument	Manufacturer	Wavelength range	Dome/diffuser	Detector	Parameter measured
Pyranometer, model SR75	Spectrolab	280-2800nm	Two WG295 Schott filter domes	Thermopile	Global and reflected solar irradiance
Pyranometer model 8-48	Eppley Laboratory	280-2800 nm	One WG295 Ssschott filter dome	Thermopile	Diffuse solar irradiance
Pyrheliometer, model NIP	Eppley Laboratory	280-2800 nm	WG295 window	Thermopile	Direct-normal solar irradiance
Pyrgeometer, model PIR	Eppley Laboratory	4000-50,000 nm	Silicon dome with interference filter coating	Thermopile	Upwelling and downwelling thermal infrared irradiance
UVB Radiometer, model UVB-1	Yankee Enviromental Systems	280-320 nm	Schott WG280 quartz dome and UG11 filter	GaAsP photodiode	Erythemal UVB irradiance
Quantum Sensor, model LI-190SA	LI-COR	400-700 nm	Acrylic diffuser	Silicon photodiode, interference filters	Photosynthetically active radiation
MFRSR	Yankee Environmental Systems	415, 500, 614, 670, 870, 940 nm and broadband solar	Spetralon diffuser	Silicon photodiode, interference filters	Global and diffuse spectral irradiance
Total Sky Imager	Yankee Environmental Systems	N/A	Reflective mirror	Camera	Total sky image, fractional cloud cover
Wind monitor, model 05103	R. M. Young	N/A	N/A	Propeller and vane	Wind speed and direction
Temperature and RH probe	Vaisala	N/A	N/A	Platinum resistance thermometer/INTERCAP capacitive chip (for RH)	Temperature and relative humidity
Barometer, model PTB110	Vaisala	N/A	N/A	Silicon capacitor	Air pressure

pyranometer was shaded to measure diffuse solar, but during the 2001 instrument exchanges we replaced them with Eppley model 8-48 pyranometers that do not have a thermal offset error that is common to single-detector pyranometers. We corrected thermal offsets in all diffuse solar data prior to introduction of the model 8-48. During the instrument exchanges in 2000, we moved the up-looking pyrgeometer from the main platform to the solar tracker so that its dome could be shaded according to accepted standards. Shading the pyrgeometer dome averts errors in the downwelling IR measurements caused by uneven dome heating by the solar beam, and also blocks the very small amount of thermal infrared contained in the solar beam. A complete history of radiometer deployments and their calibration values are accessible by station at http://www.esrl.noaa.gov/gmd/grad/surfrad/getcals.html.

We have changed the model of the temperature and RH probe at SURFRAD sites at least three times, but accuracy has not been affected. During the annual instrument exchanges in 2010 (2011 for Table Mountain), we added a second temperature and RH probe at the level of the solar tracker, which is nominally 2 m AGL. We have not yet added the "screen level" meteorological data to the processed data files. We installed total sky imagers (TSI) at SURFRAD stations in 1999 and 2000. At Fort Peck, Montana, we added a small trailer to support the TSI installation. We removed the enclosure that originally housed that station's UPS and the UPS was relocated to the trailer. At the Goodwin Creek, Mississippi station a small pre-existing shed within the fenced station enclosure originally housed the UPS, TSI computer and other support equipment. In November 2010, we replaced the shed with an underground shelter. Although the Sioux Falls station was installed in June 2003, we did not install a TSI there until 2008.

SURFRAD PRODUCTS

The GRAD group makes daily quality-controlled SURFRAD data files in UTC available the following workday via the GMD anonymous FTP site ftp://aftp.cmdl.noaa.gov/data/radiation/surfrad/. We also make monthly averages of the measurements and computed variables available at ftp://aftp.cmdl.noaa.gov/data/radiation/surfrad/averages/. We reorganize SURFRAD data to local standard time, formatted into monthly tables of hour averages, and send to the National Centers for Environmental Information (NCEI), formerly the National Climatic Data Center (NCDC). From there we forward the hour-averaged SURFRAD data to the World Radiation Data Center in St. Petersburg, Russia. SURFRAD stations represent a large part of the U.S. contribution to the international Baseline Surface Radiation Network (BSRN). We routinely send SURFRAD data and local radiosonde soundings to the BSRN data archive in Bremerhaven, Germany. Through the BSRN, all SURFRAD stations became members of the Global Climate Observing System (GCOS) in April 2004.

We originally recorded SURFRAD broadband radiation and meteorological data as three-min averages of one-sec samples. On 1 January 2009, data collection switched to one-min averages of one-sec samples. We have always recorded Total Sky Imager data at a one-min frequency. We make text files of cloud fraction data derived from the TSI images available at ftp://aftp.cmdl.noaa.gov/data/radiation/surfrad/TSI/, and the one-min raw and processed TSI images available upon request.

The Multi-Filter Rotating Shadowband Radiometer (MFRSR) records spectral data for aerosol optical depth (AOD) calculations. Its channels are nominally centered at 415 nm, 500 nm, 615 nm, 670 nm, 870 nm, and 940 nm, although the 940 nm channel data are not processed for AOD because it is in a water absorption band. The way that MFRSR data are recorded has gone through several variations. Before March 2008, SURFRAD-owned MFRSRs recorded 2-min averages of 15-sec samples, but on 1 March 2008 they began collecting 20-sec samples that are combined into 1-min averages in post analysis for AOD processing. SURFRAD uses data from MFRSRs operated by the USDA at Bondville and Fort Peck, but we are constrained by their three-min data. The MFRSR is the only radiometer that is not replaced annually because it is calibrated in situ and enables instrument consistency. We compute aerosol optical depth at the frequency of the raw MFRSR data and make it available in cloud-screened daily files for each station at ftp://aftp.cmdl.noaa.gov/data/radiation/surfrad/aod/. Eventually, we will install down-viewing MFRSR heads on SURFRAD towers. We will synchronize those measurements with the existing up-looking MFRSR to compute spectral albedo. A prototype of that set-up has been operating at Table Mountain since 2010.

The sensitivity of several MFRSR channels has degraded over the long deployments and subsequently, as of 2012 and 2013, AOD data quality has declined. In the worst case, AOD had not been computed for the Penn State station since 2009. However, we are purchasing new MFRSRs and a slow replacement process has begun. In 2013 the Sioux Falls MFRSR was the first to be replaced with a newly designed model. In the new models we selected a near IR channel centered on 1623 nm to improve the retrieval of aerosol size distribution, replacing the 615 nm channel.

Vertical profiles of temperature and moisture are desirable for initiation of radiative transfer models. Unfortunately, SURFRAD stations are typically not close to National Weather Service (NWS) radiosonde sites. To provide such information, we interpolate vertical profiles of air temperature, dew point temperature, and wind from the national radiosonde network to SURFRAD station locations. Twice per day (0000 and 1200 UTC), interpolated soundings at station locations for the entire SURFRAD data record are available at: ftp://aftp.cmdl.noaa.gov/data/radiation/surfrad/sounding/. Desert Rock, Nevada was the only station that was collocated with an operational radiosonde, however in January 2011 the NWS moved that launch site about 75 mi southeast to the Las Vegas airport.

We have made all of the processed SURFRAD radiation, meteorological, AOD, interpolated soundings, and monthly mean products viewable graphically on interactive web pages at http://www.esrl.noaa.gov/gmd/grad/surfrad/.

We apply the objective "QCrad" data quality control method to SURFRAD data on a daily basis and the files produced are available by request. The QCrad files are used as input to an algorithm that computes equivalent clear-sky irradiance at the temporal resolution of the input data for all radiation parameters. Besides equivalent clear-sky irradiance, that product also hosts the original data and a calculation of fractional cloud cover at the temporal resolution of the data. You can access daily clear-sky files for all SURFRAD stations at ftp://aftp.cmdl.noaa.gov/data/radiation/surfrad/clearid/.

SURFRAD QUALITY ASSURANCE

Maintenance of long-term measurements requires preemptive measures to deter problems before they occur, i.e., quality assurance. For example, we ventilate or heat SURFRAD instruments to prevent snow and dew buildup on the protective domes. The north-south alignment of the stations prevents the station infrastructure from interfering with the measurements. We shield radiometers to prevent problems with stray light and direct heating of the instruments by the solar beam, and to prevent sampling of the direct solar beam at sunrise and sunset by the inverted pyranometer on the tower. We replace batteries, fans, multiplexer relays, and other equipment that gradually deteriorates on a regular schedule. We exchange instruments on an annual basis for two reasons: 1) to keep calibrations current, and 2) to negate sensor drift in any long-term trend analysis. All instrument calibrations are traceable, recognized world standards. Pyrgeometers are referenced to the World Infrared Standard Group (WISG) and pyranometer and pyrheliometer calibrations are directly traceable to the World Radiometric Reference (WRR), both of which are at the World Radiation Center in Davos, Switzerland. Before 2005 we calibrated SURFRAD solar radiometers at the National Renewable Energy Laboratory in Golden, Colorado, and from 2005 on, they have been calibrated by the World Meteorological Organization Region 4 Regional Solar Calibration Center in Boulder, Colorado. Both of our centers use essentially the same method and WRR-traceable equipment. We use mitigation at all stations to minimize interference by birds, especially the mirrored surfaces of the TSI and pyrgeometers. We installed a buried lightning protection system at Goodwin Creek, Iowa and Sioux City, Iowa to protect against ground surges from nearby lightning strikes. Finally, to ensure a reputable product, an analyst checks all data before being released.

7.4 UV MONITORING

OVERVIEW

The need for accurate long-term, ground-based solar UV measurements arose in response to the discovery of the Antarctic ozone hole in the 1980s. Several U.S. government agencies and many international governments established UV monitoring stations or large networks to understand the relationship between the changing ozone layer and surface UV radiation. The NOAA UV monitoring program now includes a six-station continental U.S. network, a three-station Antarctic network, and two high-resolution NIWA UV spectroradiometers

located at Boulder, Colorado and Mauna Loa, Hawaii, all of which are described here.

In the early 1990s there was little quality UV data available for research and some of what was available suffered from poor calibration and characterization techniques. The long-term measurement of high-quality UVA and UVB is necessary to further the research in human health effects, the impact on plants, animals, and ecosystems, material degradation, and radiative transfer modeling. Our latest solar UV monitoring effort began with the establishment of a Central UV Calibration Facility (CUCF) in 1994. The laboratory serves as a central facility to calibrate and characterize UV monitoring instruments for many U.S. government agencies involved with the measurement of solar UV radiation.

CENTRAL UV CALIBRATION FACILITY

Introduction and Mission

The Surface Radiation Research Branch of NOAA's Air Resources Laboratory established the Central UV Calibration Facility (CUCF) in 1994. On 1 October 2005 the CUCF became part of the Global Radiation group of NOAA's newly formed Earth System Research Laboratory, Global Monitoring Division. The facility was developed under a Memorandum of Understanding (MOU) between several government agencies, including NOAA and NIST. We designed and constructed our systems under a joint project between scientists at NOAA and the Optical Technology Division of NIST in Gaithersburg, Maryland. Our mission is to provide long-term repeatable and highly accurate calibrations and characterizations of solar UV monitoring instrumentation for the participating agencies. The CUCF was charged with hosting national and international intercomparisons of UV monitoring instruments. In addition to working with U.S. government agencies and universities the CUCF has also performed calibrations and characterizations and developed standards of spectral irradiance for many international agencies and universities around the world. You can find information and services for the CUCF at the CUCF website, http://www.esrl.noaa.gov/gmd/grad/calfacil/cucfhome.html.

Highlights and Modifications to Systems

The CUCF acquired a Cary 5e spectrophotometer from the Chemistry Department at the University of Colorado at Boulder. The spectrophotometer measures the spectral transmission as a function of wavelength of filters and absorption glasses.

We built and characterized a new spectral response measurement system in 2010 that was designed for measuring the spectral response function of visible MFRSRs.

We upgraded the Irradiance Scale Transfer System to include additional capability for calibrating 200-W quartz-tungsten halogen lamps for NOAA's Antarctic UV Monitoring program. The calibrated spectral range for those lamps is from 290–650 nm. Their irradiance scale is traceable to the 1990 NIST source-based irradiance scale. Biospherical Instruments has maintained this scale and disseminated it to the Antarctic network instruments since 1990.

The CUCF hosted several intercomparisons of UV spectroradiometers and narrow and moderate-band filter radiometers at Table Mountain, Colorado in 1994, 1995, 1996, 1997 and 2003. The 2003 intercomparison was the first international intercomparison hosted by the CUCF and included groups from Germany and New Zealand. You can find the data from these intercomparisons on the GRAD ftp site, ftp://aftp.cmdl.noaa.gov/data/radiation/CUCF. On 3 May 2004, we made an intercomparison of 1000 W FEL-type standards of spectral irradiance between the CUCF and the European Reference Centre for UV Radiation Measurements (ECUV), Institute for Health and Consumer Protection, and European Commission – Joint Research Centre in Ispra, Italy. Our intent for the intercomparison was to compare calibrations performed by the CUCF and those performed by the ECUV laboratory.

Researchers from the U.S. and around the world have used the services and facilities of the CUCF. A partial listing of many past and current users of the facility follows: U.S. Environmental Protection Agency (EPA); U.S. Department of Agriculture (USDA); the Smithsonian; Biospherical Instruments Inc.; NIST; NASA; Hampton University, Hampton, VA; University of Houston, Houston, TX; ENEA, Rome, Italy; Queensland University of Technology, Brisbane, Australia; University of Hobart, Hobart, Tasmania, Australia; University of Southern Queensland, Toowoomba, Australia; Aristotle University of Thessaloniki, Thessaloniki, Greece; MeteoSwiss, Switzerland; University of Rome-La Sapienza, Rome, Italy; European Joint Research Center, Ispra, Italy; Chinese Academy of Meteorological Sciences, Beijing, China; and New Zealand Institute of Water and Air, Lauder, New Zealand

NEUBREW (NOAA-EPA BREWER SPECTROPHOTOMETER NETWORK)

History and Mission

The EPA established a 21-station UV monitoring network in the United States and its territories beginning in 1994. In 2004 the EPA stopped network operations and removed all Brewer spectrophotometers from the field sites. In 2005, NOAA and EPA agreed to establish a smaller six-station network using the Brewer Mark IV spectrophotometers from the previous network. The new network is called the NOAA-EPA Brewer Spectrophotometer UV and Ozone Network (NEUBrew), and its mission is to provide spectral UV irradiance data to the research community. Unlike the former EPA network, the NEUBrew network Brewer spectrophotometers were also calibrated for total column ozone measurements.

Sites and Instrumentation

The NEUBrew network is comprised of six stations all operating within the continental U.S. (Figure 7-4). NOAA and EPA equipped each station with a Mark IV Brewer spectrophotometer (Brewer) that is collocated with other solar and climate monitoring instrumentation. The Brewer operates in scanning mode for measuring UV irradiance from 290–363 nanometers and in fixed grating mode with a movable slit mask in direct sun measurements. The Brewer is a single monochromator-scanning instrument.

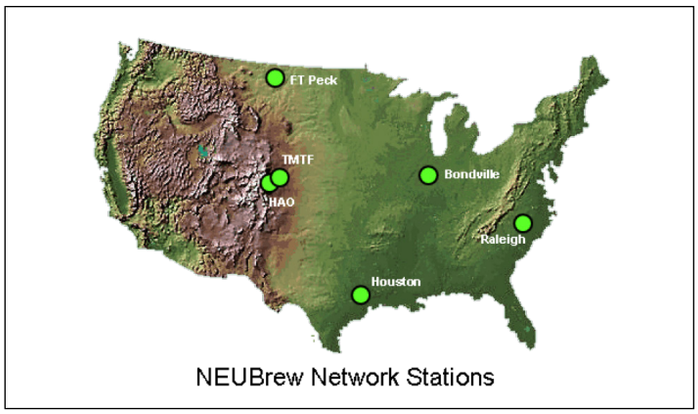


Fig. 7-4: The six NEUBrew site locations in the continental U.S.

The NEUBrew network stations are Raleigh, North Carolina; Bondville, Illinois; Houston, Texas; Ft Peck, Montana; Mountain Research Station, Niwot Ridge, Colorado; and the Table Mountain Test Facility near Boulder (Table 7-7). We established all six NEUBrew sites between July and November 2006. Only the Boulder and Mountain Research Station sites remain from the original EPA network. The Boulder, Bondville, and Ft Peck sites are collocated with NOAA SURFRAD sites. The Houston and Raleigh sites are collocated with USDA monitoring sites. You can find complete network and instrument information at the following website, http://esrl.noaa.gov/gmd/grad/neubrew/.

Data Products

The NEUBrew network currently produces spectral UV irradiance, erythema, total column ozone, and ozone profiles as data products. It is also potentially possible to produce aerosol optical depth in the UV and some visible wavelengths and total column NO_2 from the raw data files. To more fully use the measurement capability of the Brewer, we calibrated each network instrument for total column ozone measurements before they were deployed to the field sites. When measuring sky radiance, the instrument can operate in either direct sun or zenith sky measurement mode. The Mark IV performs measurements of both total column ozone and NO_2 in these two modes. We have made data from the NEUBrew network available through the NEUBrew website at http://esrl.noaa.gov/gmd/grad/neubrew/Data.jsp. We use erythema from the Brewer spectrophotometers to validate the NOAA NCEP UV Index forecast. The NEUBrew website provides a comparison of the measurement to the five-day UV Index forecast.

Table 7-7: NEUBrew monitoring station locations and installation dates.

Station	Latitude	Longitude	Elevation (m)	Install Date
Bondville, IL	40.053	88.372	213	26 Sep 2006
Boulder, CO	40.126	105.238	1689	5 Jul 2006
Houston, TX	29.718	95.341	64	5 Jun 2006
Ft Peck, MT	48.308	105.102	634	6 Nov 2006
Mountain Research Station, CO	40.032	105.533	2923	10 Oct 2006
Raleigh, NC	35.728	78.68	272	12 Oct 2006

Calibration and Quality Control

International Ozone Services (IOS) in Toronto, Canada performed the calibrations for seven of the network Brewers in June 2006 and for Brewer 154 in Houston, Texas in February 2007. IOS used Brewer 017, which serves as a transfer standard between the WMO Brewer calibration triad, operating at Environment Canada in Toronto and the NEUBrew network Brewers. IOS recalibrated Brewers 131, 134, and 154 for total column ozone after considerable instrumental changes in May 2013 with calibrations performed by comparing to the traveling standard Brewer 109.

We calibrate all network Brewers in the field for UV spectral irradiance against 1000 W FEL lamps that are traceable to the 2001 NIST detector-based irradiance scale. The CUCF's portable field calibrator is used to perform the calibration during the annual site visit. However, due to funding shortfalls for the network, our site visits have been sporadic and calibrations few after 2009.

We have experienced high data retrieval at most sites with few downtimes associated with instrument failure. Each site is still equipped with the same Brewer that was originally installed in 2006. We have made no site changes since the initial installation of each site in 2006 that have modified the instrument's field of view or affected the Brewer data. Some instrumental problems have occurred since 2006 that affected either the ozone or UV calibrations for several instruments. You can find that information in the electronic logs for each instrument at the NEUBrew website http://esrl.noaa.gov/gmd/grad/neubrew/BFileComments.jsp.

THE ANTARCTIC UV MONITORING NETWORK

Introduction and Mission

The NOAA Antarctic UV monitoring program is a network of three stations (Figure 7-5). The National Science Foundation originally established the network in 1988 and Biospherical Instruments, Inc. (BSI) maintains it to provide ground-based measurements of spectral UV irradiance. It was intended that the data provide station personnel with information to protect themselves against increased levels of solar UV radiation during ozone hole events. Radiative transfer modelers, and researchers involved in understanding biological effects of increased and rapidly changing UV exposure and dose rates, use the data. GMD assumed

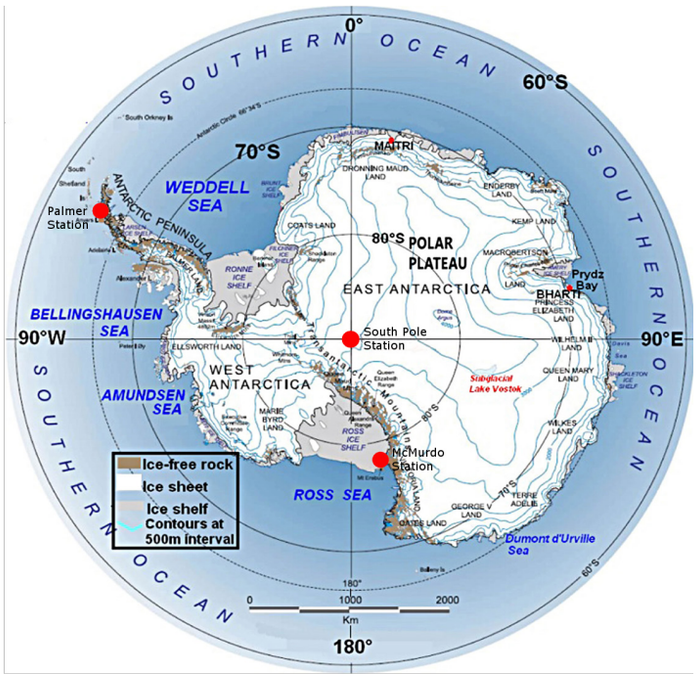


Fig. 7-5: The Antarctic UV monitoring stations are located at the three U.S. Antarctic research sites and represent different radiation environments across the continent.

management of the network in May 2010 after 23 years of NSF operation.

Sites and Instrumentation

Station information is listed in Table 7-8. You can access network information and data through the internet at http://esrl.noaa.gov/gmd/grad/antuv/. We equipped each site with a BSI-built SUV-100 spectroradiometer, solar pyranometer, Eppley TUVR broadband UV radiometer, and either a BSI GUV-541 or GUV-511 radiometer. The SUV-100 scans from 280 to 600 nm with a resolution of 1 nm. The GUV-541s are a five-channel, narrow-band filter radiometer. The 10 nm wide filters are nominally centered at 305, 313, 320, 340, and 380 nm. The GUV-541 and GUV-511 differ in that the 511 does not have the 313 nm channel, but has a photosynthetically active radiation (PAR) sensor in its place.

Table 7-8: The site locations and installation dates of the three US Antarctic UV Monitoring stations.

Station	Latitude	Longitude	Elevation (m)	Install Date
Palmer	64° 46' S	64° 03' W	21	May 1988
McMurdo	77° 50' S	166° 40' E	183	March 1988
South Pole	90° 0' S	0.0° E	2,835	February 1988

Data Products

Each site produces spectral irradiance from 280–600 nm plus derivative products. Derivative products include UV index, UV dose, Setlow, Caldwell, and other action spectra-weighted doses. We derive the total column ozone from measurements taken by the GUV filter radiometers at all three stations. We submit the Antarctic UV level 2 data to the World Ozone-UV Data Center in Toronto, Canada and the Network for the Detection of Atmospheric Chemistry and Composition (NDACC) databases.

Calibration and Quality Contro

We calibrate the SUV-100 with standards of spectral irradiance that are traceable to the NIST 1990-scale of spectral irradiance. The SUV-100 is calibrated once every two weeks with one of three standards and we rotate them throughout the year. We run all three standards against each other twice per year to verify their stability. The field person operates two traveling standards against the stations three standards during the biennial site visits. This serves to periodically recalibrate the station triad of lamps.

Additionally, we operate an internal QTH 45 W lamp once per day. Its irradiance is tied to the operation of the station triad. We create a pseudo-irradiance on a daily basis from the operation of the internal QTH lamp and the bi-weekly calibration of one of the station's triad. This provides a daily calibration for the SUV-100. We calibrate the GUV-541s or GUV-511s against the SUV-100 once per year. They have historically shown to be stable over short-term periods.

Since NOAA has taken over program management in 2010, there have been no changes to instrumentation or the site that would affect data quality. We explain data gaps in each site's electronic log file, which can be found at the Antarctic UV Monitoring (AntUV) website http://esrl.noaa.gov/gmd/grad/antuv/InstLogsTextDisplay.jsp. You can choose a station at this website along with the date range of interest. You can also find detailed operation of the instrument and any maintenance or repairs in the logs.

NOAA-NIWA HIGH-RESOLUTION UV SPECTROMETERS

Introduction and Sites

In October 2005, the NOAA Climate Modeling and Diagnostics Laboratory (CMDL), precursor to GMD, acquired two UV spectroradiometers that had been built by the National Institute of Water and Atmospheric Research (NIWA) at Lauder, New Zealand. The two high-resolution UV spectroradiometers are now located at Boulder and Mauna Loa and have been in operation since 1998 and 1995, respectively. The present coordinates of both instruments and their installation dates are listed in Table 7-9.

Table 7-9: The NOAA-NIWA High-resolution UV spectroradiometer site locations and installation dates.

Station	Latitude	Longitude	Elevation (m)	Install Date
Boulder,CO	39.991° N	105.261° W	1650	June 1998
Mauna Loa, HI	19.536° N	155.576° W	3397	May 1995

Instrumentation and Modifications

The original spectroradiometers were designed and built by the Lauder group but, due to several factors were swapped with more recently built instruments and redeployed at both locations. The evolution of the instrument serial numbers, locations, and dates deployed are shown in Table 7-9. The spectroradiometers that are currently deployed are designated as UV3 (Mauna Loa) and UV5 (Boulder), replacing ones designated as UVL. We constructed the UVL from different components than those used in UV3 and UV5. The main difference is that UVL was equipped with a Jobin-Yvon DH10 double-monochromator. We equipped the UV3 and UV5 with Bentham DTM300 monochromators that have a focal length of 300 mm and incorporate 2400 g/mm gratings and slit widths of 1.0 mm. Their spectral scanning range is 285–450 nm with a sampling step of 0.2 nm.

Data Products

The NIWA spectroradiometers produce spectral UV irradiance from 280–450 nanometer in 0.2 nanometer increments. This data product can be convolved with many different UV action spectra to produce derivative products (e.g., Erythema, Setlow, Caldwell). We archive the data from both the Mauna Loa and Boulder stations at the World Ozone and UV Data Center (WOUDC) and the Network for the Detection of Atmospheric Chemistry

and Composition (NDACC) data repositories.

Calibration and Quality Control

The absolute calibration of both instruments is traceable to NIST primary standards of irradiance. Horizontally calibrated field standards created by the CUCF are used in the CUCF's portable field calibrator on UV5. We perform absolute calibration against the 1000-W, FEL-type lamps twice per year. At Mauna Loa, we lower the UV3 instrument from the roof hatch on a cable elevator on which it resides to an indoor laboratory. In the lab, we use 1000 W FEL vertical standards of irradiance that are calibrated against the CUCF irradiance scale to calibrate UV3 for absolute spectral irradiance. Additionally, both UV3 and UV5 scan an internal 45-W quartz-tungsten-halogen lamp on a weekly basis. We document interruptions in the operations of the instruments in daily paper log sheets, which are converted into electronic pdf files and are archived at NIWA in Lauder and the CUCF in Boulder. You can find more detailed instrument and data processing information in the NIWA manual, NIWA Lauder UV Spectral Irradiance Measurements: Overview of Instrumentation, Logging Procedures and Data Processing, which can be obtained from the NOAA CUCF.

7.5 SPECIAL PROJECTS

ARCTIC PERMAFROST AND ACTIVE-LAYER MONITORING

In August 2004, GMD began monitoring permafrost temperatures in the upper 120 cm of soil at Alert, Canada (ALT). We installed a commercially available probe in close vicinity to the BSRN albedo rack at the GAW facility. We measure soil temperature at ten levels every minute for the purpose of producing sub-surface profiles of Tsoil and time series in conjunction with other geophysical variables measured there. Subsequently, the NOAA SEARCH Program (Study of Environmental Arctic Change) supported the deployment of like probes at Eureka, Canada (1 June 2008) and Tiksi, Russia (1 April 2011).

The U.S. Geological Survey (USGS) uses similar probes throughout the Circumpolar Active Layer Monitoring (CALM) Program Network: http://nsidc.org/data/ggd313. GMD provided robust evaluation of the probe used by USGS and as a consequence developed an improved active layer sensor. The prototype was installed near the albedo rack in December 2011 in Barrow, Alaska (BRW). We can resolve processes that impact permafrost stability over time, as well as changes in active layer depth, by comparing coincident time series of permafrost temperatures with meteorological and radiometric data at high temporal resolution.

Figure 7-6 shows an example of how clouds during the Arctic winter radiatively warm the permafrost, despite the insulating layer of snow cover. Events such as this have a cumulative effect that can modulate active layer depth on a broad scale during

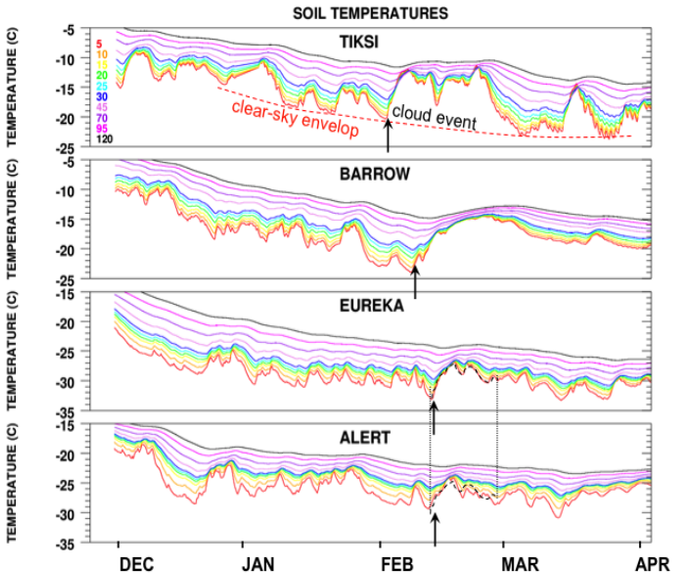


Fig. 7-6: Time series of permafrost temperatures for the period 1 December 2011 to 1 April 2012 at (top to bottom) Tiksi, Barrow, Eureka, and Alert stations. Note the different scales in the top two and bottom two plots. Measurements are made at depths of 5, 10, 20, 25, 30, 45, 70, 95, and 120 cm; shown here resolved twice daily. Depths are color-coded, from red at 5 cm to violet at 120 cm. The event is discussed in the NSF Report as an example of how soil temperatures respond to cloud radiative forcing and atmospheric dynamical forcing.

the annual thaw. In this case, a large-scale synoptic event occurred that was tracked from northern Siberia to the Canadian Arctic, characterized by optically thick clouds that tend to warm the surface. We saw similar features in the temperature traces from station to station as the storm tracked eastward, systematically warming the soil via propagation of warmth from the surface to depths of >120 cm. Figure 7-7 shows how using data from soil temperature probes enables the depth of the active layer to be monitored from year to year. At ALT, for example, the active layer has become

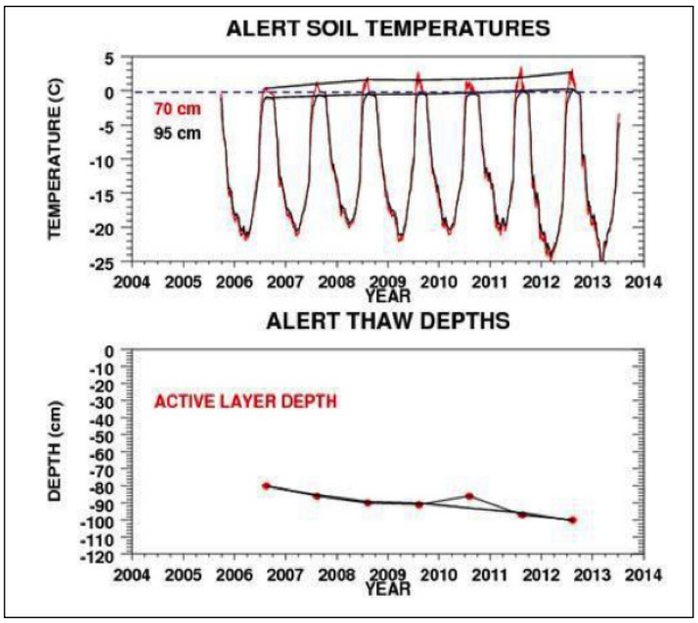


Fig. 7-7: Time series of 12-hour resolved soil temperatures at ALT at the 70 cm and 95 cm depths where the peak thaw occurs during summer. The active layer depth (ALD) typically falls within the 70–95 cm depth range (bottom). Estimates of ALD for the years of available data (2005–2012) are smoothed to show inter-annual and multi-year trend toward deeper thaw.

deeper by nearly 20 cm over the six years we have been monitoring it. Understanding why is an ongoing investigation but some preliminary analyses can be found in a U.S. National Science Foundation (NSF) Report accessed via the GRAD group.

BARROW SNOWMELT DATE

To understand global climate change more fully, we must assess the variability of Earth's cryosphere in response to other climatic factors. In particular, the timing of the disappearance of snow each year can influence the net energy budget for an entire season. Feedbacks involving the change in surface albedo may enhance or diminish any response, which may be manifested in the regional temperature regime. In recent years, GMD has made a determination of the snow disappearance date on the basis of objective, radiometric measurements made over open tundra at the GMD Barrow Observatory (BRW).

NOAA selected a threshold of 30% albedo, the ratio of upward-to-downward SW irradiance, as a good indicator of final melt out. We determined the melt date to be that of the first daily average albedo below 30%. Once this occurs each spring the surface albedo seldom increases again until autumn except for an occasional late snowfall of brief duration that can occur even during summer. The timing of seasonal snow melt at high latitudes is potentially one of the most important but least understood processes that affects global climate through the "temperature-albedo feedback" mentioned above. Any long-term, regional trend in the distribution and melt of the snowpack may be interpreted as a manifestation of climate change. Therefore, we are examining the history of the Barrow snowmelt date in great detail to understand why it varies and to determine if it is occurring earlier in response to global warming.

MOBILE SURFRAD

GMD is successfully using a new, quickly deployable mobile surface radiation budget station to support regional air quality research, NOAA satellite cal/val activities, and renewable energy research studies (Figure 7-8). The mobile platform measures upwelling and downwelling shortwave and longwave broadband radiation, direct broadband solar radiation, diffuse, direct and total spectral irradiance, spectral aerosol optical depth, spectral surface albedo, and cloud fraction. The instrumentation suite is the same as a long-term SURFRAD

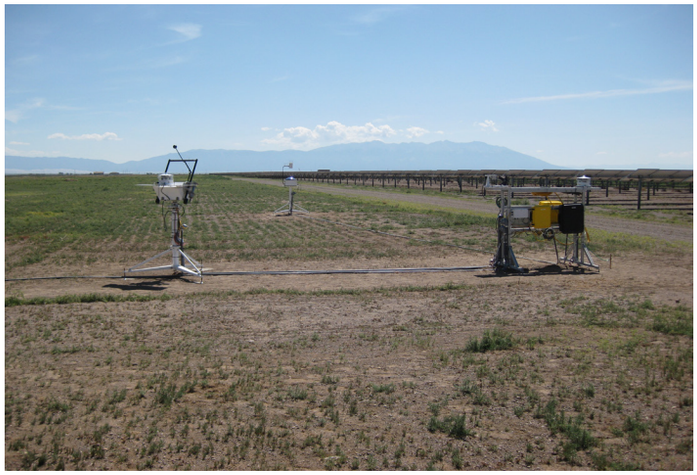


Fig. 7-8: The Mobile SURFRAD platform deployed at DISCOVER-AQ, Central Valley, CA, January 2013.

station but also includes spectral upwelling solar radiation for determination of spectral albedo. We switched the Multi-Filter Rotating Shadowband Radiometer (MFRSR) and Multi-Filter Radiometer (MFR) in the mobile facility from the 615-nm channel to a 1625-nm channel. This gives more informa-

tion on aerosol properties of larger particles and helps derive spectral albedo to longer wavelengths. Initially, we tested and deployed the mobile SURFRAD platform at the DOE Atmospheric Radiation Measurement (ARM) Program, Two-Column Aerosol Program (TCAP) site in Cape Cod, MA during July and August 2012. The data are archived on the DOE ARM site at http://www.archive.arm.gov/armlogin/login.jsp. We also deployed the mobile SURFRAD platform as part of the NASA DISCOVER-AQ campaign, Phase II, in the Central Valley, CA, during January and February 2013 and for Phase III in the area surrounding Houston, Texas, during September and October 2013. DISCOVER-AQ is a four-year campaign to improve the use of satellites for air quality assessment. The data are archived on the DISCOVER-AQ site at http://discover-aq.larc.nasa.gov.

MAUNA LOA APPARENT TRANSMISSION (AT)

GMD has measured atmospheric solar transmission for five and a half decades at the Mauna Loa Observatory (MLO). We show the updated clear-sky apparent transmission from 1958 through December 2013 in Figure 7-9. We compute monthly clear-sky averages shown by the black dots from daily morning values to remove local influences due to upslope wind changes in the afternoon. The aerosol signal from the eruptions of Agung, El Chichon, and Mt Pinatubo in 1964, 1982, and 1991, respectively, are clearly visible in the record. The green line in Figure 7-9 is a 6-month running smoothed loess fit to the monthly values to highlight the seasonal trends in the data that have been attributed primarily to aerosol Asian transport in the spring. This seasonal variability has an amplitude of 0.007 AT. A 24-month running smoothed loess fit is shown by the red line and highlights the longer-term changes. The dashed line reflects the cleanest background observed from 1958–1962 in the record.

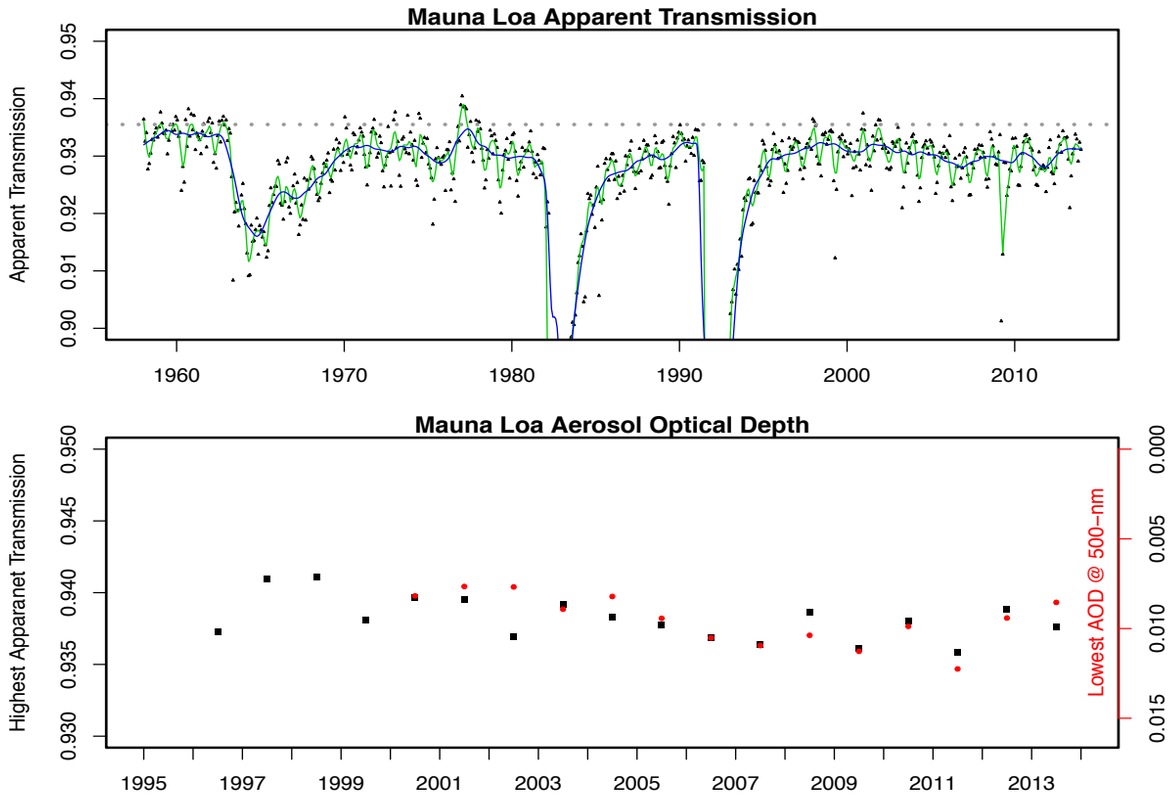


Fig. 7-9: Top: Monthly mean of the clear-sky Apparent Transmission at MLO. Means are determined from the early morning values. The green line is the 6-month running smoothed fit, and the blue line is the 24-month smoothed fit using only monthly means that include at least ten days. The dashed line is the background level from 1958 – 1972. Bottom: Annual averages of the 10 cleanest days of the year for the clear-sky Apparent Transmission (black squares) and the aerosol optical depth from a collocated PFR (red dots).

In addition to long-term trends in the monthly means of the clear-sky apparent solar transmission, annual averages of the 10 cleanest days are useful for viewing stratospheric background air without the influence of air pollution events, e.g., Asian transport. Previous studies showed that the annual clear-sky AT returned to near-background conditions after the eruption of Mount Pinatubo. There was a subsequent slow decrease in the clear-sky AT that was in concert with a slow increase in the background annual average aerosol optical depth also from the 10 cleanest days as measured by a Precision Filter Radiometer (PFR) at MLO from the years 2000 to 2010. Aerosol optical depth measurements from the MLO lidar and combined satellite observations (50°N to 50°S) confirmed an increasing "persistently variable background" stratospheric aerosol since 2000 attributed to possible smaller volcanic eruptions.

AOD MONITORING AT NOAA POLAR OBSERVATORIES AND AFFILIATE STATIONS

The need for accurate long-term aerosol optical depth (AOD) measurements at high-latitude sites was recognized in the late 1990s, when the Scientific Committee on Antarctic Research recommended the establishment of an international network of Sun photometers to monitor spectral irradiance at Arctic and Antarctic stations. Since January 2000, GMD has made continuous photometric measurements (during sunlit periods) at the NOAA Barrow (BRW) and South Pole (SPO) observatories. The activity is described at http://www.esrl.noaa.gov/gmd/grad/Porano9EXTabs.pdf.

GMD deployed four-channel Sun photometers to BRW and SPO in 2000. The nominal wavelengths are 412, 500, 675, and 862 nm. In 2006, BRW was upgraded to an 8-channel system, adding nominal wavelengths of 368, 610, 778 and 1050 nm.

GMD has continued to play an active role in the Polar-AOD project that was established during the 2007–2008 International Polar Year as described at http://www.ipy.org/index.php?ipy/detail/polar_aod/. In August 2004, GMD initiated a similar program at the Alert Global Atmosphere Watch (GAW) station located at 82.5°N (ALT). A pair of Carter-Scott SP02 Sun photometers measure spectral irradiance between 368 nm and 1050 nm at one-minute resolution during the sunlit part of the year at ALT. These observations complement measurements of the surface radiation budget (SRB) at ALT as part of the Baseline Surface Radiation Network (BSRN). NOAA assists Environment Canada (EC) in this endeavor through technical support, lending instruments and performing calibrations.

To date, GMD holds the BRW, SPO, and ALT AOD archives in Boulder, Colorado, accessible via a web interface for those who request data. Data are scaled on the basis of routine calibrations performed at the GMD Mauna Loa Observatory (MLO). GMD also makes the MLO calibration histories available through the GMD web interface. Data listings of spectral AOD are available every one minute or as daily means, with an option to obtain preliminarily cloud-screened data. Climatologies of AOD for BRW, SPO, and ALT have been produced through 2012 and are expected to be published in future peer-reviewed papers.

ANCILLARY AOD OBSERVATIONS AND COLLABORATIVE STUDIES

GMD engineers designed and fabricated a portable 8-channel Sun photometer system in collaboration with the Institute of Atmospheric Sciences and Climate (ISAC) in Bologna, Italy (http://www.isac.cnr.it/). This system is comprised of a pair of Carter-Scott SP02 Sun photometers, having spectral range 368–1050 nm. It is completely portable in that it can be operated anywhere, powered by either rechargeable batteries or using line power. It has on-board GPS and a dedicated data logger and is mountable either on a solar tracker or tripod for manual use at remote locations. As with other NOAA photometers, the instruments are thermally controlled and calibrated on a routine basis. The system was first tested at Terra Nova Bay in Antarctica and used during a campaign at Dome Concordia (elev. 3240 m) during January 2002 and during subsequent austral summers. The Dome C data have been used recently to develop an AOD climatology for that site.

ARCTIC MOON PHOTOMETRY

In producing climatologies of AOD for the Polar Regions it became clear that we lack knowledge of processes that occur during dark periods of the Polar night. This is evidenced by gaps of several months each year in time series. During winter for instance, there is a buildup of aerosols within the Arctic Vortex, which can perturb the surface radiation budget and also modulate cloud microphysical

properties and radiative impacts that are poorly understood. There is a need for nighttime observations of AOD to fill both the gaps in the climatologies of AOD and also knowledge of these processes. A simple cost-effective means to do this is by using the techniques well established for Sun photometry, but using the Moon as a target. GMD, with support of CIRES, developed the first lunar photometry program in the Arctic during winter 2012/2013. Results of this experiment are available at http://www.esrl.noaa.gov/gmd/grad/CIRESirpPoster-Nov2013.pdf. Following the lead of NOAA other institutes are developing similar programs in an effort to better fulfill goals of the Polar-AOD project. Systems are planned for Ny-Alesund (February 2014); Eureka, Canada; and ALOMAR (Norway) in 2014–2015 with BRW resuming operations in 2014.

during the sunlit portion of the annual cycle. In addition, the Polar-AOD community has conducted two campaigns to intercompare a variety of Sun photometers used throughout the Polar-AOD network.

The network is shown in Figure 7-10. In 2006, representatives from throughout the Polar-AOD community gathered at Ny-Alesund, Svalbard to compare results obtained from their systems. They met again in 2008 at the Izana Observatory, Tenerife, Spain for the purpose of inter-calibrating their systems. The NOAA SP01-A and SP02s were found to perform very well and consistently as compared with the ensemble, and we show that AOD at 500 nm can be retrieved with an accuracy of better than 0.005.

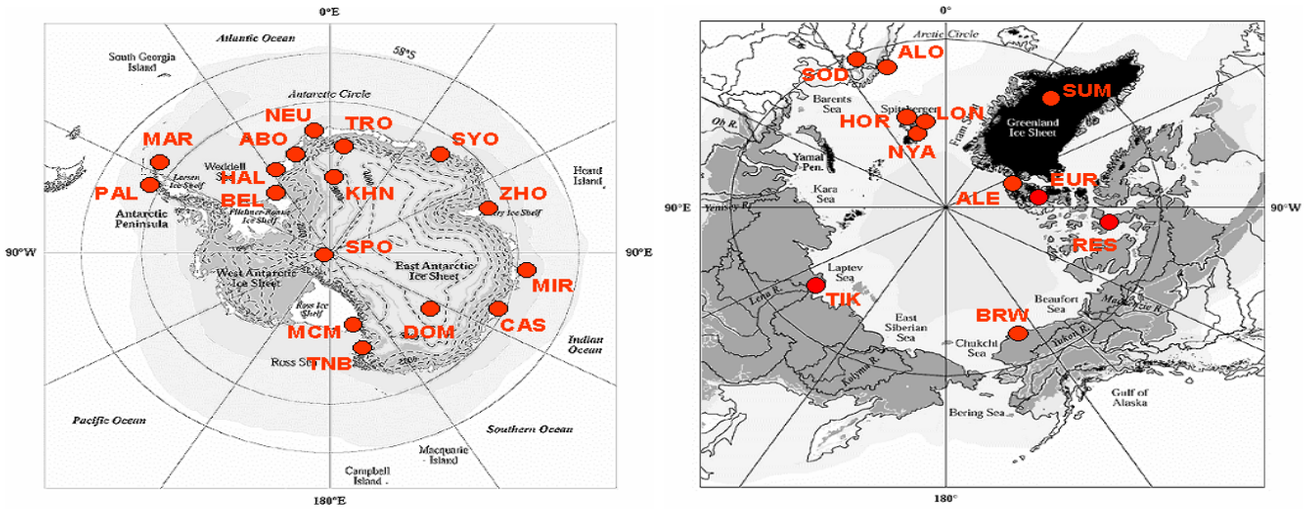


Fig. 7-10: Left: Antarctic stations that have carried out AOD measurements. Right: Arctic stations that monitor AOD within the framework of Polar-AOD; see: http://polaris.nipr.ac.jp/~ipy/usr/sympo/proc-files/76-Vitale.pdf

POLAR AEROSOL OPTICAL DEPTH COMPARISON CAMPAIGNS

Routine calibration is critical to AOD monitoring efforts, wherever photometers are operated. This is especially true when operating at high-latitude locations where atmospheric turbidity is very low much of the time. NOAA is fortunate to have MLO as its primary calibration facility for photometers. Polar devices are rotated through MLO during the dark periods each year and returned for service

ARCTIC AOD FROM AIRCRAFT

We deployed the NOAA/ISAC, 8-channel Sun photometer system (described above) on the Alfred-Wegener Institute (AWI) research aircraft, Polar 5, as described at; http://www.awi.de/en/infrastructure/aircraft/research_aircraft/polar_5/, http://www.awi.de/en/infrastructure/aircraft/research_aircraft/polar_5/

Polar 5 was Germany's most significant contribution to IPY 2007/2008, which was extended through spring 2009. The aircraft was ferried from

Table 7-10: Arctic Sun Photometer Deployments.

Station	Nominal Wavelengths	Latitude	Longitude	MASL	Data From
SPO	367, 413, 499, 865	-90	Pole	2837	Jan 2000 to Feb 2000
SPO	413, 499, 675, 865	-90	Pole	2837	Nov 2000 to Mar 2001
SPO	412, 500, 675, 862	-90	Pole	2837	Nov 2001 to present
BRW	367, 413, 499, 865	71.32	-156.61	8	Mar2000 to Jul 2000
BRW	412, 500, 675, 862	71.32	-156.61	8	Mar 2001 to Jun 2002
BRW	413,499,675,865	71.32	-156.61	8	Jun 2002 to Nov 2005
BRW	412, 500, 675, 862	71.32	-156.61	8	Mar 2006 to Aug 2006
BRW	368, 412, 500, 610, 675, 778, 862, 1050	71.32	-156.61	8	Aug 2006 to present
BRW_lunar	412, 500, 675, 862	71.32	-156.61	8	Nov 2012 to Feb 2013
ALT-GAW	368, 412, 500, 610, 675, 778, 862, 1050	82.45	-62.52	210	Aug 2004 to present
NOAA/ISAC Dome C	368, 412, 500, 610, 675, 778, 862, 1050	75.1	123.35	3233	Jan 2006 to Feb 2006, Mar 2007 to Apr 2007, Oct 2009 to Jan 2010
NOAA/ISAC Polar-5	368, 412, 500, 610, 675, 778, 862, 1050	variable	variable	variable	Apr 2009 aircraft campaign
NOAA/ISA Baranov, Russia	368, 412, 500, 610, 675, 778, 862, 1050	79	102	TBD	Slated; Spring 2014

Germany to Svalbard in March 2009, where test flights were conducted. Polar 5 then was flown across the central Arctic to BRW, with stops at several Arctic stations along the flight track, including a landing near North Pole. We used the NOAA/ISAC photometers to collect a unique set of AOD spectra along the track and from near sea surface to over 4000 m altitude, giving a three-dimensional view of Arctic aerosols during the peak Arctic haze season. AWI archives the data and GMD makes them available upon request. The success of the 2009 campaign prompted AWI to develop a robotic Sun photometer system as part of their permanent Polar 5 measuring platform. The robotic system was first used on Polar 5 in 2011 and on subsequent campaigns.

RUSSIAN ARCTIC AOD ACTIVITY

NOAA and ISAC deployed their portable photometric system to the North Pole-40 station in 2013, in collaboration with the Arctic and Antarctic Research Institute (AARI) in St. Petersburg, Russia, Although limited data were obtained due to the breakup of the ice camp and evacuation, we made plans to redeploy the system to Cape Baranov (79°N) for continuous operation beginning spring 2014. Baranov Station is being re-established after closure in the early 1990s and will be a key climate observing site in future years. It is located strategically to monitor AOD and also provide validation data for retrieval of AOD from satellite platforms.

We listed the sites where NOAA has initiated AOD monitoring in Polar Regions in Table 7-10.

SOLARCELL UV SMARTPHONE APPLICATION

GMD developed a mobile smart phone application named “SolarCell” to manage sun protection and vitamin D production (Figure 7-11). A team of diverse experts including Health Educators, Skin Cancer Specialist, Dermatologist, and UV Radiative Transfer and Radiation Measurement Scientists collaborated to lead the smart phone application. SolarCell integrates NOAA’s five-day, hourly UV Index (UVI) forecasts, time, date, and location from the cell network (or GPS), and user information, and displays sun safety advice using predictive algorithms. It estimates the user’s time until sunburn from the UV Index and user’s skin type and can be corrected for shade, application/reapplication of sunscreen with designated SPF. Countdown timers send audio and visual sun safety alerts (e.g., to reapply sunscreen or get out of the sun). SolarCell

Fig. 7-11: Mock-up of the SolarCell smart phone application for UV Index.

estimates amount of vitamin D produced by the skin taking into account skin type and skin coverage. A five-day planning mode is available. We can improve the UVI forecast using observed sky conditions from a validated algorithm. User information is saved in "person" and up to five "profiles" per person can be retrieved to manage sun protection for yourself and others. Preferences identified during focus groups with adults (n=16) guided production of SolarCell. Adults were overwhelmingly positive that it would improve their sun safety. We conducted in-house alpha testing in April 2010 to identify and fix bugs and demonstrated that SolarCell was interoperable across five handsets and two carriers. In two rounds of usability testing (n=12 adults), the prototype was improved; 11 of 12 tasks were completed by at least 75% of users; and 11 participants said they would use SolarCell if available.

SOLAR CALCULATOR

GMD created and maintains the NOAA Solar Calculator interactive web page, which allows users to calculate the time of sunrise, sunset, solar noon, and the position of the sun for any location on Earth, and any time between the years 2000 BC and 3000 AD. This project started out as an internal resource for the solar radiation group to use for fieldwork. Field technicians needed to align sensitive solar instruments with true north, and a shadow cast by a plumb bob at solar noon on a horizontal surface indicates the direction of north.

Over the years, citizens from around the world have used the calculator for such varied purposes as scheduling fishing trips, planning outdoor filming for motion pictures, photography, prayer times, science fair experiments, architectural designs for passive solar lighting and heating, planting gardens, making sundials, and even dating a historical film of San Francisco from before the great earthquake and fire of 1906.

We based the solar position algorithms used in the NOAA calculator on those presented by Jean Meeus in Astronomical Algorithms. We wrote the web programs in JavaScript to run within a user's web browser. We updated the programs over the years to improve efficiency and modularity, to make use of Google Maps API for inputting location, and to improve calculations for next and previous sunrise and sunset in the Arctic and Antarctic. GMD has also made the algorithms available in a spreadsheet for researchers and hobbyists interested in exploring further. You can find the Solar Calculator on the GRAD home page at http://www.esrl.noaa.gov/gmd/grad/solcalc.

SECTION 8 - CALIBRATION AND QUALITY CONTROL ACTIVITIES

8.1 OVERVIEW AND WMO ACTIVITIES

The NOAA Carbon Cycle Greenhouse Gases (CCGG) and Halocarbons and other Atmospheric Trace Species (HATS) Research Groups contribute to the WMO Global Atmosphere Watch program in a number of ways. We act as the Central Calibration Laboratory for CO_2 (since 1995), CH_4 (since 2005), CO (since 1998), N_2O (since 2005), and SF_6 (since 2007). Through this role, we maintain the WMO mole fraction scales and provide to the WMO measurement community reference gas standards that are traceable to those scales. In 2010, WMO signed a Mutual Recognition Agreement (MRA) with the International Committee for Weights and Measures (CIPM), an agreement that insures compatibility among standards of the participants, mostly national metrology laboratories. Since WMO has no laboratories, it has designated NOAA/ESRL as its representative in the MRA for CO_2, CH_4, CO, N_2O, and SF_6. As WMO's representative, one major responsibility involves developing a quality system in accordance with ISO 17025 and ISO Guide 34. Development of this system continues, with NIST review conducted in January 2014.

We organized and hosted the 13th WMO/IAEA (International Atomic Energy Agency) Meeting of Experts on Carbon Dioxide Concentration and Related Tracers Measurement Techniques, 19–22 September 2005. Members of the CCGG and HATS groups play major roles in WMO GAW meetings of measurement experts by leading discussions on measurement comparisons, data management, propagation of standards, and recording and organizing meeting recommendations (for meetings in 2011 and 2013). The recommendations define requirements for data quality, and good measurement practices to achieve those. We have ongoing comparisons of measurements with GAW participants at 16 sites. One GMD member chaired the Scientific Advisory Group (SAG) for Greenhouse Gas Measurements since 2003, another is a member of the SAG for reactive gases, and we contribute to many GAW reports, including meeting reports (Nos. 206, 194, 186, 168, and 161), measurement guidelines for CH_4 and N_2O (No. 185), CO (192),CO_2 (in preparation), and GAW Strategic Plans (Nos. 197, 172, and 156).

8.2 STANDARDS

As of 2013, in addition to the WMO scales, we continue to maintain calibration scales at various levels of maturity for 60 trace gases, see http://www.esrl.noaa.gov/gmd/ccl/ and http://www.esrl.noaa.gov/gmd/ccl/scales.html. Calibration of our instrumentation is based on analysis of air from high-pressure gas cylinders with known composition. Hierarchies of reference gas standards are used to support measurement programs. For ozone-depleting gases, long-lived greenhouse gases, and related trace gases, primary standards are prepared in aluminum or stainless steel cylinders by gravimetric methods. For CO_2, primary standards consist of modified natural air in aluminum cylinders, with CO_2 mole fractions determined by a manometric method.

8.3 CALIBRATION SCALE UPDATES

Several calibration scales were updated between 2004 and 2013. We performed significant updates for N_2O, CFC-12, CH_4, CO, and CO_2 and introduced minor updates for SF_6, CCl_4, and HCFC-22, halon-1211, and halon-1301 scales. For information on current calibration scales, see http://www.esrl.noaa.gov/gmd/ccl/ and http://www.esrl.noaa.gov/gmd/ccl/scales.html.

WMO N2O SCALE UPDATE

The X2006 N_2O scale is based on 13 gravimetrically prepared standards over the range 261371 ppb, and supersedes the X2000. The X2006 scale was updated to X2006A in 2011 after a drifting secondary standard was discovered. Assignments on the 2006A scale are based on the same 13 gravimetric standards, but corrected for apparent scale drift of 0.024 ppb yr^{-1} that occurred from 2006 to 2011 due to drift of a secondary standard. For most calibrations, differences between assignments on the X2006 and X2006A scales are less than 0.1 ppb.

WMO CFC-12 SCALE UPDATE

The update to the X2008 CFC-12 scale involved preparation of new gravimetric standards that also contained halon-1211. By including halon-1211 and better quantifying residual CFC-12 in the balance gas, the new set of primary standards is more consistent than the sets that defined the X1997 or

X2001 scales. In addition, we prepared primary standards with two different methods, using both liquid and gaseous pure CFC-12 starting material. Standards prepared by these different methods show remarkably good agreement.

WMO CH4 SCALE UPDATE

The NOAA-2004 CH_4 scale is based on a suite of 16 gravimetrically prepared standards covering the nominal range 300–2600 nmol mol^{-1} (ppb); five other original gravimetrically prepared standards, not used in the scale, can extend the range from 30 nmol mol^{-1} to 20.5 µmol mol^{-1} (ppm). Because NOAA is the WMO GAW CCL for CH_4, this scale is also the WMO CH_4 mole fraction scale used by GAW participants. We will initiate several changes in mid-2015 to meet the needs of the GAW community in analyzing air outside the narrow background range, and improve our internal consistency over a wider range of CH_4 mole fractions: New primary standards prepared with gravimetric methods covering the nominal range from 2200 to 8000 nmol mol^{-1} were prepared in 2013 and will expand the scale at the high end. To account for potential varying non-linearity of our GC/FID system used for calibrations, we prepared a suite of 14 secondary standards covering the nominal range 390 to 5000 nmol mol^{-1}, and we are calibrating them against the primaries. We will employ the new secondary standards to define a response curve that will be used for routine calibration of tertiary standards. Response curves generated with the primary and secondary standards are now based on a power function that allows the non-linearity of the detector to change over the range of values measured.

WMO CO SCALE UPDATE

We produced new sets of CO gravimetric standards in 2006 and 2011 and compared them to the 1999/2000 gravimetric standards. These new gravimetric standards showed that the 1999/2000 gravimetric standards were biased low at the low end of the range (standards less than 200 ppb). This confirmed the suspected bias seen when the highest members of the 1999/2000 set were compared against the lower members. We revised the CO scale in 2014 to account for this bias.

WMO CO2 SCALE UPDATE

During 2012, Brad Hall and Duane Kitzis performed a full set of manometric measurements of the Primary cylinders that define the WMO scale. This was the first time the manometric measurements were not performed by Conglong Zhao, who had last carried out the analyses in 2009–2010. Despite several changes to the apparatus, the 2012 calibration agreed closely with previous ones. The average of all cylinders was 0.01 ppm higher than the average of previously assigned values. The assignment of mole fraction values to each of the Primaries, which takes all previous calibrations into account, did not change by more than 0.01 ppm.

8.4 INSTRUMENT CHANGES

In addition to scale updates, instruments used for calibration were also improved. We improved the precision for SF_6 analysis by adding an additional analytical column and changing the order of peak elution for N_2O and SF_6. Prior to 2006, we analyzed N_2O and SF_6 using a Porapak Q column (with SF_6 eluting after N_2O). In 2006, we installed a molecular sieve 5A column behind the Porapak Q column

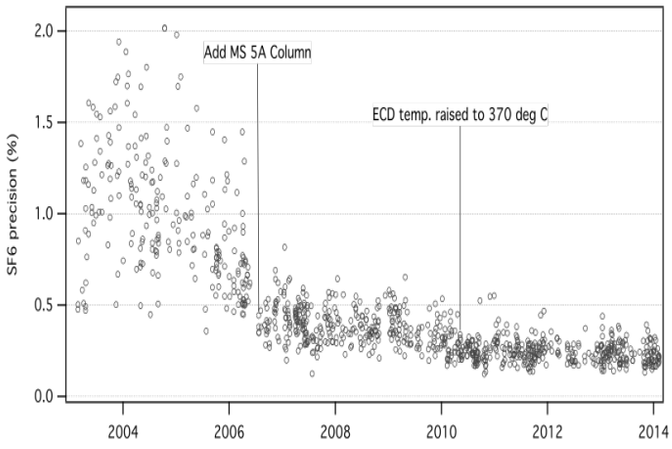


Fig. 8-1: Analytical precision (%) of SF_6 calibration measurements since 2003 for SF_6 mole fractions in the range 4–12 ppt. Note the improvement in precision in 2006 corresponding to the addition of the molecular sieve 5A column.

(SF_6 now elutes before N_2O). The effects of this and other changes are shown in Figure 8-1.

CO calibration system transfer measurements have benefited from several instruments purchased under funding by the NOAA OAR Atmospheric Chemistry, Carbon Cycle, & Climate (AC4) program (formerly ACCP). We replaced the older gas chro-

matograph in 2004 with an instrument based on resonance fluorescence in the VUV (Aero-Laser, Germany). In 2011, we replaced the Aero-Laser instrument with a new one based on off-axis spectroscopy (Los Gatos, USA). Measurement precision improved by a factor of ten from early 2004 to 2013.

8.5 NEW CAPABILITIES

In 2008, we prepared new gravimetric standards to support the measurement of HFC-23, HFC-32, HFC-125, and HFC-143a, along with CFC-13 and CFC-115 (see Section 5.2, Flask and In Situ Programs). Around that same time, we prepared gravimetric standards containing a number of hydrocarbons (acetylene, ethane, propane, n-butane, iso-butane, n-pentane, iso-pentane, n-hexane, benzene, and toluene) in support of flask measurements made by GMD and INSTAAR. The standards we prepared were in Aculife-treated aluminum cylinders, at ppb and ppt levels consistent with mole fractions found in the unpolluted troposphere. Later, in support of work related to measurement of fugitive emissions from oil and gas production (see section 5.3, Special Projects), standards with higher mole fractions of hydrocarbons were prepared (up to 300 ppb propane). We also compared GMD scales for a number of these hydrocarbons with those established by National Metrology Institutes (NMIs) and found them to be consistent within a few percent.

8.6 COMPARISONS

In 2010, WMO signed the Mutual Recognition Arrangement (MRA) with the Comité International des Poids et Mesures (CIPM). GMD serves as a Central Calibration Laboratory with WMO/GAW. Under the CIPM MRA, GMD is required to establish a "Quality System", and conform to international standards for calibration and measurement (ISO 17025, ISO Guide 34). We implemented this type of quality system and have also taken an active role in the Consultative Committee for Amount of Substance (CCQM) Gas Analysis Working Group.

Table 8-1: Formal and informal comparisons of gas standards

Comparison	Year Conducted	Gases	Participants
Informal	2005	CO_2 in air	NIES (Japan)
Informal	2005	N_2O in air	SIO
Informal	2005-2007	CO in air	Five E.U. lab
Informal	2008-2010	CO in air	Ten E.U. labs
Informal	2013	CO in air	Five
Informal	2011	SF_6 in air	KMA (Korea)
Informal	2011	N_2O in air	KIT (Germany)
Informal	2012	Hydrocarbons in air	NIST, others
Informal	2012	N_2O in air	NIST, SIO
CCQM P-41	2003	CO_2, CH_4 in air	Many
CCQM K-68	2008	N_2O in air	Many
CCQM K-82	2012	CH_4 in air	Many
CCQM P-151	2012	Halocarbons in air	Many
CCQM K-84	2013	CO in synthetic air	Eleven
Cucumber series	Ongoing	Whole air (CarboEurope, InGOS)	Many
IHALACE	2004-2007	Halocarbons in air	Many
CCQM K84	2008-2012	CO in air	Many
WMO RR #4	2002-2007	Whole air	Many
WMO RR #5	2009-2012	Whole air	Many
WMO RR #6	2014 -	Whole air	Many

This group consists mainly of representatives from National Metrology Institutes (such as NIST) interested in gas analysis and calibration. We have participated in a number of comparisons, both formal and informal, with NMIs and others (see Table 8-1). Comparisons are the first step in monitoring how well WMO/GAW scales are propagated to other laboratories. Comparisons with independent scales provide information on traceability to the SI, as well as scale stability and scale uncertainties.

SECTION 9 - ACRONYMS/GLOSSARY

9.1 INSTRUMENTS, NETWORKS, ORGANIZATIONS, AND SATELLITES

AAO	Airborne Atmospheric Observatory
AARI	Arctic and Antarctic Research Institute
ABL	atmospheric boundary layer
AC4	Atmospheric Chemistry, Carbon Cycle, & Climate
ACATS	airborne chromatograph for atmospheric trace species
ACCP	Atmospheric Composition and Climate Program
AERO	aerosols group (GMD)
AERONET	Aerosol Robotic Network (NASA)
AGAGE	Advanced Global Atmospheric Gases Experiment
AGGI	Annual Greenhouse Gas Index
AGL	above ground level
AIDA	Aerosols Interaction and Dynamics in the Atmosphere
ALT	Alert, Canada sampling site
AMF	ARM Mobile Facility
AMibA	Array for Microwave Background Anisotropy
AntUV	Antarctic UV Monitoring
AOD	aerosol optical depth
AOT	aerosol optical thickness
ARCPAC	Aerosol, Radiation, and Cloud Processes affecting Arctic Climate
ARL	Air Resources Laboratory (NOAA)
ARM	Atmospheric Radiation Measurement (DOE)
ARO	Atmospheric Research Observatory (South Pole, Antarctica)
ASIAA	Academia Sinica Institute of Astronomy and Astrophysics
ASL	above sea level
AT	apparent transmission
ATDD	Atmospheric Turbulence and Diffusion Division
ATTREX	Airborne Tropical Tropopause Experiment
AVE	Aura Validation Experiment
AWEX	Atmospheric Infrared Sounder Water vapor Experiment
AWI	Alfred Wegener Institute
BAO	Boulder Atmospheric Observatory
BER	A Bermuda sampling site
BESOS	Balloon Experiment on Standards for Ozone Sondes
BIF	Balloon Inflation Facility
BND	Bondville, Illinois sampling site
BRM	A Bermuda sampling site
BRW	Barrow Observatory, Barrow, Alaska (CMDL)
BSI	Biospherical Instruments Inc. (San Diego, California)
BSRN	Baseline Surface Radiation Network
BVSD	Boulder Valley School District
CALNEX	The California Research at the Nexus of Air Quality and Climate Change
CART	Cloud and Radiation Testbed
CARVE	Carbon in Arctic Reservoirs Vulnerability Experiment
CAS	Clean Air Sector
CATS	chromatograph for atmospheric trace species

CCGG	Carbon Cycle Greenhouse Gases group
CCL	Central Calibration Laboratory
CCN	cloud condensation nuclei
CCQM	Consultative Committee for Amount of Substance
CDIAC	Carbon Dioxide Information Analysis Center
CERES	Clouds and the Earth's Radiant Energy System
CFC	chlorofluorocarbon
CFH	cryogenic frost point hygrometer
CGO	Cape Grim Observatory, Tasmania, Australia
CIFEX	Cloud Indirect Effects Experiments
CIPM	Comité International des Poids et Mesures
CIRES	Cooperative Institute for Research in Environmental Sciences (University of Colorado)
CLAP	continuous light absorption photometer
CMDL	Climate Monitoring and Diagnostics Laboratory (NOAA)
COBALD	compact optical backscatter aerosol detector
CN	condensation nuclei
CNC	condensation nuclei counter
CPC	condensation particle counters
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
CT	CarbonTracker
CU	University of Colorado
CUCF	Central UV Calibration Facility
DEW	distant early warning
DOE	U.S. Department of Energy
DOI	digital object identifier
DU	Dobson unit
EC	Environment Canada
ECC	electrochemical concentration cell
ECD	electron capture detector
ECMWF	European Centre for Medium-Range Weather Forecasts
EPA	Environmental Protection Agency
ESDIM	Environmental Services Data and Information Management
ESRL	Earth System Research Laboratory
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FMI	Finnish Meteorological Institute
FP	frost point
FPH	frost point hygrometer
FSL	Forecast Systems Laboratory
FSU	Florida State University
GAGE	Global Atmospheric Gases Experiment
GAW	Global Atmosphere Watch
GC	gas chromatograph
GC-ECD	electron-capture gas chromatograph with detector
GC/FID	gas chromatograph flame ionization detector
GCM	global circulation model

GC-MS	gas chromatograph-mass spectrometer
GC-MSD	gas chromatograph-mass selective detector
GCOS	Global Climate Observing System
GEOSummit	Greenland Environmental Observatory (Summit)
GGGRN	Global Greenhouse Gas Reference Network
GHG	greenhouse gas
GMCC	Geophysical Monitoring for Climatic Change (now GMD) (NOAA)
GMD	Global Monitoring Division
GOES, GOES-R, GOES-8	Geostationary Operational Environmental Satellites
GOSAT	Greenhouse gases Observing SATellite
GPS	Global Positioning System
GRAD	Global RADiation
GV	NCAR Gulfstream V
HAA	Molokai Island, Hawaii sampling site
HATS	Halocarbons and other Atmospheric Trace Species group
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HFM	Harvard Forest, Massachusetts sampling site
HIAPER	High-performance Instrumented Airborne Platform for Environmental Research
HIPPO	HIAPER Pole-to-Pole Observations
IAEA	International Atomic Energy Agency
IAP	in situ aerosol profiling
IASOA	International Arctic Systems for Observing the Atmosphere
ICARTT	International Consortium for Atmospheric Research on Transport and Transformation
ICP	intercomparison
ID	internal diameter
IGAC	International Global Atmospheric Chemistry
IGACO	Integrated Global Atmospheric Chemistry Observations
INTEX	Intercontinental Transport Experiment
IONS	INTEX Ozonesonde Network Study
IOC	International Ozone Commission
ISAC	Institute of Atmospheric Sciences and Climate
ISIS	Integrated Surface Irradiance Study
ISO	International Organization for Standardization
IZO	Izaña Atmospheric Observatory
JOSIE	Julich Ozone Sonde Intercomparison Experiment
JPL	Jet Propulsion Laboratory
KWJ	Kwajalein, Marshall Islands sampling site
LACE	Lightweight Airborne Chromatograph Experiment
LDR	Lauder, New Zealand sampling site
LED	light-emitting diode
LEF	Park Falls, Wisconsin sampling site
LPDM	Lagrangian particle dispersion model
LTO	long-term observatory
MACPEX	Mid-latitude Airborne Cirrus Properties Experiment

MBL	marine boundary layer
MFR	multi-filter radiometer
MFRSR	multi-filter rotating shadowband radiometer
MLO	Mauna Loa Observatory, Hawaii
MODTRAN	Moderate Resolution Transmittance
MOHAVE	Measurements of Humidity in the Atmosphere and Validation Experiments
MOPITT	Measurement Of Pollution in The Troposphere
MOS	Mobile Observing System
MOU	memorandum of understanding
MPL	micro-pulse lidar
MRA	mutual recognition arrangement
NACP	North American Carbon Program
NASA	National Aeronautics and Space Administration
NASA ER-2	high-altitude aircraft
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center (NOAA)
NCEI	National Center for Environmental Information (NOAA)
NCEP	National Centers for Environmental Prediction (NOAA)
NDACC	Network for Detection of Atmospheric Composition Change
NDIR	non-dispersive infrared analyzer
NEON	National Ecological Observatory Network
NIST	National Institute of Standards and Technology (U.S. Dept. of Commerce)
NIWA	National Institute of Water and Atmospheric Research (New Zealand)
NOAA	National Oceanic and Atmospheric Administration (U.S. Dept. of Commerce)
NOAA FPH	NOAA frost point hygrometer
NSF	National Science Foundation
NWAS	NOAA whole air sampler
NWR	Niwot Ridge, Colorado, sampling site
NWS	National Weather Service (NOAA)
OASIS	Ocean-Atmosphere-Sea Ice-Snowpack
OAR	Oceanic and Atmospheric Research (NOAA)
ObsPack	observation package
ODGI	Ozone Depleting Gas Index
OD	outside diameter
ODS	Ozone Depleting Substance
OHP	l'Observatorie Haute Provence
OZWV	ozone and water vapor
PAN	peroxyacetyl nitrate
PANTHER	PAN and other Trace Hydrohalocarbons Experiment
PAR	photosynthetically active radiation
PFA	Poker Flat, Alaska, sampling site
PFP	programmable flask package
PFR	precision filter radiometer
PMEL	Pacific Marine Environmental Laboratory (NOAA)

ppb	parts per billion
ppm	parts per million (by dry mole fraction)
ppmV	parts per million (by volume)
ppt	parts per trillion
PSAP	particle soot absorption photometer
PTU	pressure, temperature, and humidity
PTH	Perth, Australia, sampling site
QBO	quasi-biennial oscillation
QUOBI	Quantitative Understanding of Ozone Losses by Bipolar Investigations
RF	radiative forcing
RH	relative humidity
RITS	radiatively important trace species
RT	radiative transfer
RTA	Rarotonga, Cook Islands
SAG	Scientific Advisory Group on Ozone
SASP	Surface Air Sampling Program
SAUNA	Sodankylä Total Column Ozone Intercomparison
SAW	sound acoustic wave
SEACIONS	SouthEast American Consortium for Intensive Ozonesonde Network Study
SEARCH	Study of Environmental Arctic Change
SGP	Southern Great Plains (Lamont, Oklahoma)
SHADOZ	Southern Hemisphere additional ozonesondes
SMO	Samoa Observatory, American Samoa
SMPS	scanning mobility particle spectrometer
SOLRAD	Solar Radiation Network
SOP	standard operating procedure
SOWER	soundings of ozone and water in the Equatorial region
SPARC	stratosphere-troposphere processes and their role in climate
SPO	South Pole Observatory, Antarctica
SPSM	South Pole Station Modernization
SRB	Surface Radiation Budget
SRRB	Surface Radiation Research Branch
SS	stainless steel
SST	sea surface temperature
STAR	STEM Teacher and Researcher Program (Cal Poly, San Luis Obispo)
START-08	Stratosphere-Troposphere Analyses of Regional Transport
STE	Stratosphere-Troposphere Exchange
STEM	Science Technology Engineering and Math
SUM	Summit Greenland Observatory
SURFRAD	Surface Radiation network
SW	shortwave irradiance
TAWO	Temporary Atmospheric Watch Observatory
TCAP	Two-Column Aerosol Program
TC4	tropical composition, cloud, and climate coupling
TCCON	Total Column Carbon Observing Network

TDL	tunable diode laser
TES	Tropospheric Emission Spectrometer
THD	Trinidad Head Atmospheric Observatory California, sampling site
TROICA	TRans-siberian Observations Into the Chemistry of the Atmosphere
TSI	Thermo Systems, Incorporated also total sky imager
TTL	tropical tropopause layer
UAF	University of Alaska, Fairbanks
UAS	unmanned aircraft systems
UCATS	unmanned aircraft systems chromatograph for atmospheric trace species
UCEC	University of Cambridge electrochemical sensors
UNAVCO	University NAVSTAR Consortium (NAVSTAR is a type of GPS)
UNECE	United Nations Economic Commission for Europe
UPS	uninterruptible power supply
USAF	United States Air Force
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UTC	Universal Time Coordinated
UTLS	upper troposphere/lower stratosphere
UV	ultraviolet
UVB	ultraviolet B band
VYSOS	Variable Young Star Optical Survey
WCC	World Calibration Centre
WIS	Negev Desert (Israel)
WISG	World Infrared Standard Group
WITN	Tower in Grifton, North Carolina sampling site
WKT	Moody, Texas, sampling site
WLEF	Tower in Park Falls, Wisconsin sampling site
WLG	Mt Waliguan Observatory (China)
W m^{-2}	watts per meter squared
WMO	World Meteorological Organization, Geneva, Switzerland
WOUDC	World Ozone and Ultraviolet Data Centre (Canada)
WPCP	water-based condensation particle counter
WRR	World Radiometric Reference

9.2 Chemical Compounds

^{12}C	carbon-12
^{13}C	carbon-13
^{14}C	carbon-14, or radiocarbon
$^{14}CO_2$	carbon-14 CO_2
$\delta^{13}C$ in CO_2 and CH_4	carbon isotopic composition of carbon dioxide and methane
CCl_4	carbon tetrachloride
CFC	chlorofluorocarbon
CFC-11	trichlorofluoromethane
CFC-12	dichlorodifluoromethane
CFC-13	chlorotrifluoromethane

CFC-113	trichlorotrifluoroethane
CFC-115	pentachlorofluoroethane
C_2Cl_4	tetrachloroethylene
C_6H_6	benzene
CH_3Br	methyl bromide
$CHBr_3$	bromoform
CH_2Br_2	dibromomethane
CH_2Cl_2	dichloromethane
CH_3CCl_3	methyl chloroform
CH_3I	methyl iodide
CH_3Cl	methyl chloride
$CHCl_3$	chloroform
CH_4	methane
δD in CH_4	hydrogen isotopic composition of methane
CO	carbon monoxide
CO_2	carbon dioxide
COS	carbonyl sulfide
DMS	dimethyl sulfide
H	hydrogen
H_2	molecular hydrogen
H_2O	water
Halon-1211	bromochlorodifluoromethane
Halon-1301	bromotrifluoromethane
Halon-2402	1,2-dibromotetrafluoroethane
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HCFC-22	chlorodifluoromethane
HCFC-23	trifluoromethane
HCFC-32	difluoromethane
HCFC-125	pentaflouroethane
HCFC-141b	1,1-dichloro-1-fluoroethane
HCFC-142b	1-chloro-1, 1-diflouroethane
HFC	hydrofluorocarbon
HFC-134a	1,1,1,2-tetrafluoroethane
HFC-152a	1,1-difluoroethane
Hg	mercury
KI	potassium iodide
KBr	potassium bromide
^{18}O	oxygen-18
O_2	oxygen
O_3	ozone
OH	hydroxyl (radical)
MSA	methane sulfonate
N_2O	nitrous oxide
NF_3	nitrogen triflouride
N_2O	nitrous oxide
NOx	nitrogen oxides
PAN	peroxyacetyl nitrate

PFC	perfluorocarbon
SF_6	sulfur hexafluoride
TFA	trifluoroacetate
VOC	volatile organic carbon