GLOBAL MONITORING Laboratory

Summary Report No. 29
2014 - 2018

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Boulder, Colorado
April 2018

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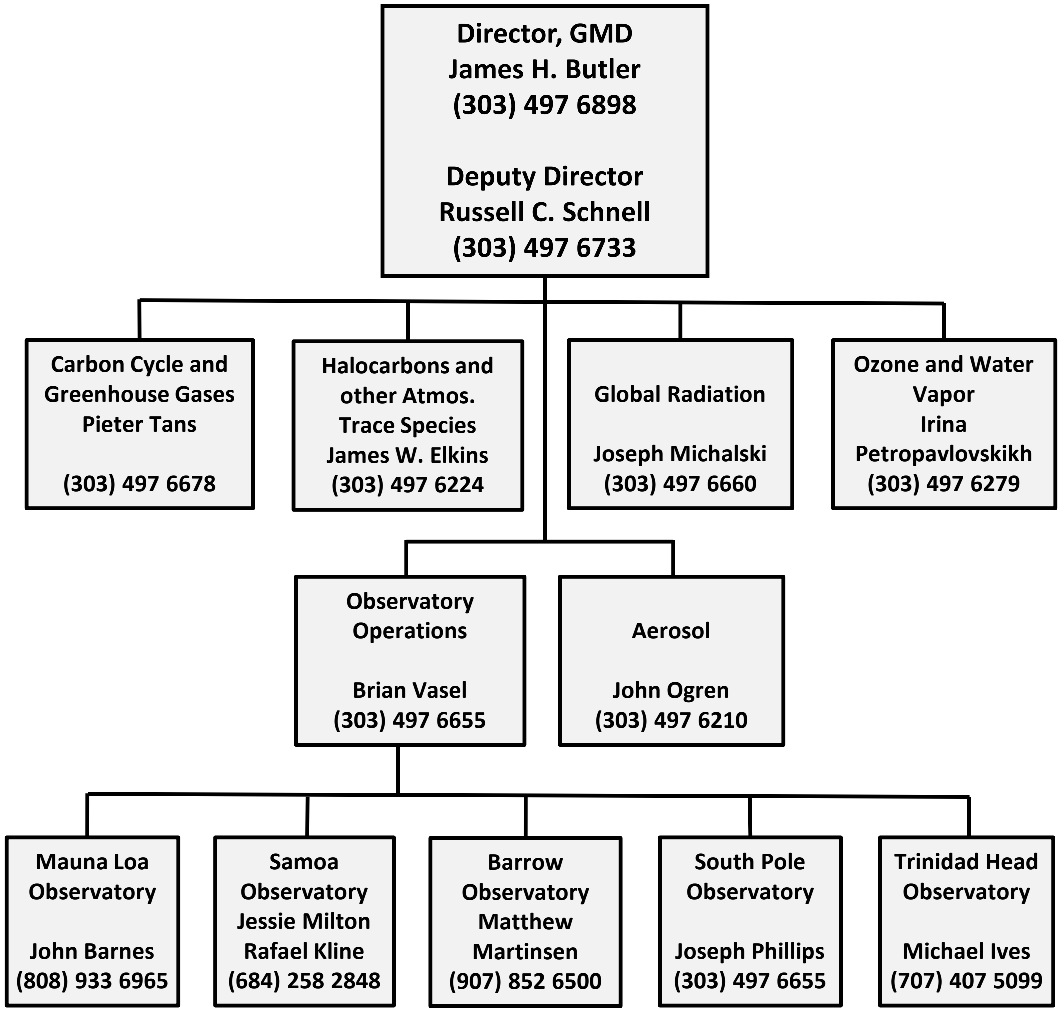
Organizational Chart, 2014



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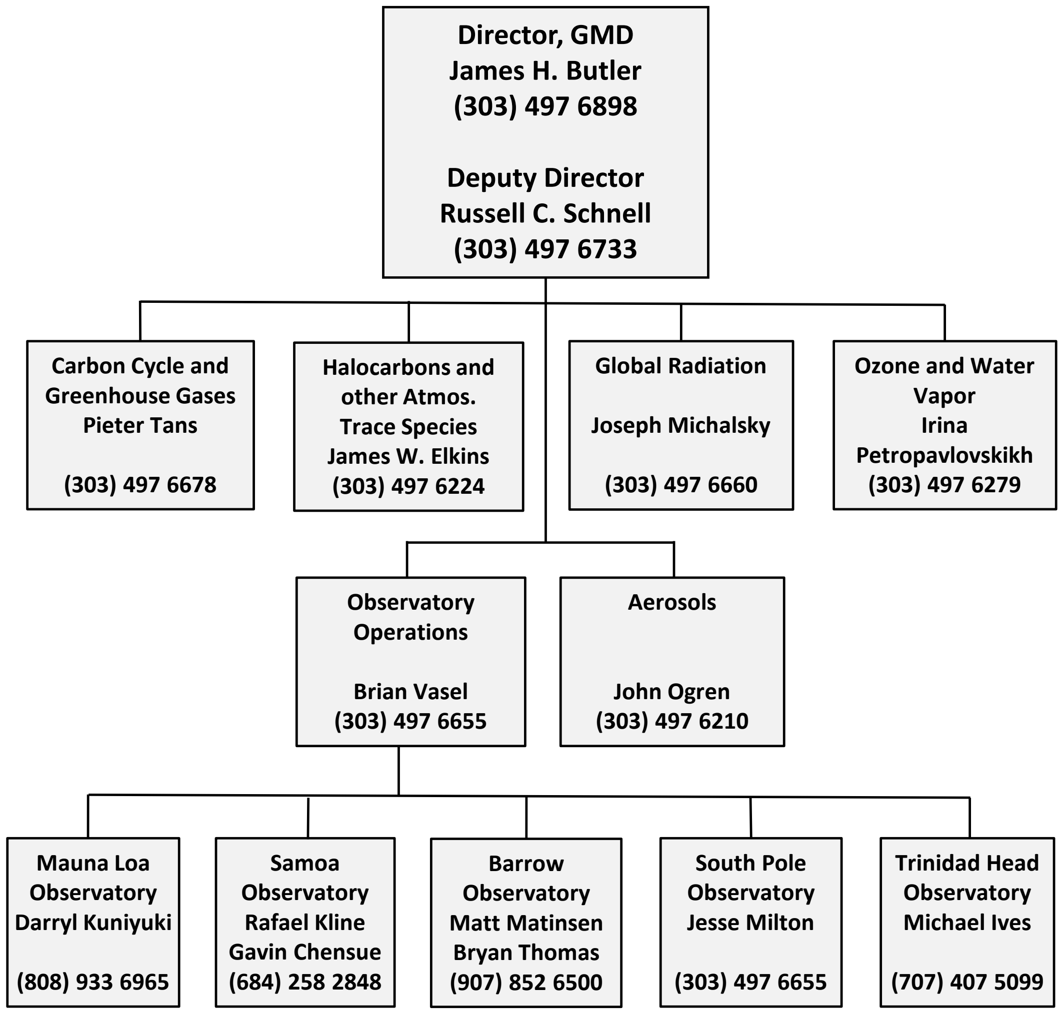

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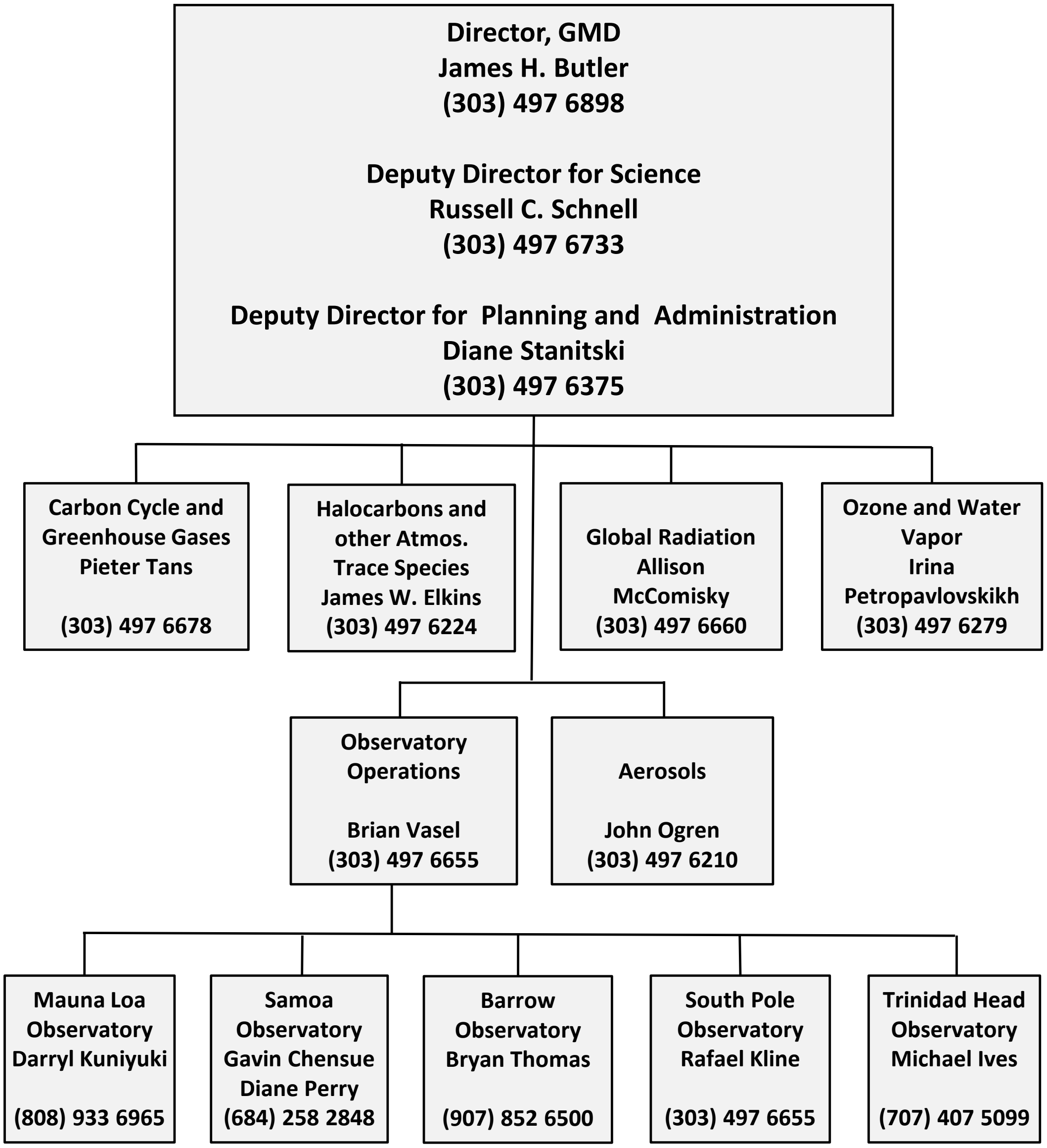

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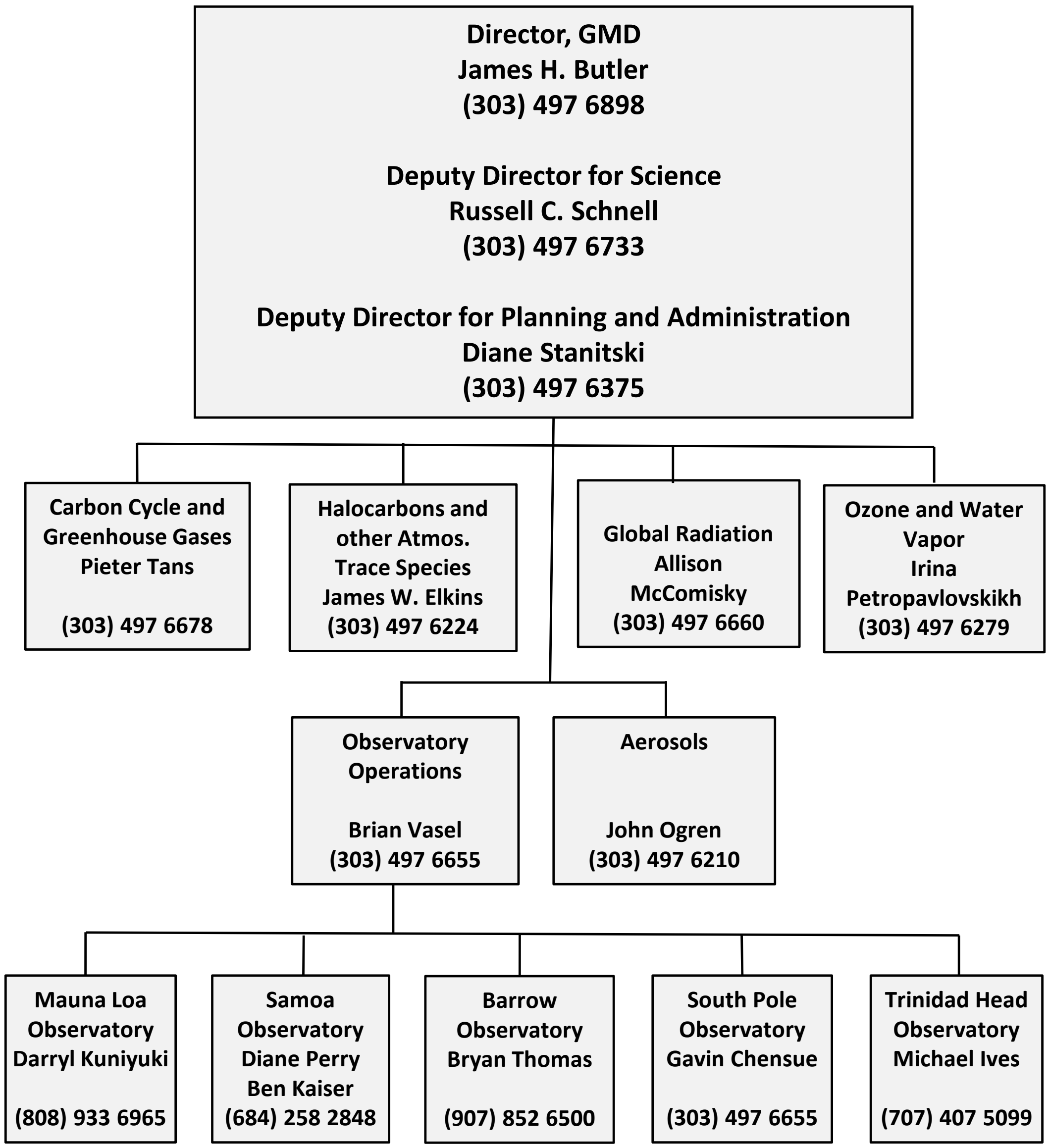

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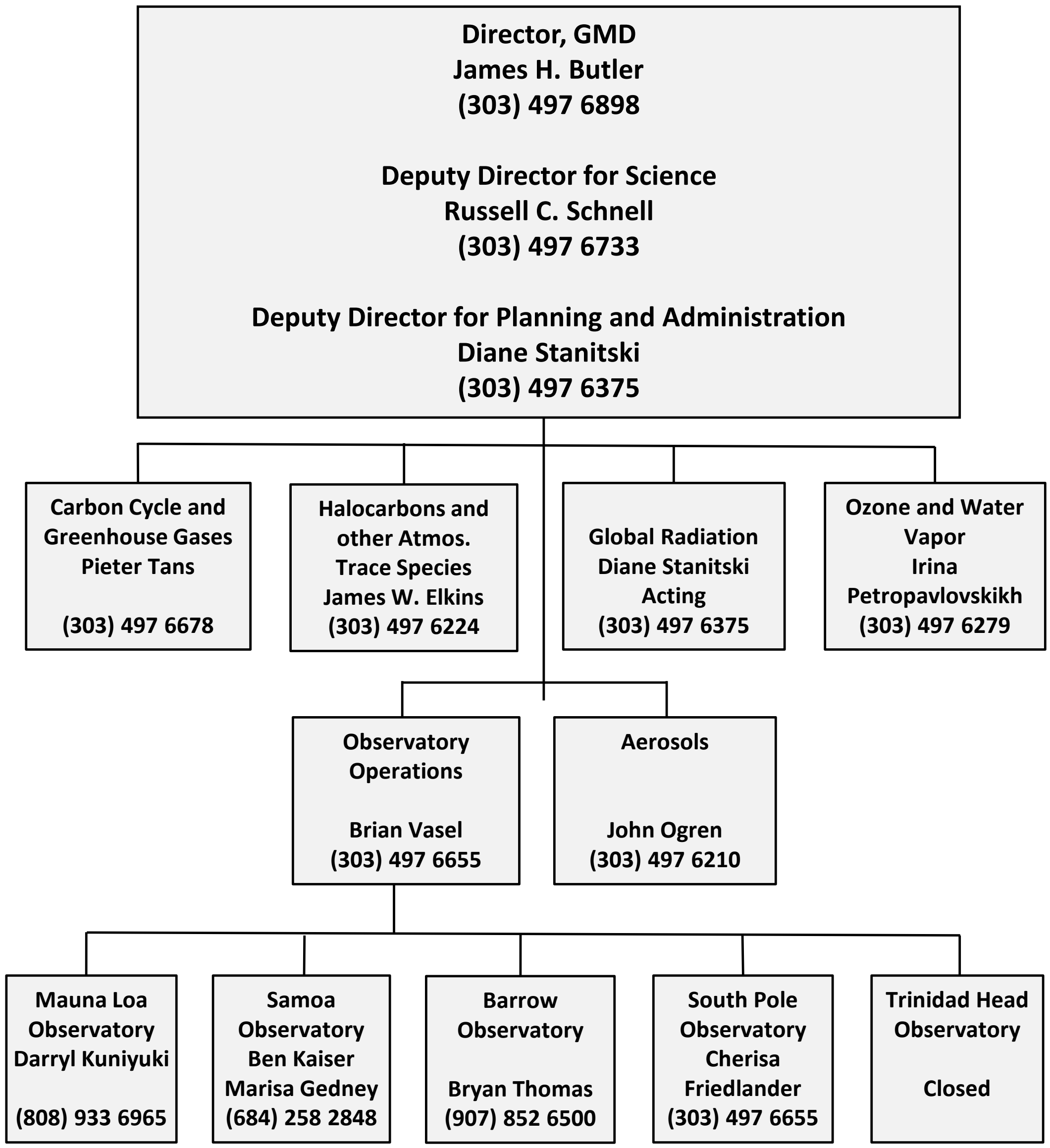

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SECTION 1 - INTRODUCTION

1.1 DIRECTOR'S INTRODUCTION

This is the 29th Summary Report of NOAA ESRL's Global Monitoring Division (GMD) and its predecessor organizations1. These reports, which began in 1972, capture the organization, successes, challenges, and routine operations of our long- term observing systems for monitoring the composition of Earth's atmosphere. Initially, the reports were produced annually, but soon after the organization advanced to Laboratory status in 1990, the reports became biennial. This continued through 2003, when their production was held in abeyance. The primary reason for this pause was the uncertainty associated with anticipated major reorganizations at OAR and NOAA levels. Once it was clear that GMD would remain largely intact, we reevaluated the content of these reports, which had become highly scientific, time consuming to produce, and redundant with resulting publications in the refereed literature, and returned to providing a message on our operations, as initially envisioned. The first of these was a 10-year report for 2004-2013. This is the second, a 5-year report for 2014-2018. Our goal is for subsequent reports to return to biennial production.

The initial focus of these reports was on GMD's four Atmospheric Baseline Observatories, but with time they began to include information on our broader observing systems, which are currently operated by all four Divisions in the laboratory and include measurements at approximately 150 sites. These include systems for observing radiation at Earth's surface, tall towers and aircraft for evaluating gas fluxes, flask sampling networks to broaden global coverage, and a large network for monitoring aerosol properties. Two observatories, Summit, Greenland, and Trinidad Head, California, were added in the early 2000s and operated nearly 20 years before budget constraints forced their closure. These Summary Reports provide a solid historical reference should questions arise about any of our data or procedures. In this sense, they ground everything that we do as we seek to understand the trends and distributions of substances in the atmosphere and how they influence the Earth system. Much of the present understanding of climate change, ozone depletion, and air quality in the remote atmosphere derives from GMD's careful and consistent observations over decades.

1.2 REPORT RATIONALE

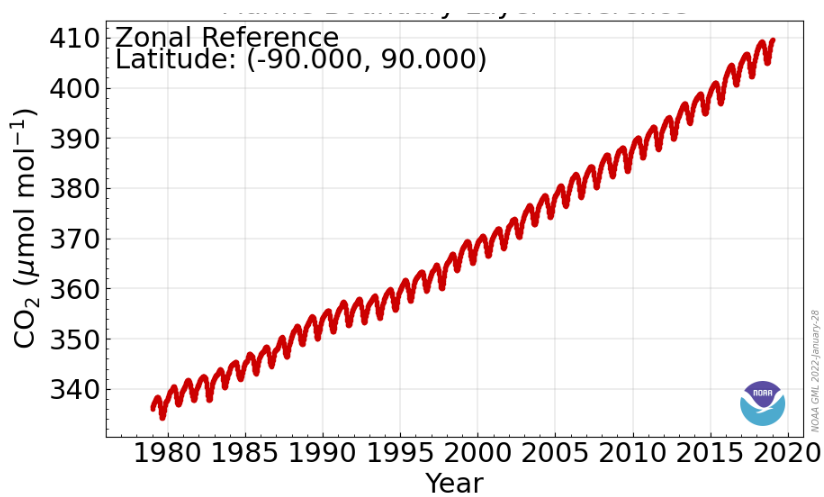
The last summary report, Summary Report No. 28, covers the years 2004–2013. The long-term mission and research themes of GMD have not changed and are summarized in the GMD Research Plan that was updated in 2013. However, the operational changes that have occurred over the last decade are not succinctly captured in one place. While the vision and mission of the organization have not changed, the way we get the job done certainly has evolved over the last decade. This report serves to bridge the gap from 2014–2018 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 capturing 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: Aerosols (AERO), Carbon Cycle and Greenhouse Gases (CCGG), Halocarbons and other Atmospheric Trace Species (HATS), Global Radiation (GRAD) and Ozone and Water Vapor (OZWV). The unique observing systems operated by each research group come together at GMD's baseline observatories, which serve as the backbone of the GMD observing system. GMD's research groups develop and maintain their observing networks and advance our understanding of the Earth system through data interpretation and published research results. Much of GMD's research crosscuts these groups and this operations report will highlight the synergy of the research projects.

1.4 GMD PRODUCTS AND SERVICES

NOAA GREENHOUSE GAS MARINE BOUNDARY LAYER REFERENCE



Global Monthly Mean CH_4

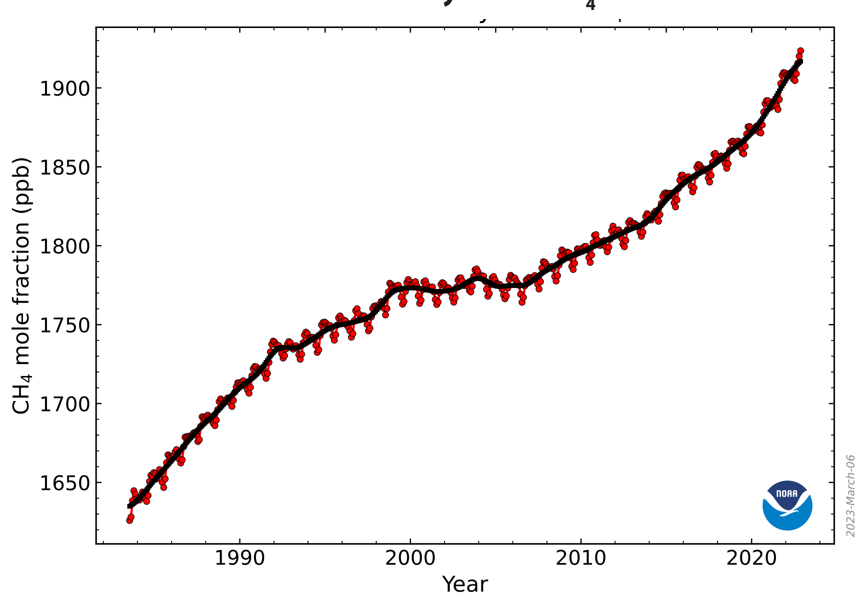


Figure 1.1: The Global Monitoring Division measures carbon dioxide (upper panel) and methane (lower panel), the most important greenhouse gases, from a globally distributed network of sampling sites.

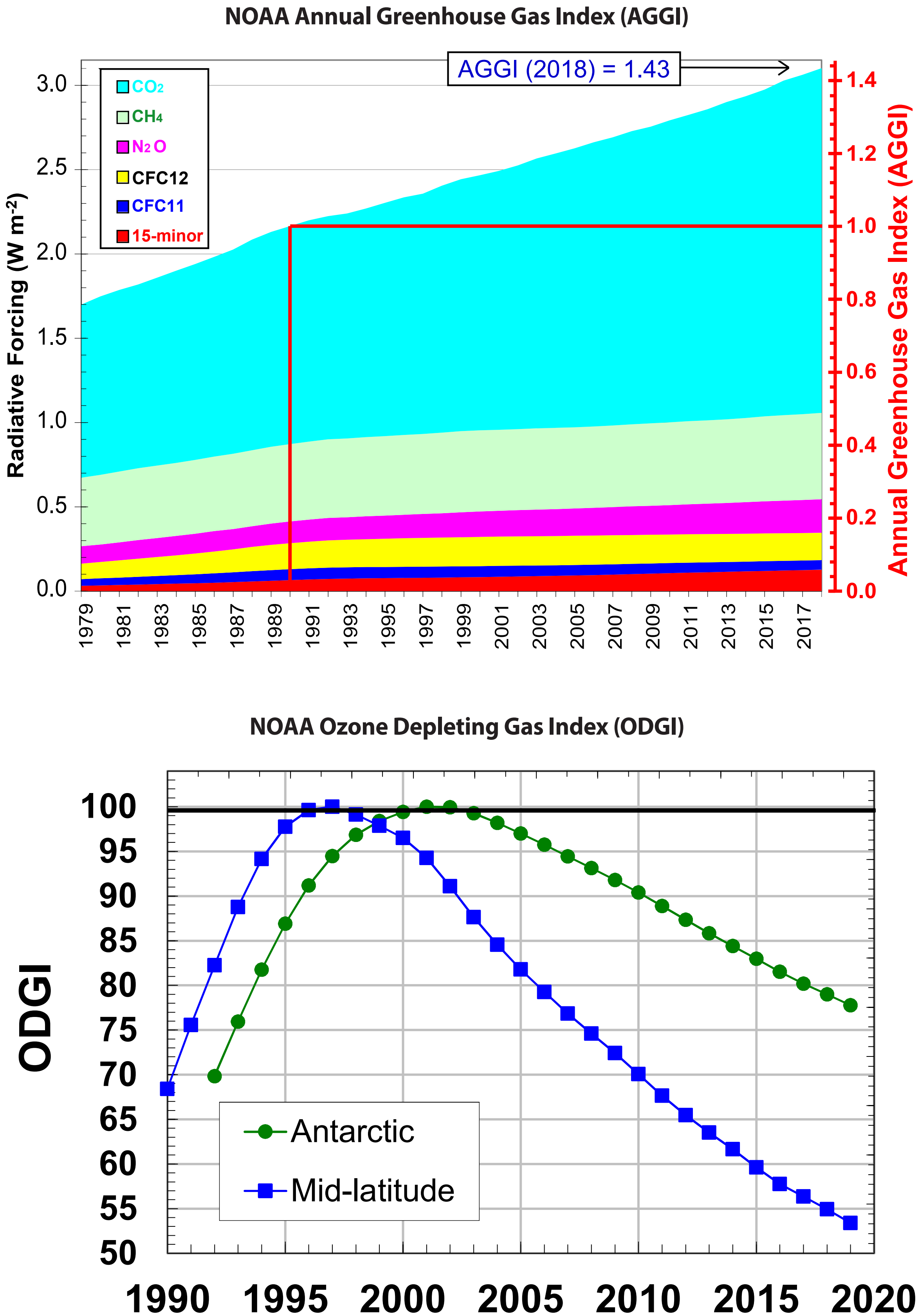


Figure 1.2: Global mean burdens of the most abundant long-lived gases affecting climate (upper panel) and the stratospheric ozone layer (lower panel) are aggregated into the Annual Greenhouse Gas Index (AGGI) and the Ozone Depleting Gas Index (ODGI). These indexes provide an overall understanding of how the greenhouse gas-warming and stratospheric ozone-depleting potentials supplied by these atmospheric gases change from year to year.

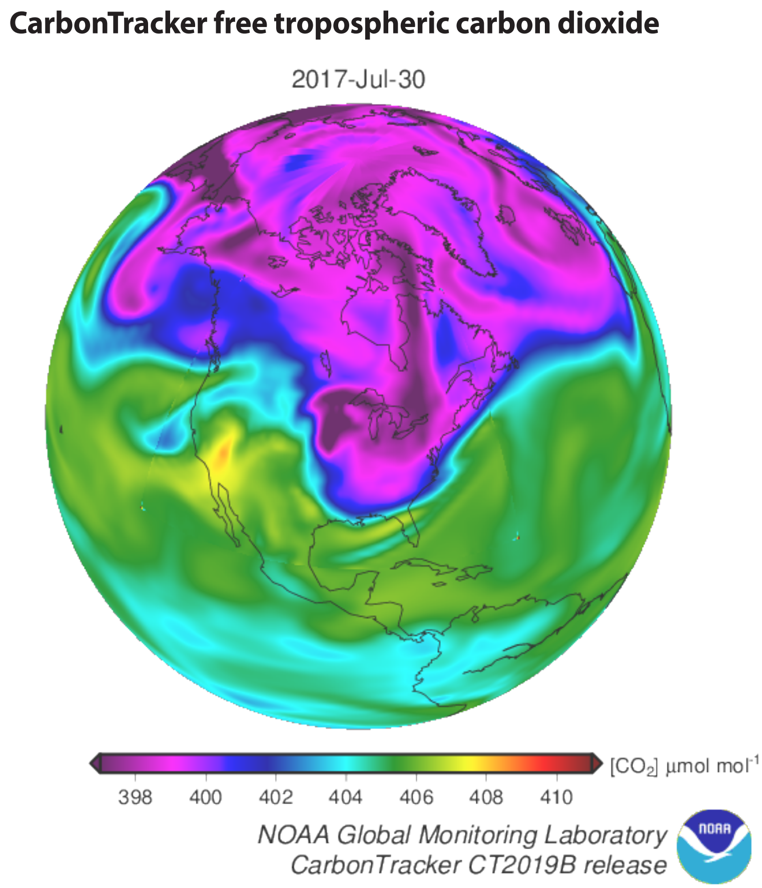


Figure 1.3: CarbonTracker is a CO2 measurement and modeling system to track sources (emissions to the atmosphere) and sinks (removal from the atmosphere) of carbon dioxide and methane around the world. CarbonTracker uses atmospheric CO2 and CH4 observations from many collaborators and simulated atmospheric transport to estimate surface fluxes of CO2 and CH4.

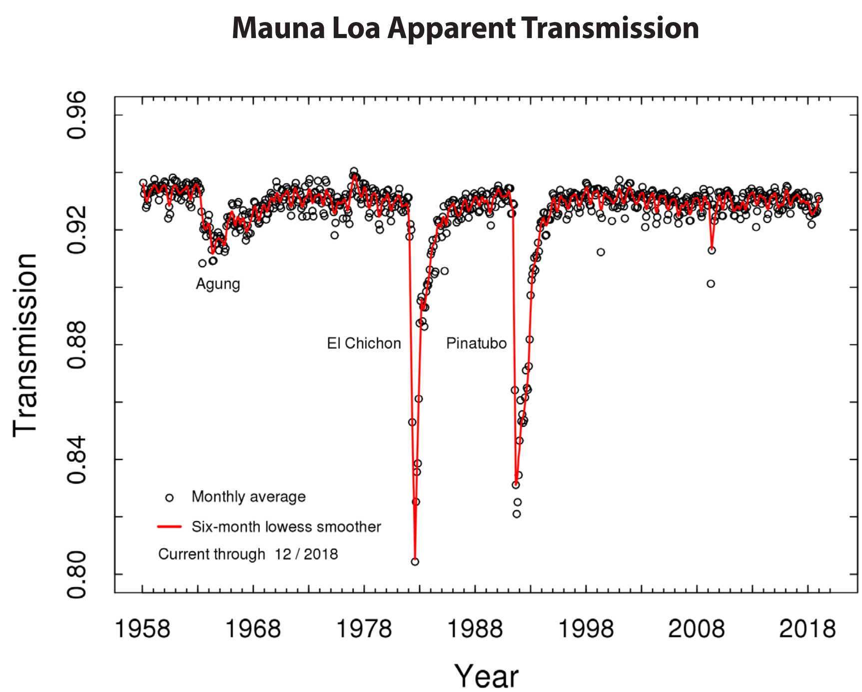


Figure 1.4: The MLO apparent solar transmission record shows the effects of volcanic eruptions that reduce surface solar radiation and the springtime transportation of aerosols from Asia (better seen in an expanded view).

Observation Package (ObsPack) Data Products

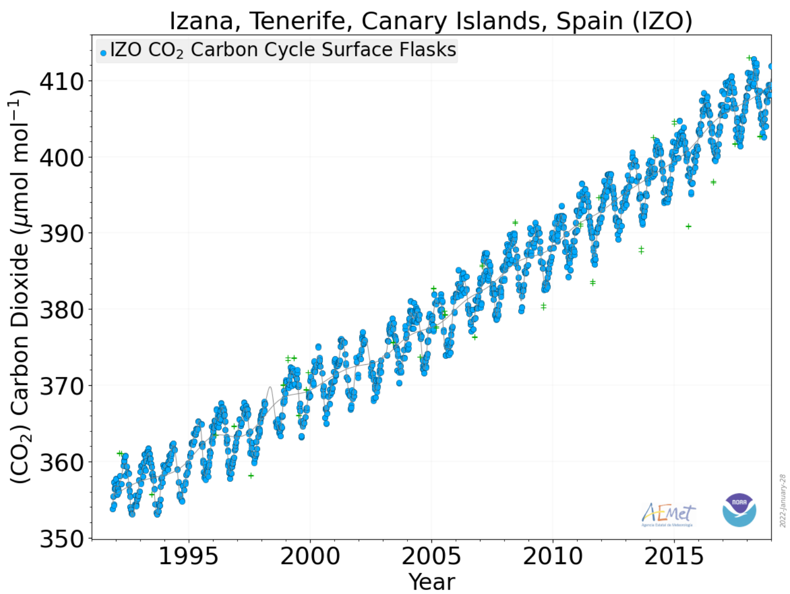


Figure 1.5: Observation Package (ObsPack) data products are intended to stimulate and support carbon cycle modeling studies by bringing together direct atmospheric greenhouse gas measurements derived from one or more laboratories, prepare them with specific applications in mind, and package and distribute them in a set of self-documenting files. The above figure is an illustration of such an application for data from the Izana, Canary Islands, Spain atmospheric monitoring site.

South Pole Ozone and Temperature: 14-21 km

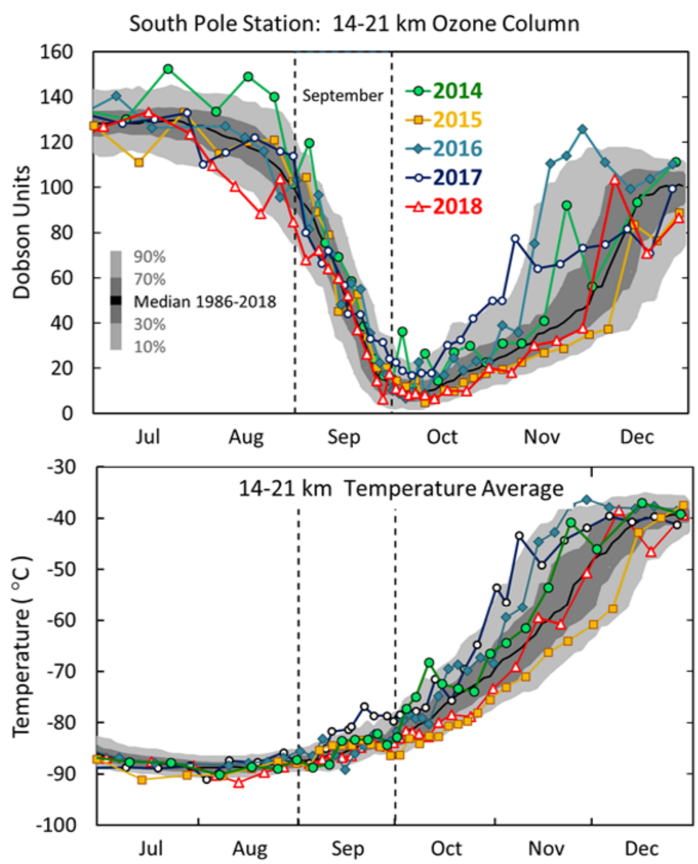


Figure 1.6: South Pole ozone (upper panel) and temperature (lower panel) graph for the 14-21 km layer of the stratosphere. The 2015 polar vortex stands out for the low ozone and cold temperatures lasting longer than normal.

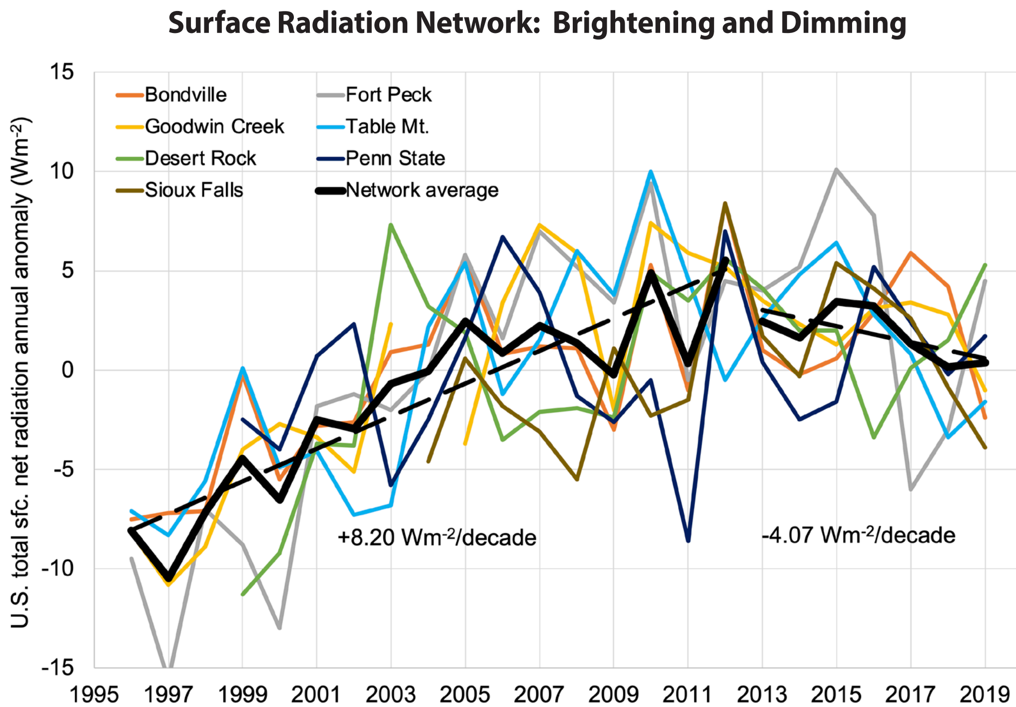


Figure 1.7: Net surface radiation budget (SRB) and its components from the Surface Radiation (SURFRAD) network reveal strong but temporally varying trends with the solid black line depicting the annual average of the net surface radiation anomaly and the dashed black lines the best-fit linear trends for the periods 1996–2011 and 2012-2018. These data show that the increase in the SRB is dominated by an increase in the downwelling radiation due to an observed decrease in cloud cover. The trend for the first 15 years shows a 12.9 W m-2 increase in the net surface radiation anomaly and for the second 7 years constitutes a 0.1 W m-2 decrease.

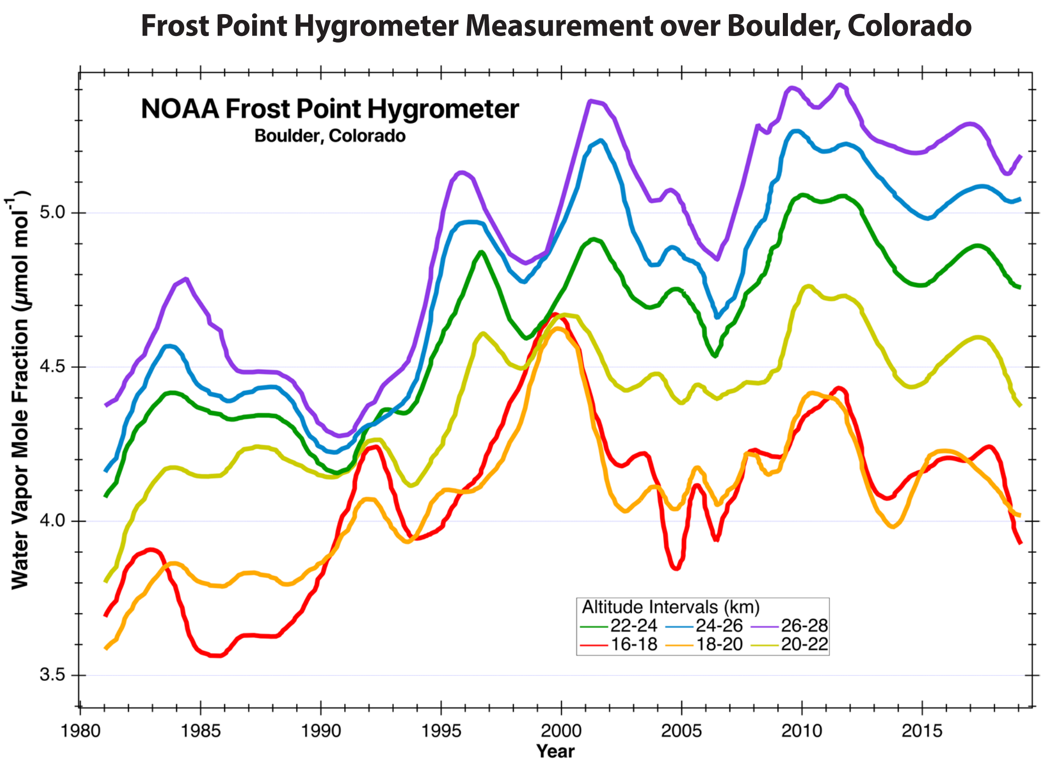


Figure 1.8: Smoothed time series of stratospheric water vapor mixing ratios at six altitude intervals over Boulder, Colorado, obtained with the GMD-developed Frost Point Hygrometer (FPH). Each data point represents a uniquely measured vertical profile by a high-altitude balloon-borne FPH. This long-term record shows a 25% increase in stratospheric water vapor from 1980 through 2017.

NOAA GMD Solar Calculator

Figure 1.9: The NOAA GMD Solar Calculator quickly provides highly accurate sunrise, sunset, solar noon, and solar position for any place on Earth. At Mount Everest, expedition planners use it to determine sunrise angle (green line) and sunset angle (red line), as well as time of sunrise (09:30) and sunset (19:27) for a particular day; December 31, 2018 is illustrated here.

Decreasing Aerosol Loadings in the Midwestern United States

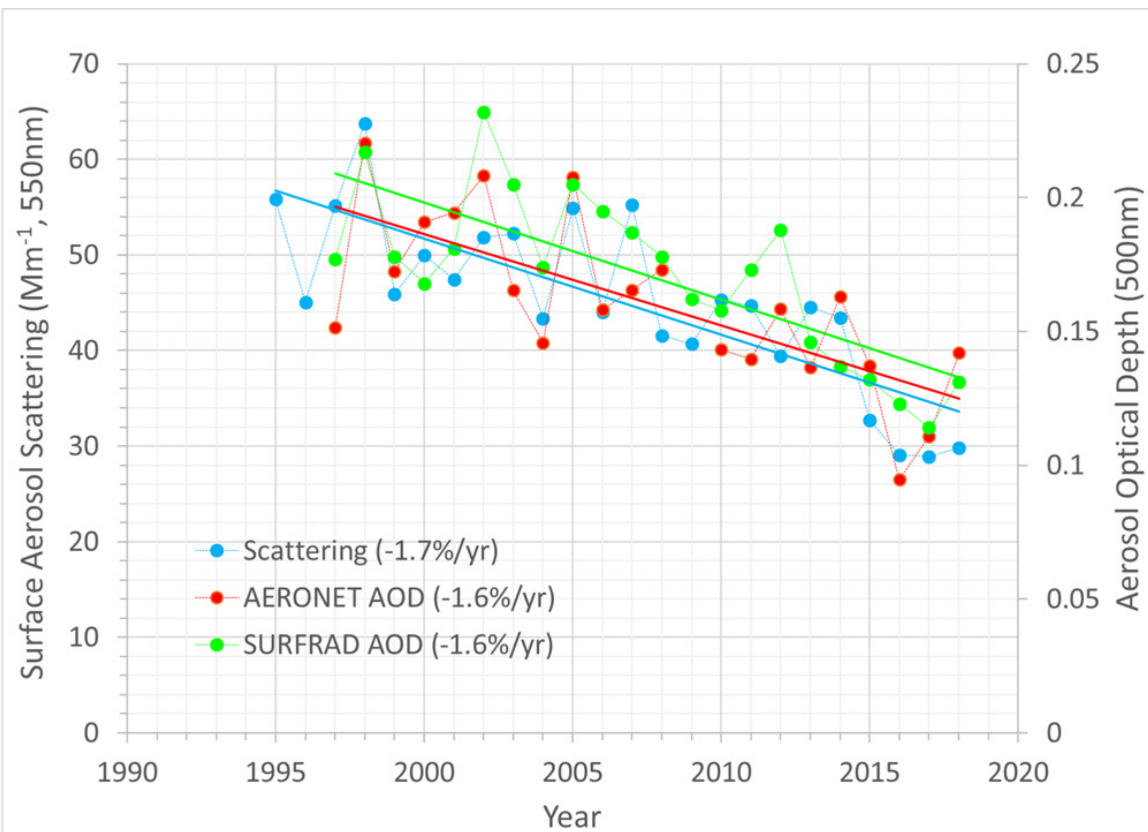


Figure 1.10: Since the 1980s, a significant decrease in aerosol loadings has occurred in the eastern and midwestern United States as shown in these data from the Bondville, Illinois, cooperative monitoring site. This trend of decreasing aerosols may be due to increased regulation and enforcement following the Clean Air Acts of 1970 and 1990.

Aerosol Light Scattering Trends at Mauna Loa

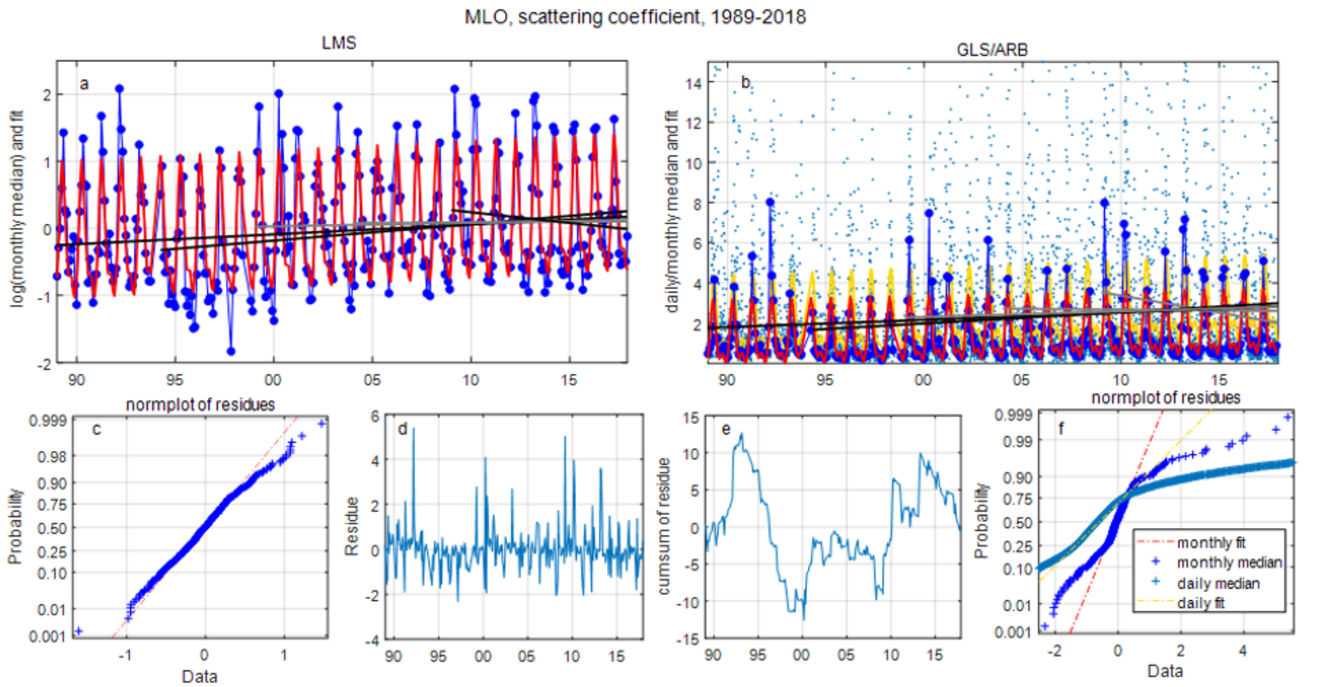


Figure 1.11: Aerosol light scattering trends at Mauna Loa Observatory, Hawaii, for monthly median data (blue dots) showing the annual aerosol cycle. The positive 25- and 30-year aerosol trends up to 2018 are statistically significant and the 15- and 20-year trends are not, whereas the 10-year trend from 2008 to 2018 is negative but statistically significant at only the 90% confidence level.

SOUTH POLE OBSERVATORY WIND ROSES

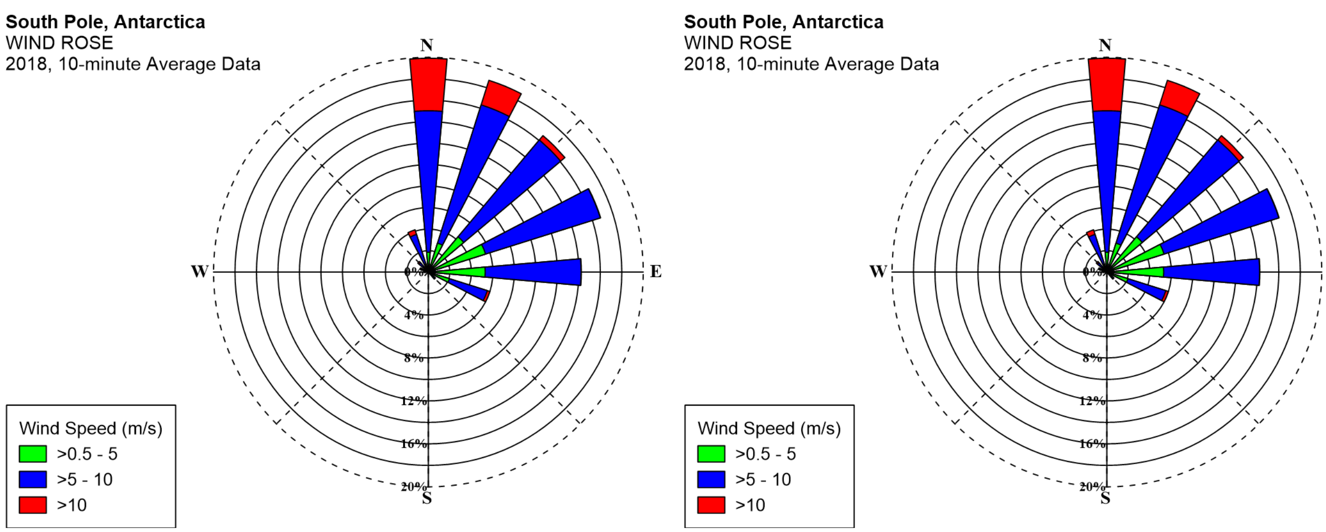
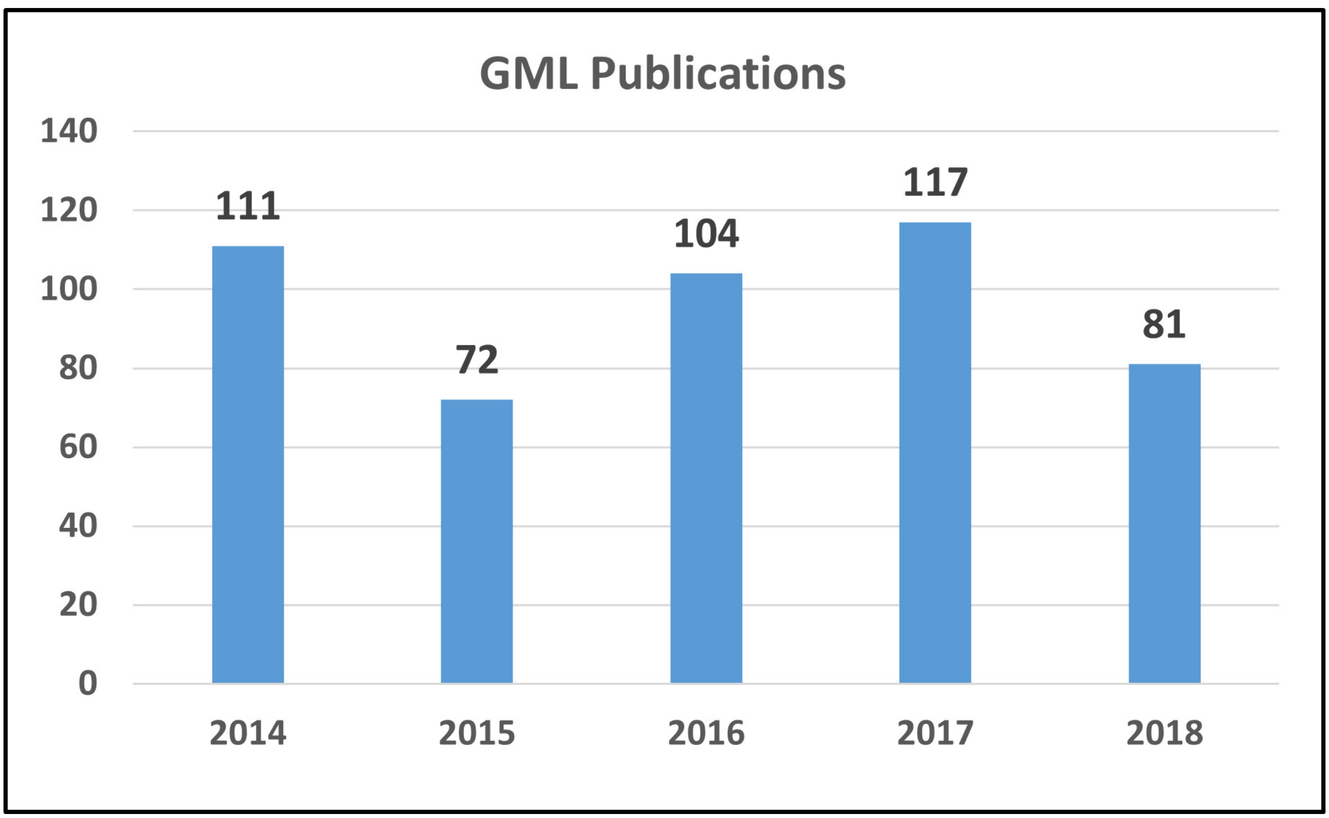


Figure 1.12: As illustrated for the South Pole, wind directions and speeds were significantly different between 2016 and 2018. Such wind roses help researchers understand changes in the sources of atmospheric species monitored at a measurement site. Wind roses can be produced for all atmospheric observatories and at time periods of a single day, a week, a month, a year, etc.

Figure 1.14. The NOAA GMD Interactive Atmospheric Data Visualization (IADV) web site provides graphs of GMD data, including our most up-to-date measurements, to the scientific community, general public, educators, students, media, businesses, and government policymakers. Visitors may view all data including near real-time preliminary Carbon Cycle measurement results; review details about each sampling location; create custom graphs; and view their plots online and save graphs in PDF format.

5.1 PUBLICATIONS & REFERENCES

This chart shows the number of GMD publications by year from 2014 through 2018. Complete publication data can be found at: https://gml.noaa.gov/publications/



1.6 GMD ORGANIZATION

The GMD structure features one observatory operations group and five research groups focused on the following scientific disciplines:

(1) Observatory Operations and Meteorology
(2) Aerosols
(3) Carbon Cycle and Greenhouse Gases
(4) Halocarbons and other Atmospheric Trace Species
(5) Global Radiation
(6) Ozone and Water Vapor

1.7 OUTREACH AND EDUCATION ACTIVITIES

The ESRL Global Monitoring Division takes an "all hands-on-deck" approach to education. As a result, GMD works through many different programs across NOAA and with external partners who have a role to play in supporting NOAA's mission through education. Through outreach event planning, material support, and educational guidance, GMD Outreach increases awareness and knowledge of GMD's sciences and data, and is instrumental in developing educational resources that benefit students from high school age to postgraduate studies.

GMD actively supports the NOAA Office of Education's Hollings and Educational Partnership (EPP) Scholarship Programs by providing a multitude of scientific, engineering, mathematics, computer science, policy, and public outreach summer internship opportunities to student participants. GMD 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 organization and the student.

GMD strives to create a workplace where everyone feels welcomed and empowered to reach their full potential while supporting NOAA's mission. We embrace diverse perspectives from each other and celebrate everyone's unique experiences and expertise. GMD actively promotes changes towards Diversity, Equity, Inclusion, and Accessibility (DEIA goals) by supporting leadership in expanding and strengthening the diversity of our workforce, fostering a more inclusive environment, and attracting, retaining, and supporting the professional advancement of historically excluded minority groups in the environmental fields.

SECTION 2 – OBSERVATORY OPERATIONS AND METEOROLOGY

2.1 BARROW, ALASKA

BACKGROUND

Barrow Observatory (BRW), established in 1973, is located near sea level 8 km east of Utqiaġvik, Alaska at 71.32 degrees north latitude. BRW has a prevailing east- northeast wind off the Beaufort Sea and receives minimal influence from anthropogenic effects. Due to its unique location, dedicated and highly trained staff, and excellent power and communications infrastructure, BRW is host to numerous cooperative research projects. This facility is staffed year-round by two people.

Figure 2.1: Barrow Atmospheric Baseline Observatory compound with the Department of Energy facility in upper right center and NESDIS Polar Orbiting Satellite downlink antenna in the lower right in winter.

After the observatory operated for 45 years in the original building, NOAA provided funding for a new facility. A design-build contract was awarded in September 2018 and will result in a structure that provides more than twice as much space. In addition to more science capacity, the facility will have running water, a Dobson room modeled after South Pole's Atmospheric Baseline Observatory, and fiber communications.

STAFF FACILITIES

Year	Station Chief	Technician
2014	Matthew Martinsen	Shannon Coykendal (January - May), Ross Burgerner
2015	Matthew Martinsen (Jan - Sept), Bryan Thomas (Sept - Dec)	Ross Burgener
2016	Bryan Thomas	Ross Burgener
2017	Bryan Thomas	Ross Burgener
2018	Bryan Thomas	Ross Burgener (January - October)

- **2015**
  Electrical cleanup was performed on racks, benches, walkways.

2016

- Stairs were constructed down the embankment of the driveway toward the Observatory.
- The water pump and IQ boiler control board were replaced at the 8434 housing unit.
- In July, NOAA/OAR conducted a Facility Condition Assessment at the Observatory.
- Ross Burgener drove the new replacement GSA truck from Fairbanks to Prudhoe Bay in July. The truck was backhauled on the barge to Barrow. The old truck was auctioned locally.

•

2017

- Matthew Martinsen visited BRW from MLO and conducted a comprehensive electrical situation report for the observatory.
- Carbon monoxide detectors were installed in all buildings.
- Weathergoose temperature monitor was installed in the Observatory and programmed to email warnings if the building became too warm or cold.
- In May, metal roofing was installed on the main observatory building.
- In August, Arctic Spark Electric installed LED lighting for the driveway and walkway.

2018

- In June, the Bobcat thaw pad was re-sealed and the garage door adjusted.

NESDIS upgraded their microwave and fiber optic connection for data communications.

Matthew Martinsen visited BRW from MLO and conducted a comprehensive electrical situation report for the observatory. Carbon monoxide detectors were installed in all buildings. Weathergoose temperature monitor was installed In the Observatory and programmed to email warnings if the building became too warm or cold. In May, metal roofing was installed on the main observatory building. In August, Arctic Spark Electric installed LED lighting for the driveway and walkway.

Cooperative Projects

2015

- Mercury project installed.
- UCAR added a radio occultation receiver to the UNAVCO GPS antenna.

2016

- July: The BSI UV-B monitoring equipment was decommissioned, removed from the NARL facility at the request of UIC Science, and stored at the 3-bedroom NOAA house.
- September: The retired NOAA/NESDIS 2.4m SeaSpace radome and antenna were retro'd.

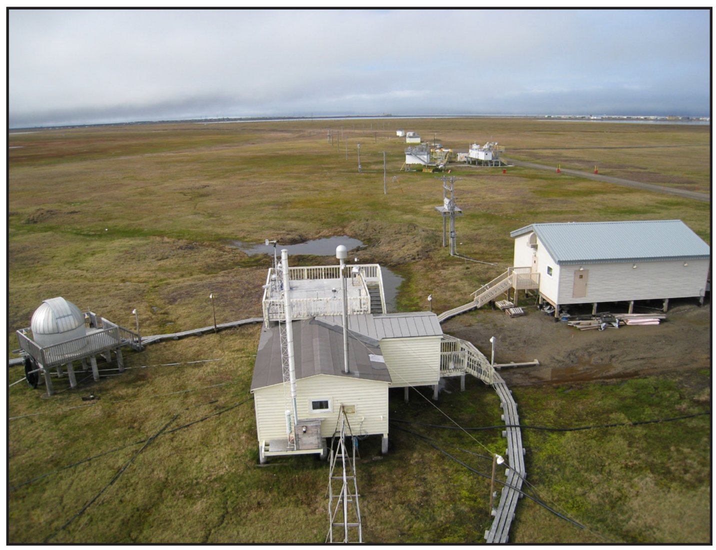


Figure 2.2: Barrow Observatory viewed from the meteorological tower in late summer.

2017

- Indoor and outdoor methane spike detectors were installed for the University of Colorado's Dr. Maslanik.
- In July, the DOE SP2 was decommissioned.
- In August, the ESRL/Physical Sciences Division (PSD) D-ICE project was installed. The project's goal was to identify the best method to mitigate ice and minimize adverse effects on solar and terrestrial radiation measurements during icing conditions.
- USDA precipitation measurements were discontinued.

2018

- In July, the ESRL/PSD D-ICE installation was demobilized.
- From June to August, extensive troubleshooting of USGS instrument problems took place.

- The NWS Alaska Region Fairbanks Weather Forecast Office COOP installed an 8" rain gauge in September and a snow stake in October. This installation replaced precipitation measurements that had been recorded by NWS personnel in town.
- In December, the UC Davis Black Carbon instrument (COSMOS) was returned to Japan for repair.

SPECIAL EVENTS

2015
- NESDIS replaced their 2.4m antenna and dome.

2016
- In February, NOAA Corps officer Jesse Milton assisted with operations and covered staff leave.
- In April, staff provided information at a public meeting for an erosion risk map extending from Icy Cape to Demarcation Point, supporting Michael Brady's (Rutgers University) research.
- DOC security specialist Michael Shearin conducted a security audit at the observatory.
- In June, NOAA Corps officer Diane Perry trained at BRW before her deployment to SMO.
- In August, SPO Technician David Reibel trained at BRW before deploying to Antarctica.
- In October, voters approved an initiative to change the name of the City of Barrow to Utqiaġvik.

2017
- Summer camp at Ilisaġvik College connected ASRC Federal and NESDIS, and NSSL to get students interested in STEM careers.
- Two Garmin InReach devices were added, making new emergency communications possible, including text and email sent via satellite if all communications on/off the island are down. Two units were purchased, for the station chief and the station technician.
- In June, NOAA Corps officer Ben Kaiser trained at BRW before his deployment to SMO.
- In August, NOAA Corps officer Cherisa Friedlander and technician Sabrina Shemet trained at BRW prior to SPO deployment

2018
- NOAA Corps officer Marisa Gedney trained at BRW in May before her deployment to SMO.
- From September to October, the design-build contract for the new Observatory was awarded to Nippairit, a UIC affiliate. The kick-off meeting for the contract was held in Utqiaġvik in October.

OUTREACH

2015
- Greg Fishel of WRAL-TV in Raleigh, NC, visited BRW.

2016
- One hundred sixty-nine people toured BRW in 2016.
- March: Bryan Thomas attended Arctic Science Summit Week 2016 in Fairbanks, AK.
- 29 April: Ross Burgener presented observatory background information at the Ilisagvik College Earth Day celebration.

Figure 2.3: Barrow Observatory instrument racks with CO2, meteorology and the station data networking system controllers.

- From 28 April to 1 May: A producer and camera operator from the MSNBC program, "All In with Chris Hayes"
- visited to interview Gaby Petron (GMD) for a story about greenhouse gas monitoring and climate change in Alaska. The segment aired in June 2016.
- Bryan Thomas conducted a Skype interview with the Weather Channel as part of their "longest days of the year" coverage.
- Bryan Thomas led 19 children and 14 adults on a Lagoon Walk to learn about clouds and weather.
- In December, during the 2016 American Geophysical Union conference, Bryan Thomas was interviewed live as part of the San Francisco Exploratorium "Conversations About Landscape: Climate, Carbon, and the Changing Arctic" event. Approximately 75 people attended in person at the San Francisco venue.
- BRW was featured in a New Yorker magazine article about North Slope, Alaska.

2017
- Two hundred three people toured BRW in 2017.
- Jeremy Mathis was interviewed in Barrow by CBS News; local ASOS temperature quality control algorithm made the Washington Post; Washington Post Kids' Post featured the Observatory.
- On 25 January, Bryan Thomas spoke to the Alaska National Guard members visiting Utqiaġvik for the dedication of their expanded building in town.
- In March, Bryan Thomas presented an overview of the Observatory during the UIC Arctic Business Development Tour.
- On 12 March, the Ilisagvik Arctic history class visited BRW.
- On 21 March, CBS News visited BRW. The recorded clips aired around Earth Day.
- In May, a Congressional delegation, accompanied by National Science Foundation staff, toured the Observatory.
- From 2 to 4 August, Bryan Thomas presented at the UIC Science 1st Annual BARC Science Fair.
- In August and September, Bryan Thomas and Ross Burgener were interviewed and photographed by the New York Times.

2018
- Two hundred two people toured BRW in 2018.
- On 24 February, Bryan Thomas gave a presentation about BRW at the Tuzzy Consortium Library.
- On 27 February, Bryan Thomas gave a presentation at the UIC Arctic Business Development Tour.
- On 28 February, Bryan Thomas presented during the NOAA Networking Committee meeting in Anchorage.
- On 26 April, Bryan Thomas presented at the Ipalook Elementary Science Night.
- In June, Bryan Thomas was interviewed by the Voice of America.
- On 14 July, Bryan Thomas gave a presentation at the "BARCbeque" community barbeque hosted by DOE.

2.2 SUMMIT, GREENLAND

BACKGROUND

GMD added the Summit Greenland Observatory (SUM) to its network in 2005 to provide a critical understanding of the Arctic and global climate change over 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 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 Greenland Environmental Observatory (GEOSummit) on the summit of the Greenland Ice Sheet (3200 m above sea level) was established by the U.S. National Science Foundation (NSF) and the Danish

Figure 2.4: Summit Temporary Atmospheric Watch Observatory

Commission for Scientific Research in Greenland to provide year-round, long- term measurements for monitoring and investigating the Arctic environment. The multidisciplinary facility is home to several year-round investigations and seasonal campaigns that take advantage of the observatory's unique location. In addition, GEOSummit provides investigators easy 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. Logistical support at Summit is provided by CH2M HILL Polar Services, 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 data continuity. Starting in 2005, NOAA staff members served regularly as technicians throughout the year. From August 2009 to YYYY, NOAA staff were 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. NOAA staffing was discontinued in 2016 due to Greenland tax law; Polar Field Services took over staffing because the company could handle the tax requirements.

The facility was downgraded from its status as a full "Observatory" to a "Sampling Site" on 1 August 2017, and NOAA technicians and cargo-intensive projects in the NOAA measurement suite were removed from the site. However, surface ozone monitoring instrumentation, a basic meteorology system, aerosol instrumentation, and halocarbon and greenhouse gas flask sampling capabilities continue to operate in partnership with the NSF. The downgrade followed a GMD-wide evaluation of scientific goals and global observing network capabilities that resulted in realignment to meet NOAA's mission and the nation's scientific needs.

STAFF

Year	Phase	Months	Tech	Tech	Tech
2013-2014	Winter	Oct - Feb	Brandon Strellis (NOAA)	Jennie Mowatt (PFS)	John Lyons (ICECAPS)
2014	Spring	Feb - Jun	Lance Roth (NOAA)	Alia Westlund (PFS)	Ward Handley (ICECAPS)

2014	Summer	Jun - Oct	Dominique Paxton (NOAA)	Sara Cohen (PFS)	Lana Cohen (ICECAPS)
2014	Fall	Jun -Sep	Dominique Paxton (NOAA)	Sara Cohen (PFS)	Jennie Mowatt (ICECAPS)
2014-2015	Winter	Oct - Feb	Lance Roth (NOAA)	Hannah James (PFS)	Jennie Mowatt (ICECAPS)
2015	Spring	Feb - Jun	Jason Johns (NOAA)	Yuki Takahashi (PFS)	Sam Dorsi (ICECAPS)
2015	Summer	Jun - Sep	Neal Scheibe (NOAA)	Clair Von Handorf (PFS)	Sam Dorsi (ICECAPS)
2015	Fall	Sep - Oct	Neal Scheibe (NOAA	Clair Von Handorf (PFS)	Hannah James (PFS)
2015-2016	Winter	Oct - Feb	John Gallagher (NOAA)	Nate Bowker (PFS)	Michael Finnegan (ICECAPS)
2016	Spring	Feb - May	Jason Johns (NOAA)	Marci Beitch (PFS)	Sam Dorsi (ICECAPS)
2016	Summer	May - Aug	Elissa Barris (TAWO)	Travis Guy (TAWO)	Hannah James (ICECAPS)
2016	Fall	Aug - Oct	Elissa Barris (TAWO/ ICECAPS)	Travis Guy (TAWO/ICE-CAPS)	
2016-2017	Winter	Oct - Feb	Marissa Goerke (NOAA)	Nate Bowker (TAWO)	Sam Dorsi (ICECAPS)
2017	Spring	Feb - May	Adam Maerz (TAWO)	Aurora Roth (TAWO)	Hannah James (ICECAPS)
2017	Summer	May - Jul	Marissa Goerke (TAWO)	Heather McInyre (TAWO)	Marci Beitch (ICECAPS)
2017	Fall	Aug - Oct	Heather McIntyre (TAWO)	Sam Dorsi (ICECAPS)	
2017-2018	Winter	Oct - Feb	Holly Abercrombie (TAWO)	Hannah James (ICE-CAPS)	
2018	Spring	Feb - Mar	Sam Dorsi (TAWO)	Rex Nelson (ICECAPS)	
2018	Summer	Apr - Aug	Nate Bowker/Mara Menahan (TAWO)	Marci Beitch/Hannah James (ICECAPS)	
2018	Fall	Aug - Oct	Mara Menahan (TAWO)	Hannah James (ICE-CAPS)	
2018	Winter	Oct - dec	Troy Nave (TAWO)	August Allen (ICECAPS)	

FACILITIES

2014
No facilities information is available.

2015
- The Temporary Atmospheric Watch Observatory (TAWO) was raised in July to maintain CRREL's recommended height above the snow for wind scouring. Because the crane was inoperable, a large snow pad had to be built for other equipment to complete the raise. Welding at TAWO during the raising process caused particulate contamination noticed by technicians in the Clean Air Sector.
- In July, instruments and NOAA inlets were raised on the tower as part of routine maintenance due to snow accumulation.
- In October, Detlev Helmig reported a possible P5 leak in TAWO, contaminating his project's methane measurements. Measures were taken to identify a possible leak. Summit technicians repaired the P5 regulator.
-

2016
- In February, investigation into a methane leak in TAWO continued. Several small leaks were found in the GC plumbing. Over the summer, the system was modified to use a combination of nitrogen and carbon dioxide as carrier gases, replacing the P5.
    - The Rohn tower was mounted to the deck of TAWO and extended several meters above the TAWO roof to act as a sampling inlet mast.
      The surface ozone, HATS GC, and aerosol instrumentation inlets were installed on the mast. The advantage of sampling off the mast versus the TAWO tower was that inlets would not need to be raised annually but would stay above the building, which is raised often.
    - In conjunction with the switch to the sampling mast, the interior layout of TAWO was reconfigured to minimize the distance of the aerosol instrumentation to the mast and more efficiently use the space in the building.
- In July, the roof deck on TAWO was extended and the GRAD instruments were moved to the southern edge of the TAWO roof on a platform that mitigated shadows from building supports.
- In July, the NOAA meteorology system was moved from the TAWO tower to the Swiss tower to eliminate the building's impact on meteorology measurements. During the move to the Swiss tower, the suite was upgraded to a new acquisition system.
- On 27 December, Summit experienced high winds, which reached 25 m/s with higher gusts. During the high wind event, the 50-m Swiss tower experienced a major failure. The tower split 10 meters above the surface, and the upper section collapsed towards the WSW. No crew were injured, but the NOAA meteorology suite had to be taken offline.
-

2017
- In July, the NOAA meteorology suite was relocated to a new tower 80 m upwind (south) of TAWO—far enough to be outside of the building's influence.
- In July, Instrumentation was removed from Summit Station as part of the downgrade from an observatory to a sampling site.
    - The HATS gas chromatograph, GRAD instrumentation, and ozonesonde instrumentation were removed from the site, leaving instruments that take little time and energy to maintain.
    - The surface ozone, aerosol suite, meteorology suite, and CCGG and HATS flask sampling remained at TAWO.

» Meteorology support was maintained at Summit for NOAA metadata and New York Air National Guard flight support.

Special Events

2014
- No special events.

2015
- July: The United States Ambassador to Denmark visited Summit.

2016
- No special events.

2017
- On 1 August, SUM was downgraded from its status as a full "Observatory" to a "Sampling Site." NOAA technicians and cargo-intensive projects were removed from the site in July. However, surface ozone monitoring instrumentation, basic meteorology, aerosol instrumentation, and halocarbon and greenhouse gas flask sampling capabilities continued to operate.

Figure 2.5: Trinidad Head Observatory building located on the west side of the Head facing the Pacific Ocean.

2.3 TRINIDAD HEAD, CALIFORNIA

BACKGROUND

The Trinidad Head Atmospheric Baseline Observatory (THD) was located on Trinidad Head near the town of Trinidad, Humboldt County, California (41° 3.238'N, 124° 9.064'W). The THD observatory consisted of a 24 ft. by 8 ft. wood-sided commercial trailer. The instrument trailer was placed in its location on United States Coast Guard (USCG) property in April 2002, coinciding with the ITCT-2k2 study. Initially, two trailers were co-located at the site. GMD removed one of the trailers at the conclusion of the study.

In 2015, GMD began the process to construct a new building for both the NOAA and Scripps Institution of Oceanography instrumentation at Trinidad Head. The facilities for both organizations were at the end of their useful life and required replacement. NOAA planned to cost share the construction of a single-story, 624 square-foot building on a concrete pad where the Advanced Global Atmospheric Gases Experiment (AGAGE) building was located on the USCG property, and clean up unused equipment towers, fencing, and buildings to reduce the footprint at the site. In 2015 and 2016 during the permitting process with the California State Historic Preservation Office, GMD consulted with the California Coastal Commission, City of Trinidad, the Yurok Tribe, Tsurai Ancestral Society, and the Cher-Ae Heights Indian Community of the Trinidad Rancheria.

In November 2016, all design work and site cleanup activities for the new building were halted when GMD encountered a delay in the permitting process from USCG. During the delay, GMD leadership re-evaluated the scientific value of THD versus the mounting operational costs and shrinking annual budget. In early 2017, the decision was made to close THD permanently.

In June 2017, THD was decommissioned. A crew of five GMD staff spent one week removing instrumentation from the THD trailer, shipping it back to Boulder, and removing trash from the site.

Following the site visit, the trailer and other NOAA infrastructure were removed as well. After THD was closed, weekly ozonesonde launches were taken over by California Air Resources Board, launched from Humboldt State University by Michael Ives. Aerosol and surface ozone instrumentation remains at the site, housed and maintained by Scripps Institution of Oceanography partners in the Keeling Building.

Staff

Year	Station Chief
2014	Michael Ives
2015	Michael Ives
2016	Michael Ives
2017	Michael Ives

Facilities

2014

- In March, major roof repair were completed using a marine epoxy patch.
- On 24 March, a new base support for the tower was fabricated and installed.
- In June, the Miles electric truck's (NEV's) brakes and battery failed, making it no longer serviceable.
- On 20 September, the GSA Ford Fusion Hybrid was delivered and put into service.
- On 1 October, survey monuments delineating USCG property were located and marked.
- On 5 November, the Bard air conditioner failed and an HVC contractor was contacted. The repairs were completed on 12 November.
- On 11 November, rusted landing outside the main door was repaired with ¾" exterior grade MDF.

2015

- In January: Design consultation began for a joint NOAA/AGAGE laboratory building.
- 27 August: A GSA Ford Focus Electric was put into service. The Ford Fusion Hybrid was later returned on 18 September.
- 14 December: The trailer roof was patched after discovering rain water inside the trailer.

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2016

- In January, a waterproof charging station was installed at the Humboldt State University Telonicher Marine Lab where the vehicle is parked.
- In January and February, areas of the roof showing surface rust were painted with reflective aluminized asphalt paint, and repair work was done on the roof soffit above the eastern-most door.
- In November, water leaks reappeared over the computers and instrumentation in the trailer. Investigation during patch/repair work revealed that the entire roof was water-logged. The water was drained and additional asphalt roof patching was applied.

2017

- June: Five GMD staff removed all instrumentation from the THD trailer and surrounding area, and the trailer was removed and disposed of by Trinidad Bay Construction.

COOPERATIVE PROJECTS

2014

- 29 May: The THD micro pulse lidar (MPL) was shipped to NASA-GFSC for repair.

2015

- On 5 May, the THD MPL was returned to the site for installation. Less than one week later, on 11 May, NASA-GSFC was notified that the THD MPL laser would not power up and was not operational. The decision was made to take the THD MPL out of service indefinitely.
- THD staff conducted multiple coordinated ozonesonde launches coinciding with NASA's Aura TES satellite overpass. Seven flights were coordinated in 2015.
- THD staff also coordinated multiple flights to coincide with the NASA Alpha Jet Atmospheric EXperiment (AJAX) Project.

2016

- No changes to cooperative projects.

2017

- In May and June, all cooperative projects were taken offline and shipped back to their respective laboratories.

SPECIAL EVENTS

2015

- On 12 February, Brian Vasel and NOAA Corps officer Joe Phillips visited the site and held a meeting to discuss building plans with USCG, AGAGE, Humboldt State University, Trinidad Bay Construction, and the City of Trinidad.
- Two internet-connected video cameras were installed on the tower.
- On 13 May, station personnel met with BLM and Tribal representatives to discuss new building plans. Brian Vasel presented building plans and discussed GMD's mission with the Trinidad City Council.

2016

- In March, the THD meteorology computer was hacked into and had hidden accounts added to the machine. GMD IT worked with the NOAA Computer Incident Response Team (NCIRT) to determine how the hack occurred, recover from the incident, and fix vulnerabilities.

2017

- On 5 June, all instruments were shut down and the observatory was officially decommissioned. Five observatory personnel removed and shipped all GMD instrumentation to Boulder

OUTREACH

2014

- Thirty-one people visited THD in 2014.

2015
- Three people visited THD in 2015.

2016-2017
- No notable outreach conducted.

2.4 MAUNA LOA, HAWAII

BACKGROUND

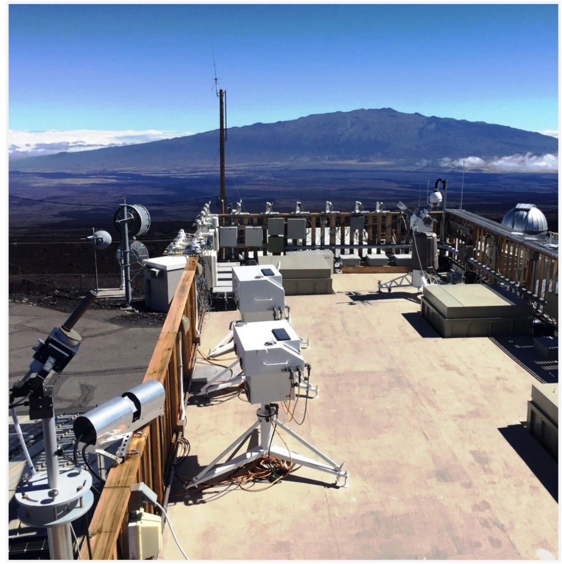

Figure 2.6: Mauna Loa Atmospheric Baseline Observatory solar radiation deck looking to the north with Mauna Kea Mountain in the background.

The Mauna Loa Observatory (MLO) is located at 20 degrees north on the northern flank of the Mauna Loa volcano on the island of Hawaii, at an elevation of 3397 m. Established in 1957, MLO has become the premier long-term atmospheric monitoring facility on Earth, where increasing concentrations of global atmospheric carbon dioxide were first identified. The observatory consists of 23 buildings—16 of them owned and operated by NOAA—where up to 250 different atmospheric parameters are measured.

In 2015, MLO was recognized by the American Chemical Society as a National Historic Chemical Landmark, honoring its contributions to the Keeling Curve and the study of carbon dioxide in the atmosphere. The following year, the observatory celebrated its 60th anniversary as a research site.

In 2018, Kilauea's East Rift Zone erupted for nearly four months, destroying homes and roads, closing the Hawaii Volcanoes National Park, causing significant earthquakes, and affecting air quality across the entire Big Island. Lava flows cut off access to the Cape Kumukahi sampling site, affecting MLO's sea level flask sampling operations. In 2018, many short-term projects examined Kilauea's outgassing and the aerosol distribution around the island.

STAFF

Year	Station Chief	Technician
2014	Darryl Kuniyuki	Preston Sato
		Aidan Colton
		Paul Fukumura-Sawada
		Nash Kobayashi
		David Nardini
		Greg Rose
2015	Darryl Kuniyuki	Preston Sato
		Aidan Colton
		Paul Fukumura-Sawada
		Nash Kobayashi
		David Nardini

		Greg Rose Matthew Martinsen (Oct - Dec)
2016	Darryl Kuniyuki	Preston Sato Aidan Colton Paul Fukumura-Sawada Nash Kobayashi David Nardini Greg Rose Matthew Martinsen
2017	Darryl Kuniyuki	Preston Sato Aidan Colton Paul Fukumura-Sawada Nash Kobayashi David Nardini Greg Rose Matthew Martinsen
2018	Darryl Kuniyuki	Preston Sato Aidan Colton Paul Fukumura-Sawada Nash Kobayashi David Nardini Greg Rose Matthew Martinsen

FACILITIES

2014

- On 14-15 May, HELCO shut off power to the MLO site to replace and upgrade equipment in the relay station feeding the observatory site. This upgrade provided better power quality and reliability.

2015

- From March to May, the wooden deck on top of the AEC building was removed. It was declared unsafe and had to be demolished because the half-century-old deck joints were loose and the deck was leaning to one side. The deck held the antennae for the communications equipment in the back room of the AEC building. Before deck removal, the communications equipment and antennae were moved next door to the Uchida building.
- From 13 August to 9 September, the final portion of the 17-mile MLO access road paving project was completed. During this time, the road was closed

Figure 2.7: Mauna Loa Observatory instrument rack containing mainly surface ozone instrumentation.

because the large equipment could not move to the side to let cars pass. MLO staff followed a modified work schedule to accommodate the road work.

- In December, the NCAR Mauna Loa Solar Observatory (MLSO) building's interior was renovated. The construction of the dome wall was modified to fit the new dome.
- The gate keypad device was hardwired to the entry receiver security gate controller after wireless operations of the keypad experienced issues due to interference from other wireless communications systems on site. The driveway's asphalt had to be cut, jack hammered, and trenched, and conduit, boxes, and wires were installed. The trench was then backfilled and capped with cold mix asphalt.

2016

- On 5 January, a crane was removed and we replaced the old NCAR MLSO dome.
- On 20 January, vandals broke into the Cape Kumukahi sampling tower, breaking the lock and prying open the door with a crowbar. The thieves stole the small HD fan, Kestrel 4000 weather vane, a small vacuum, pocket knife, and miscellaneous tools (wrenches, screwdrivers, etc.). The remaining equipment was removed from the facility and brought back to the Hilo office. Nash Kobayashi installed a new, more robust lock, and a new Kestrel 5000 handheld weather meter was purchased to replace the stolen one.
    - » From January to December, Greenpath Technologies installed solar panels on the NDACC and Keeling buildings. In preparation for the panel installation, the roof of the NDACC was rust-treated and repainted in January.
    - » Hardware installation was completed in September.
    - » The solar panel system was commissioned on 13 December and provides about 19 percent of the total power at the observatory site. In 2017, there was a total savings on the power bills was $10,946.

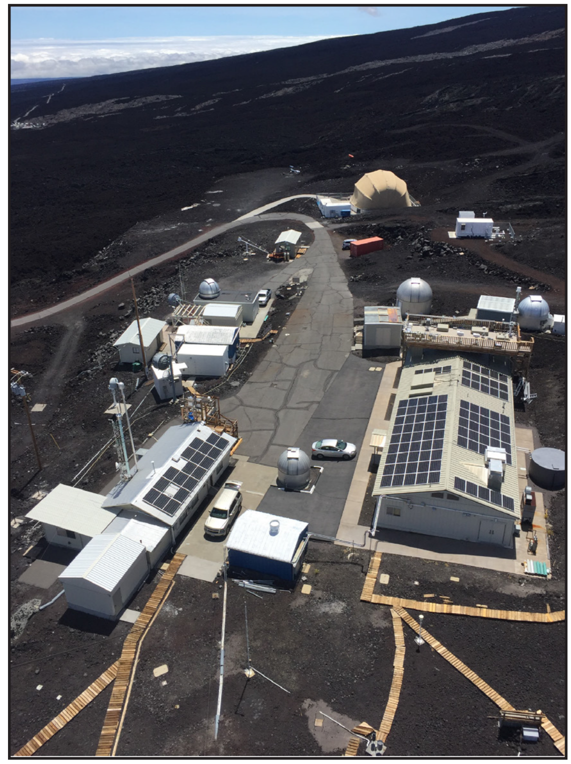

Figure 2.8: Mauna Observatory facility looking east from the sampling tower

- In July, the lease for the Hilo office ended. A new 10-year lease was signed through GSA and included requirements for annual GSA and Federal Protective Services inspections.
- Marty Martinsen spearheaded the Keeling restroom renovation. The rusted shower stall was removed, holes in the wall repaired and painted, and new floor tiles installed.

2017

- High winds during the weekend of 11 February damaged the generator building roof. The 60-year-old structure was demolished from 28 to 31 March by Marty Martinsen and student Tino Well.
- From April to September, remaining funds from the MLO Access Road painting project were used to paint lines on the road. The lines were painted over several sessions using a line painting machine purchased by the University of Hawaii Hi Sea project and NOAA paint/supplies. MLO staff and Boy Scouts working toward their Eagle Scout rank completed the line painting.
- From July to August, a HELCO inspection of Cape Kumukahi's power box cited both United States Coast Guard (USCG) and NOAA electrical panels as "hazardous" due to corrosion. The HELCO hazard ticket stipulated that the panels would need to be replaced or power would be shut down. USCG opted to shut down their power, but MLO personnel and Patrick Pajo replaced the NOAA electrical

box on 26 July. Power was restored on 11 August.

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2018

- From January to March, line painting continued (on 1/13, 3/23, 3/28, and 3/29) for the Mauna Loa Access Road.
- In May, the Kumukahi sampling site was evacuated and shut down on 14 May due to lava flow near the area. Power was secured, and all items of value were removed from the building. The lighthouse at Cape Kumukahi survived the volcanic eruption; however, the access road was completely covered with 30 ft deep lava. Lava also inundated the area one mile east and ½ mile south, but moved slowly due to the local topography.

Figure 2.9: Mauna Loa Observatory halocarbon gas chromatograph and calibration gas tanks in a room maintained at a constant temperature.

- From July to August, gates were installed to block trail access by vehicles. On 31 July, the State of Hawaii Department of Land and Natural Resources (DLNR) delivered cement poles . Gates were installed in August. All trails off the Mauna Loa Access roads are now gated and cannot be driven on by the public.
- On 11 September, Benjamin Barna and Ted Bibby from ASM Affiliates completed an archeological site inspection at the mountain site. No artifacts were found, but the archaeologists determined that the Keeling building was eligible for registration as a historic structure.
- Throughout 2018, NRL supplied ten metal walkways to replace 156 feet of the 900 feet of wooden walkways at the observatory.

COOPERATIVE PROJECTS

Recurring Projects - These projects periodically operated at MLO for short campaigns from 2014 through 2020:

- Microtops Calibrations: Chris Voth (Solar Light) conducted Microtops calibrations every year operating out of the AEC building. Each visit lasted about one week and the dates of observations were: 8/22-8/27/2014; 7/13-7/18/2015; 8/22-8/26/2016; 7/21-7/28/2017; 6/20-6/29/2018; and 7/20-7/26/2019.
- MRI Sunphotometers: MRI installed their equipment in September or October and left their instrument for about one month, during which MLO staff completed daily checks. The team returned to remove their equipment. Dates for their project were: 10/28-11/27/2014; 10/12-10/18/2015; 10/12-11/20/2016; 9/28-11/9/2017; and 10/15 -11/21/2018.
- Prede Sunphotometers: Kazu Sasamoto examined the MRI set up and operations from 10/13 – 11/18/2016. He then planned regular visits to MLO starting 2017 with Prede's own instrument. Dates for Prede sunphotometers were 9/28-11/9/2017; 10/15- 11/21/2018; and 10/7-11/20/2019.
    - » Dobson 83 Calibrations and Intercomparison: Dobson 83 visited MLO every two years to perform measurements and intercomparisons with MLO's Dobson 76.
      2014: Robert Pipes conducted summer Dobson calibration from 6/14/2014 to 9/19/2014
    - » 2016: Forrest Mims conducted measurements and intercomparisons from 6/1-8/3/2016.
    - » 2018: Tyler Tucker (NOAA -Experiential Research and Training Opportunities) conducted measurements and intercomparison from 6/19 - 10/30/2018.

- Brewer Calibrations and Intercomparisons: Every two years the Environment Canada staff calibrated and completed an intercomparison check at MLO. These were completed from 9/25-10/9/2015; 10/29-11/11/2017; and 9/28-10/11/2019.
- NASA Ames and PNNL Sunphotometer Campaign: NASA Ames and PNNL usually conducted solar campaigns together. When visiting MLO, they were housed in the Groundwinds building. Dates of collaborative campaigns were: 1/11-1/15/2016; 6/28-7/7/2016;, 11/8-11/17/2016; and 8/7- 8, 16, 20/2018. NASA Ames standalone observations were done on: 5/28-6/8/2017 and 2/6-2/15/2018.
- USDA Shadowband Radiometers: Forrest Mims set up two USDA Shadowband radiometers and his personal LED shadowband instrument when he visited MLO. The dates of Forrest's visits were: 6/19-7/1/2014; 5/27-6/8/2015; 6/1-8/3/2016; and 7/18-8/15/2018.
- GLOBE Reference Sun Photometers: Forrest Mims continued his annual calibrations of the two reference sun photometers for the GLOBE program along with calibrations of five Microtops III and his original LED sun photometer (first calibrated at MLO in 1992).
- Twilight Photometer Measurements: Twilight photometry project at MLO began in 2013 and have continued every year during Forrest Mims' visits.
- UH Cave Ice Study: Dr. Peter Bosted at the University of Hawaii examined the possibility of analyzing ice that accumulated in lava tubes over the years. Caving staff were allowed to sleep overnight at MLO before hiking to the lava tubes. Dates of hikes were: 11/22-11/23/2014; 11/13-11/14/2015; and 9/19 - 9/21/2017.
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2014

- CU MAX DOAS: University of Colorado's Ivan Ortega installed a new MAX DOAS System from 6 to 10 January. This system measured vertical profiles of halogen oxides and oxygenated hydrocarbons using passive remote sensing. Rainer Volkamer was the project's principal investigator.
- Environment Canada OCEC: A refractory black carbon, Organic Carbon, Elemental Carbon (Environmental Canada) collection unit was installed on 6 - 7 March near the GMD Aerosol system.
- RACES (Hawaii State Civil Defense): A Hawaii States Civil Defense emergency radio system was installed on 1 July and upgraded on 14 July. This system provided emergency communications between the east and west sides of the island. An alert system IP Informer was also set up at the station for alert warnings issued by the State of Hawaii Civil Defense.
- NASA Pandora: Jay Herman (NASA/GSFC) installed a Pandora instrument on the NDACC deck on 3 - 4 November. The instrument was a new prototype measuring total column ozone.
- UH Wireless Network (MLONET): The University of Hawaii (UH) installed new wireless network equipment in the Uchida building on 27 June. A new fiber cable run was installed to the old lidar building, where it provides network capabilities for the two UH projects: VYSOS and ATLAS. NCAR MLSO later switched to this network and canceled their network service with Hawaiian Telcom.
- University New Hampshire Groundwinds: Originally installed in 2001, the University of New Hampshire Groundwinds project was discontinued in 2014 due to lack of funds. Charles Richey (Michigan Aerospace) visited on 8 July to remove the laser from the site and return it to Michigan Aerospace.
- NO2/BrO (NIWA): After nearly 18 years of measurements, the NIWA
- NO2/BrO spectrometer was removed on 8 September per Richard Querel's instructions and shipped back to NIWA on 9 October.
- MLO precipitation program: Due to failed instrumentation and a lack of project support, the long-running MLO precipitation project was discontinued as of 30 September. The last rain sample was collected on 10 June and analyzed for pH and conductivity values before instrument malfunction. All data were archived, and instrumentation and accessories removed from the MLO laboratory. This marked the end of the precipitation chemistry program that lasted over 40 years.
- 2014 Short-term Projects

- » Lunar 2014 Short-term ProjectsLunar Eclipse: Dr. Elmar Schmidt (SRH University, Heidelburg, Germany) stayed overnight at the observatory from 13 - 15 April to observe a lunar eclipse on 15 April.
  - » NASA GSFC Lidar: Tom McGee performed NASA GSFC ozone lidar observations from 14 January - 7 February. On 28 January one of the two NASA trailers was removed the site. The other was left for future observations done from 2 - 27 November, 2015.
  - » CLidar: Nimmi Sharma (Central Connecticut State University) visited 30 June - 7 July to work on CLidar research in collaboration with John Barnes.
  - » ACAPEX Campaign: Mike Reynolds (Remote Measurement and Research Co.) calibrated a Multifilter Rotating Shadowband instrument for shipboard use from 1 - 15 December as part of the ACAPEX Campaign.

2015

- UH Nitrate filter: University of Hawaii's Steven Howell removed nitrate filter equipment from the tower and radon building on 22 January. This project ran for more than 26 years at MLO.
- Carbon Dioxide (Scripps Institution of Oceanography): The Scripps Institution of Oceanography's (SIO) Siemans analyzer was decommissioned on 15 February. SIO is now using a Picarro cavity ring-down spectrometer trace gas analyzer to measure CO2 and CH4.
- NOAA/ARL Mercury Analyzers: From 23 March - 19 April, NOAA Air Resources Laboratory's Winston Luke installed two mercury analyzers to run with MLO's other instruments.
- World Radiation Center "Physikalisch-Meteorologisches Observatorium Davos" (PMOD): Paul Fukumura installed a new PFR-98-N-022 on K&Z Tracker on 7 August.
- NRL Chloride Oxide: From 1 - 25 September, Mike Gomez and Glen Frick installed a new Chlorine Oxide Experiment (ChlOE) in the NRL building to measure stratospheric ClO profiles.
- ASTRA Tidbit: On 12 October, Tim Duly (ASTRA) installed a "Traveling Ionospheric Disturbance Detector Built In Texas" (TIDDBIT) instrument. This project monitored ionospheric disturbances and was maintained by NCAR MLSO staff.
- 2015 Short-term Projects:
  - » University of Utah Mercury: The project started on 21 July, and the calibrator from the mercury project was removed on 20 October by Trevor O'Neil (University of Utah).
  - » Aerosol Limb Imager (ALI): Adam Bourassa (University of Saskatchewan) installed an Aerosol Limb Imager (ALI) on 4 November. The project ran until 11 March, 2016.

2016

- Scripps/Earth Networks: Tim Lueker and Adam Cox installed a second Picarro analyzer and Earth Networks rack at MLO from 20-27 March.
- University of Hawaii Extraterrestrial Particles: On 1 June, Hope Ishi and Marty Martinsen installed a sampler to collect extraterrestrial particles. Marty reconfigured an old Hi-vol sampler for Ms. Ishi to use.
- UH MLONET: Pacificomm installed a UH network dish on 19 - 20 July to provide network connectivity for the UH projects at the MLO site. The old system installed in 2014 became the backup system.
- UH VYSOS: Summit Kinetics constructed a new VYSOS dome on 6 and 18 October. The old dome was removed and replaced with a sliding hatch.
- 2016 Short-term Projects:
  - » NASA Atmospheric Tomography Mission (ATom): A special ozonesonde was launched on 3 August for the ATom project. The plane landed in Kona on 3 August after flying from Alaska.
  - » University of New Mexico Water Vapor: On 8 April, Joseph Galewsky (University of New Mexico) installed a water vapor isotope analyzer in the Radon Building. The project ran until March 2017.
  - » Pyr-lios: From 24 June to 20 July, Dr. David Bolsee and Nuno Pereira (Belgian Royal Institute for Space

- Aeronomy) deployed a spectrometer for near infrared solar measurements.
- Skynet Calibrations: Chiba University solar calibrations were completed 27 October through 5 November.

2017

- USGS USGS Seismometer upgrade: A USGS technician installed a new seismometer with wireless cell connectivity on 14 January. The old phone line is no longer being used.
- CU MAX DOAS: Barbara Dix installed a new MAX DOAS system from 14-23 February.
- John Hopkins University Airglow: Syan-Yun Hsieh (John Hopkins University) installed the new Airglow project on the solar wall from 23-28 October. This project studied ionospheric plasma bubbles and traveling ionospheric disturbances and their effects on communications.
- 2017 Short-term Projects:
  - PL Microtops Calibration: Florian Schwandner (JPL) calibrated a Microtops instrument on 29 January.
  - ATom Flight: Special balloon flights for ATom-2 aircraft flights were carried out on 1 and 3 Februar
  - On 6 September, a balloon was launched for the ATom-3 flight.
  - GSFC High Mountain Asia: From 12 - 16 May, two PSP/PIR instruments, temperature sensors, GPS units, dome pressure sensors, and a Pandora were installed on the solar deck and solar wall. The instruments ran until 14 July when NASA/GSFC's Dr. Tsay removed the instruments and shipped them to their permanent home in Asia.
  - Sound Detection And Ranging (SODAR): In cooperation with John Barnes, a SODAR was installed on 20 July and ran until 14 September. The instrument was owned by Barry Neal (Atmospheric Research & Technology, LLC) and measured wind speed at various heights above the ground. The SODAR was installed next to the Groundwinds building.
  - NIST Lunar Spectral Irradiance project: From 27 November - 8 December, Steve Maxwell & John Woodward IV ran a lunar telescope and calibration source platforms to scout a permanent install location for two future domes.
  - University of Rochester 14CO: From 13-16 November, the University of Rochester's Vasili Petrenko installed a 14CO monitoring project in the radon building. The project ran for approximately one year to determine if permanent sampling would be viable. The last sample was collected on 6 November, 2018.

2018

- University of Nevada - Reno Mercury studies: On 12 February, the University of Reno's Mae Gustin installed her mercury project on the mercury tower next to the ARL mercury equipment and USGS mercury sampling unit.
- GMD Upgraded Meteorology System: An upgraded GMD Meteorology instrument suite was installed on 26 January by Andy Clarke and Marty Martinsen. This replaced the aging system and incorporated sonic anemometers.
- UH Precipitation Collector: On 15 March, a UH precipitation collector was installed by Diamond Tachera and Brytne Okuhata. This was part of the 'Ike Wai Project to develop and understand the subsurface hydrology of the Kona area. The collector was set up next to GMD's tipping bucket rain gauge and the NWS 8" precipitation collector.
- NRL Chlorine Oxide Experiment number 5: In late April, Mike Gomez set up new Chlorine Oxide Experiment number 5 (ChlOE5) instrument on Mauna Kea at the CSO facility. The instrument was fully functional in August.
- COSMIC GPS (UCAR): On 30 August, UCAR's Jan Weiss installed a GPS receiver for receiving geodetic Global Navigation Satellite System (GNSS) transmissions to process radio occultation missions for geodetic and atmospheric science projects at HAO. This project was maintained by NCAR staff.

- 2018 Short-term Projects:
  Lunar Eclipse: A super blue blood moon occurred during the early morning of 31 January
- Dr. Elmar Schmidt (SRH University of Applied Sciences in Heidelberg, Germany) measured its brightness from the observatory. Dr. Schmidt has been to the observatory during the previous lunar eclipses in 2007 and 2014.
- University of Houston special SO2 studies: MLO staff assisted with logistics for a 2-week SO2 study in February for the University of Houston. This is a prototype instrument to measure SO2 on tethered and free-release balloons.
- Invasive Plant Study: In February and January, Jim Juvik and students collected invasive plants at the MLO site and along the MLO Access Road.
- Dual Sonde flights (GMD and SHADOZ): From 16-20 April, Bryan Johnson (GMD) and Anne Thompson (NASA GSFC) visited MLO for a special intercomparison between GMD and SHADOZ ozonesonde instruments. They gave a talk at the NWS office about the data measured from the balloon flights and a talk at the Hilo office for MLO staff and Mike Gomez.
- Vertical Profiling of SO2 and Aerosols of Kilauea Volcanic Plume (VOLKILAU) Deployment (University of Costa Rica and University of Colorado): From 6/11-6/16, due to the active lava activity and summit explosions of Kilauea, several special projects were undertaken. The VOLKILAU Campaign involved University of Costa Rica and University of Colorado with support from NOAA MLO staff and NWS DCO Hilo staff. Instruments for ozonesondes were prepared at the NWS Hilo office using MLO's balloon preparation equipment. The crew would then drive to the Kau district where vog conditions are extreme. They successfully conducted 8 launches with a mix of free releases and tethered flights.
- University of Houston SO2 Balloons – Big Island SO2 Survey (BISOS): SO2 balloon sonde measurements, Pandora instruments and ceilometer. From 6/17-7/4, the team set up Pandora at MLO site for NASA GSFC to replace broken one, set up Pandora at Kamehameha schools, and Pandora and ceilometer in Kau, and released multiple balloons to measure SO2 plumes in situ. On 10/22, Ben Brawford visited the Hilo office to assist in the University of Houston's project. He picked up a CIMEL box to send back for repairs.
- Leeds University Aerosol Sampling: On 7/23 Darryl met with Dr. Evgenia Ilyinskaya (University of Leeds) and Penelope Wieser to set up an Aerosol sampler at MLO. They had set up samplers around the island to study the current Kilauea Eruption. Sampler set up began on 7/25 and ran until 8/5. Leeds staff planned to change filters on 7/29,7/31, 8/2 and remove the samplers on 8/2 and 8/5. The project ended on 8/5.
- University of Sheffield UV measurements: Dr. Andrew McGonigle, Thomas Wilkes (University of Sheffield) - UV measurements to calculate column ozone. Low-cost instrument funded by a grant from the Rolex Institute.
- Rolex "Sunny Sam" UV project: Forrest Mims installed a rotating mannequin head equipped with 7 UV sensors. Did measurements at the observatory and various sites around the island. The project measures the intensity of UV at different locations on one's head. This project was funded by Rolex and is described in detail in a formal paper and an article in MAKE magazine.
- MLO VR tour: Forrest's other task was to create a virtual tour of the facility. Equipped with a 360-view camera, he took pictures at the observatory. The link to virtual tour will be announced later.

SPECIAL EVENTS

2014

- January: On 15 January, John Barnes gave a web tour to Robert Simpson (101 years old), one of the two founders of MLO. An iPad was brought up by a friend of Robert's, Barbara Schoeberl.

- January: Tower training class held for NWS at Hilo office and at NWS DCO on 28-30 January. First Aid and CPR training was held on 31 January.
- August: Observatory was shut down on 6 August to prepare for Hurricane Iselle. Restarted all projects on 11 August after the hurricane passed. The hurricane did not damage the observatory.
- 16-20 October: Hurricane Ana approached Hawaii 17-18 October. The Observatory and Hilo office closed on 17 October. Precautionary measures were taken and selected projects at the observatory were shut down on 16 October and restarted on 20 October. The hurricane did not damage the Observatory.

2015

- 30 April: The American Chemical Society dedication was held at MLO. About 50 people came for the dedication of the Keeling Curve as a National Historic Chemical Landmark.

2016

- MLO 60th Anniversary: The MLO 60th Anniversary occurred on 28 June. A special 60th anniversary mug was created to celebrate the event. Instead of holding a large party or gathering, the Observatory did a 60-year purge and tossed out old equipment and material from the observatory site. A large dumpster was brought up to the observatory, and when the dumpster left in June 2019, it contained 2.7 tons of material. Approximately 750 pounds of electronic waste was brought to the recycling center and more than 200 pounds of electronic media were destroyed and properly disposed of.
- November: Most of the air conditioning units and unused refrigerators at the observatory site were removed, including units from the Dobson, AEC, Keeling, and Groundwinds buildings. The old refrigerator from AEC was also removed.

2017

- 24-28 March: Ken Weipert of Motorola tested the Army communications tower for interference with NRL equipment. To reduce the noise emitting from the antenna, some of the connectors had to be repaired or replaced.
- 5-8 June: NWS Pacific Region training for fall protection, tower rescue, and hydrogen generator maintenance was held in the Hilo office. Students came from Guam, American Samoa, Yap, Palau, Chuuk Islands, Marshall Islands, Pohnpei Micronesia, and Honolulu.
- 26 June: Cheryl Weiser from the Department of Commerce Western Security Office inspected the Hilo and Mountain sites. Facility access plans were developed and submitted to the DOC security office. Unescorted areas were defined at the Observatory.
- 15 December: Susanne Case (Chairperson of Hawaii's Department of Land and Natural Resources), Robert Matsuda (Deputy Chairperson), Dave Smith (DLNR Administrator), and Stephen Bergdahl and Jay Hatayama (Hilo DLNR) visited MLO to receive an operational tour from Aidan Colton and discuss the need for a land expansion and a designated "no build zone" in the MLO Clean Air Sector with Russ Schnell and Darryl Kuniyuki.

2018

- 13 January: A false emergency alert notification was sent out on a Saturday morning to the state claiming a "ballistic missile threat inbound to Hawaii." Boy Scouts were painting the line on the Mauna Loa Road when the alert was issued, and they stopped and went to Puuhuluhulu. After it was confirmed that the message was a mistake, the Scouts returned and resumed painting the line.
- Government Shutdowns
  - 20-22 January: Federal Government shutdown. Most of the staff worked on Monday, 22 Januar
  - 22 December: A second shutdown began on 22 December, 2018 and lasted through
  - 25 January, 2019, becoming the longest government shutdown in history. MLO staff continued to

work throughout the shutdown. All tours were canceled during this period, and work was limited to collecting data and maintaining data flow.

- Kilauea Eruption (4/30 - 8/4)
  - » 30 April: Pu'u"O'o eruptive vent collapsed and magma began moving down-rift toward Puna.
  - » 3 May: A magnitude 5.0 earthquake created an ash explosion at Pu'u"O'o vent, triggering the start of new events on Kilauea. Fissures began to open up in Leilani estates in Puna. Residents were ordered to evacuate, and 24 fissures opened in this region by the end of the month.
  - » 4-7 May: A magnitude 6.9 earthquake caused the observatory to lose power on Friday, 4 May. Staff shut down projects, power was restored on 5/5 by HELCO, and all instruments were restarted on 5/7.
  - » 4 May: Aidan Colton and Darryl Kuniyuki visited Kumukahi to remove air sampling equipment from the Kumukahi structure. Access to the area was restricted to residents only. High levels of sulfur dioxide were a health concern.
  - » 14 May: Equipment removal from the Kumukahi structure was completed on 5/14. At that time, the volcanic activity increased and there was a high probability the site could be overrun by lava.
  - » 17 May: Kilauea experienced an explosive eruption rising to 30,000 ft. This was the first of many explosive ash and volcanic gas explosions that injected material high into the atmosphere (greater than 10,000 ft.).
  - » 23 May: Aidan Colton and Darryl Kuniyuki scouted multiple sites around the island for temporary sea level flask sampling. Lehia Beach Park and Hawaiian Beaches were chosen as temporary sampling sites, and wind direction determined which site was chosen for sampling each day. These sites were used for sea level air sampling through 2020.
- August 5-17: At 2 p.m. on Sunday, 5 August the Hawai'i Fire Department reported a brush fire on the slopes of Mauna Loa above the volcano. The active brush fire burned in the area of Keauhou Ranch and one-quarter mile from Powerline Road and moved south towards Kapapala Ranch. More than 3,700 acres were destroyed in this fire.
- August 22-23: Hurricane Lane caused the closure of MLO on 8/22 and 8/23, when the facility was shut down and staff were instructed to stay home. NCAR restarted operations on the 8/25. MLO, JPL, and ASIAA operations resumed on 8/27. ASIAA reported the containers that house their staff sleeping quarters were ruined from excessive rainfall, and the carpets and beds had to be replaced. ASIAA staff used the NOAA bedrooms until their containers were fixed. Saddle Road experienced a landslide at the 10.5-mile marker, which closed the road for hours until county crew could clear the debris. Rainfall at the observatory caused rocks and cinder to cover the driveway. MLO staff had to sweep the road to clear it away.
- 30 July - 3 August: Thomas Bennington of DISA OS (US) tested MLO site wireless transmissions. On 2 August, the wireless communications group (including representatives from SPAWAR, U.S. Army, Pohakuloa, and the U.S. Navy) visited the MLO site. Thomas Bennington wrote a report that provided recommendations to remedy the interference issues.
- 22-26 October: From 22 - 26 October, the Korean Meteorological Association (KMA) performed a sulfur hexafluoride audit on the Halocarbon GC. KMA ran four tanks over 72 hours and two tanks at a time alongside NOAA's calibration cylinders for at least 24 hours.
- November: MLO received three pallets of LED light fixtures for the observatory on 26 November. Funding for this came from a Department of Commerce Green Grant. Light fixtures in the Keeling building and NDACC were replaced with these energy-efficient fixtures.

OUTREACH

Tours continued at the observatory, with John Barnes coordinating the tours in 2014. In 2015, Aidan Colton began coordinating the tours, giving talks and interviews with media groups, and became the public relations contact for MLO.

The observatory continued to give science fair awards annually to local science fair students. Science fair awards were provided by the MLO Employee Association from 2014 – 2016 and by the Friends of MLO organization from 2017-2020.

Beginning in 2017, outreach activities were reduced due to decreases in available staff time.

2014

- Tour Highlights:
    - 6, 12, and 19 March: John Barnes gave tours at MLO to a UHH geography class, a Cornell University class, a class from the University of Indiana, and a class from Lancaster Country Day School, Pennsylvania.
    - 22 August: Russ Schnell gave a tour of MLO to Representative Bill Flores (Texas).
    - 27 August: 54 Harvard University undergraduates and staff toured MLO. John Barnes was assisted by Alex Morgan and Ben Berkey from the Mauna Loa Solar Observatory.
    - 29 December: Senators Brian Schatz (HI) and Bill Nelson (FL) toured the observatory with Russ Schnell and John Barnes.
- May - July: From 27 May - 25 July, Alissa Phillips (Hollings Scholar focusing on science education) created lesson plans about climate change. She gave a talk to 6 groups of students at Mokupapapa on 7July 11th with the help of MLO staff. She gave a talk at the Oahu IRC symposium on 21 and 22 July.
- June - December: Robert Pipes was hired to perform calibration of the world standard Dobson from 14 June - 19 September. From 21 September - 22 December, Robert Pipes was hired under the JIMAR temp-hire program to assist John Barnes with lidar/CLidar research programming.
- 7 June: Boy Scouts visited MLO for a "Supernova" activity mentored by Darryl Kuniyuki. Three Boy Scouts were awarded the Thomas Edison Supernova award, the highest Boy Scout award in the STEM fields. These boys are the first to earn it on the Big Island.
- 3-4 September: Intern Alex Morgon worked in the Hilo office on a project with John Barnes.

2015

- Tour Highlights:
    - 6 March: Chuck Greene's Cornell University class toured MLO.
    - 6 May: A class from the University of Quebec toured MLO.
    - 3 June: 11 students from Grant MacEwan University (Canada) toured MLO.
    - 22 June: 36 students from a 6th grade Warren Tech, Colorado class toured MLO.
    - 25 June: Three researchers from Tokai University, Japan, toured MLO.
    - 16 July: John Barnes provided a tour to the Science Camp of America.
    - 10 December: 40 AGAGE Conference participants visited MLO.
- 7-9 April: James Balog filmed the greenhouse gas sampling and interviewed John Barnes. He also flew a drone and took aerial photos of MLO.
- 1 June - 31 July: Intern Poppy Goddard, from England, helped with the observations and outreach.
- 15 July - 15 September: Intern Natalie Bakker, from the Netherlands, helped with the observations and outreach.
- 24 June: MLO staff visited Kamehameha School summer program to hold science demonstrations and a radiosonde launch. John Barnes, Darryl Kuniyuki, Poppy Goddard, David Nardini, and Preston Sato participated in the outreach event. Each staff member manned an activity table that small groups of students rotated through during the event.

2016

- Tour Highlights:
    - 3 March: 15 students and three teachers from the Lancaster Country Day School toured MLO.

    - 21 March: 16 college students from the University of Wisconsin-Eau Claire toured MLO.
    - 5 May: 14 students from W&L College in Virginia visited MLO.
    - 26 May: 30 SUNY New Paltz geology students toured MLO.
    - 6 July: Aidan Colton, Matthew Martinsen, and Forrest Mims gave a tour to 40 NCAR conference participants.
    - 14 July: Aidan Colton and Matthew Martinsen gave 20 Science Camp of America participants a tour of MLO.
- 22 April: MLO staff attended the Earth Day fair on the UH Hilo campus. Approximately 1,200 people attended the fair.
- 8 July: MLO staff visited Kamehameha School in Keaau to participate in their summer school program "Halau Kupukupu Innovations Academy". Forty middle school students completed science activities with MLO staff.

2017

- Tour Highlights:
    - 22 March: John W. Merck, Undergraduate Director of Geology at the University of Maryland, and 16 College Park Scholars students toured MLO with Aidan Colton and
    - 23 March: Jeffrey Yuhas and 20 environmental science students from the Morristown-Beard School in New Jersey toured MLO.
    - 6 June: 8 students and three faculty from the McEwan University in Canada toured MLO.
    - 8 June: 22 Hawaii Environmental Education Alliance (HEEA) members toured MLO.
    - 12 June: Ten Korean Met Association (KMA) members toured MLO.
    - 19 June: 16 sixth graders, four high school counselors, and five adults from Warren Tech North visited MLO.
    - 22 June: Eight teachers from the Lamar University Educators in the Texas State University System visited MLO.
    - 18 July: Aidan Colton led a tour for 20 Science Camp of America participants.
    - 27 July: 16 elementary and high school teachers enrolled in "Geology of Hawaii", an extension class through the University of the Pacific (Stockton CA), toured MLO.
    - 26 October: Aidan Colton gave a tour to Dr. Tony Worby, the new Director for CSIRO Oceans and Atmosphere, and his entourage.
- 7 April: Aidan attended the Career Day Fair at Hilo Intermediate School.
- 18 May: OAR Assistant Administrator Craig McLean, the University of Hawaii Sea Grant Director Darren Lerner, and Sea Grant Fellow Molly Semones visited MLO and Mokupapapa. Darryl Kuniyuki and Aidan Colton hosted the tour.
- 26-28 June: Rosten Woo and Ian Biers-Gambler, a San Francisco Exploratorium film crew, shot footage of flask sampling at Kumukahi and MLO, Lidar and the general site at MLO, and a balloon launch at the National Weather Service. They also interviewed Aidan Colton, Darryl Kuniyuki, and John Chin.
- 29 August: Aidan attended Congressional staffers meeting at Mokupapapa.
- 25 September: NOVA filmed onsite for a documentary about climate change. The film crew interviewed Ralph Keeling, John Chin, and Aidan Colton.

2018

- Tour Highlights:
    - 29- 2018 About 60 High school students and teachers visited ASiAA's YTLS facility to learn about climate science and astronomy. 30 individuals per day.
    - 10/9- UH Geosciences Class field trip 13 people.
    - On 7 December: 12 Science Camp of America 20 people visited MLO.

- 7 February: Waiakea Elementary School students visited the NWS office and observed an ozonesonde balloon launch.
- 16 February: Aidan Colton and Darryl Kuniyuki attended HSTA Teacher Institute Day at Keaau High school. MLO provided information about NOAA, including contact information, and discussed services available to teachers.
- 18 May: Aidan Colton gave a lunchtime talk about MLO to 11 Kiwanis members in Hilo.
- May 15-17: Intern Aimee Golden shadowed Aidan Colton at MLO and attended a water vapor balloon launch.
- 30 May: Darryl Kuniyuki visited the Mt. View Elementary School to talk about UV protection from the sun. Materials were provided by the National Environmental Education Foundation - Sunwise Program.
- Matthew Martinsen installed a new aerosol display next to the NOAA aerosol instrument in the Keeling building. It shows legacy equipment, Asian Dust samples from the old Aethalometer filters, and sunrise pictures at MLO during the El Chichón eruption in 1982.
- New poster frames were installed for the Hilo office. The new frames have the ability to open and replace the poster inside. Posters can be updated annually more easily than with the fixed frames used previously.

Number of Visitors to the Observatory Site: Visitors to the station peaked during MLO's 60th Anniversary year in 2016.

YEAR	Number of Visitors
2014	401
2015	377
2016	573
2017	486
2018	500

2.5 AMERICAN SAMOA

BACKGROUND

The American Samoa Observatory (SMO) is located in 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 is situated on the northeastern tip of Tutuila Island, American Samoa, at Cape Matatula. The observatory was established in 1974 on a 26.7-acre site and has survived two major hurricanes, an earthquake, and a tsunami. A staff of three operates the facility year-round. In addition, this observatory has the distinction of obtaining a portion of its daytime power from solar panels.

Figure 2.10: American Samoa Atmospheric Baseline Observatory from the Blue Sky sampling tower.

The summer of 2014 marked the completion of the first full NOAA Corps officer observatory station chief rotation in 7 years. LTJG Jesse Milton completed one year at SMO in July 2014 and moved on to South Pole. SMO said goodbye to its employee with the longest history at the station, groundskeeper Lafaele Silao. Lafaele retired at the end of 2017 after more than 30 years of employment at SMO.

During a site visit in 2016, the BlueSky tower was deemed unsafe. The tower, which sits to the south of the Hudson Building, is owned by BlueSky Communications and supports NOAA inlets and meteorology instrumentation, Scripps Institution of Oceanography inlets, and BlueSky communications equipment. Due to the sea spray and humid climate, the top two-thirds of the tower were so rusted that GMD staff did not feel safe climbing up. Negotiations commenced with BlueSky later that year to replace the tower. Tower replacement commenced in late 2017 and was completed in early 2018.

Tropical Storm Gita hit Tutuila in February 2018, just after the BlueSky tower instrumentation and inlets were reinstalled. The storm lashed the island with a day of high winds and heavy rain. Most of the island lost power during the event, but SMO's emergency generator ran well, keeping all of the instruments recording data during and after the storm. The meteorology suite recorded a maximum wind speed of 90 kts, breaking the island's maximum wind speed record. Minor damage was sustained from the storm: several trees fell on the stairs down the point requiring repairs, and the north side of the property suffered a landslide that did not impact any buildings or equipment. The Environment Climate Change Canada GAPS pole had to be moved from the unstable ground. Due to a shortage of rebuilding supplies on the island, the NOAA Ship Hi'ialakai helped deliver pressure-treated wood and household generators on their port call to Pago Pago later in the year.

STAFF

Year	Station Chief	Technician	Groundskeeper
2014	Jesse Milton (Jan - Jul) Refael Klein (Jul - Dec)	Gataivai Talamoa	Lafaele Silao
2015	Refael Klein (Jan - Jul) Gavin Chensue (Jul - Dec)	Gataivai Talamoa	Lafaele Silao
2016	Gavin Chensue (Jan - Jul) Diane Perry (Jul - Dec)	Gataivai Talamoa	Lafaele Silao
2017	Diane Perry (Jan - Jul) Ben Kaiser (Jul - Dec)	Gataivai Talamoa	Selefuti Leatigaga
2018	Ben Kaiser (Jan - Jul) Marisa Gedney (Jul - Dec)	Gataivai Talamoa	Selefuti Leatigaga

FACILITIES

2015

- No facilities information available.

2016

- February: Carport solar panel installation was completed.
- April: Facility Condition Assessment (FCA) was conducted at the observatory. This report will be used by NOAA and OAR staff to allocate facility funding.
- May: Gavin Chensue installed new wiring for the GRAD suite on the observatory catwalk.

- May – June: The pump house at the sampling point was remodeled. The building paint was stripped, a cement cap was installed on the roof, the AC unit was replaced, the building was rewired, new workbenches were installed, and the entire building was repainted. Minimal down time resulted for the CO_2 in situ measurement system during this work.
- July: The wall-mounted AC unit was replaced in the CO_2 room in the main observatory.
- July: An omnidirectional antenna was installed on lidar garage roof in Tafuna to track ozonesonde launches.
- August: After months of the emergency generator being nonoperational, Peter Young installed a new generator switch.

Figure 2.11: American Samoa Observatory office.

- August: During a site visit by Boulder personnel, the BlueSky cell tower, which supported the meteorology instruments, HATS inlets, aerosol inlets, surface ozone inlet, and Scripps inlets, was deemed unsafe to climb due to corrosion.
- August: Two new 18K BTU split air conditioning units were installed in the Hudson building—one on the Scripps side of the building, and one on the NOAA side.

2017

- January: A large palm tree trunk rolled onto the station's power line during heavy rainfall. ASPA quickly cleared the power line.
- February: Water was found condensing in the Hudson Building fluorescent lights.
- March: Preventative maintenance was performed on the emergency generator: oil and a filter were changed and a temporary belt installed. Personnel found the fuel cap had rusted out and fallen apart. The open tank had approximately 30 gallons of water-contaminated fuel.
- March: Motion detection lights were installed at the Tafuna housing as a preventative measure.
- April: During a prolonged power outage, the emergency generator overheated and shut down due to a fan belt failure.
- April: A new well pump and faucet were installed in main observatory building.
- May: The contaminated fuel was removed from the bottom of the emergency generator fuel tank. The fuel lines from the tank to the generator building were replaced, and a new watertight cap was installed.
- May: The solar panels on the observatory carport roof were relocated to maximize space and allow future potential expansion of the system. An emergency shutoff was also added to the system, bringing it up to code and increasing station safety.
- July – August: Additional maintenance was performed on the emergency generator: fuel line connections were tightened, an exhaust vent was replaced, an old fuel pump was bypassed to prevent air from entering the fuel line, protective coating was added to the generator, and new grounding line was installed. A weekly test protocol was established for the generator.
- August: Lights in the Hudson Building replaced with LEDs.
- One section of stairs was cleaned and power washed by Remote Elite Services (RES).

2018

- January – March: After Lafaele Silao retired as SMO's groundskeeper in December 2017, RES was hired to mow the grass and do basic grounds maintenance once per week until a full-time groundskeeper could be hired. RES continued to work at the station through March, 2018.
- January: Water/condensation was found in the fluorescent lights on the NOAA side of the Hudson Building. A dehumidifier was placed in the room and helped the situation.
- April: Selefuti "Futi" Leatigaga was hired by STC as SMO's groundskeeper. Futi is Lafaele's son-in-law.
- April: A plumber visited the station to clear a clog that made station water inoperable.
- April: Non-skid paint was applied to the stairs leading to the observatory roof to prevent slips and falls.
- May: The solar panel communications box was not reporting power generation from the solar array.
- Working with Pacific Solar Innovation, it was determined to be a communications issue, not a solar generation issue.
- June: BlueSky began painting the tower.
- July: John Conrad fixed Tropical Storm Gita damage to the point stairs

COOPERATIVE PROJECTS

2015

- No cooperative project information is available.

2016

- 25-29 April: Ethan Miller (Johns Hopkins) installed an all-sky imager on the roof of the main observatory building. The data from this instrument were used to observe ionospheric anomalies. New brackets for antennae on the point were re-installed on the remodeled pump building in June

2017

- June: The John Hopkins instruments were officially taken offline, to be shipped back to Ethan Miller at a later date.

Figure 2.12: American Samoa Observatory Blue Sky Tower and the Hudson Building that houses the Scripps Institutions of Oceanography instruments.

2018

- February: During Tropical Storm Gita, the Johns Hopkins
- Figure 2.12: American Samoa Observatory Blue Sky Tower and the Hudson Building that houses the Scripps Institutions of Oceanography instruments. antenna rebar supports at the point were bent 45 to 90 degrees by the strong winds. The wifi antennae were also blown off the point sampling building and destroyed.
- February: The EC GAPS sampling pole was located dangerously close to the landslide that occurred during Tropical Storm Gita. It had to be relocated from the unstable soil.
- February: The NASA AERONET Cimel suffered damage during Tropical Storm Gita. The control box was blown across the roof grating, making the wiring taut and causing a break in the box's seal. Water entered the control box, but returned to normal operation after it was dried out with desiccant.
- May: A new NASA AERONET Cimel was installed.
- July: A new boom for the Scripps O2/N2 sampling project was installed on the tower.
- A new laptop was swapped out on the NASA AERONET Cimel system.

SPECIAL EVENTS


Figure 2.13: Inside the American Samoa Observatory Hudson Building with Scripps instruments including surface ozone and gas calibration tanks.

2015

- No special event information is available.

2016

- February: Tropical Storm Winston brought rain and wind to Tutuila, with no significant impacts to operations other than one power outage.
- 23 April: Cyclone Amos tracked just to the north of Tutuila. High winds with over 70 mph gusts and rainfall were recorded at the station.
- August: An ozonesonde launch was synchronized to an ATOM-1 flight.

2017

- In addition of two Garmin InReach devices enabled new emergency communications. The devices allow text and email to be sent via satellite in the event all communications on/off the island are down. One unit was purchased for the station chief and one for the station technician.
- July: Aerosol measurements were discontinued at American Samoa due to budget issues and lack of interest in the data. The CNC was removed from the Hudson Building and returned to Boulder.
- 3 November: The island experienced a magnitude 6.9 earthquake, which did not trigger a tsunami. There was no damage.
- November: BlueSky began replacing its tower adjacent to the Hudson Building. BlueSky personnel removed all inlets and instruments from the tower, impacting the following science groups: NOAA Meteorology, NOAA HATS, SCRIPPS, and AGAGE. The tower replacement continued into 2018.
- 28 December: Lafaelle Silao retired after working as the observatory groundskeeper for over 30 years. The process for hiring another groundskeeper began and continued into 2018.
-

2018

- January: The BlueSky tower was completed and all instrumentation and inlets were reinstalled on the tower at their original heights. BlueSky did not replace the original base of the tower, since there was little corrosion, and planned to paint the tower red over the months following its completion.
- 9 February: Tropical Storm Gita hit Tutuila, causing widespread damage. According to NWS, the highest wind speed recorded during the storm was 90 kts, which is a record for the island. While most of the damage occurred in the Nu'uuli and Tafuna areas of the island, it took a significant amount of time to restore power and water to the majority of residents. In addition, high winds caused trees to fall on the tower lines and block the roads. The station itself experienced minimal damage and data loss:
  - » Five trees fell across the stairs to the sampling point, causing minor structural damage.
  - » The A/C unit was blown out of its mount and into the pump house at the point, letting water into the building.
  - » There was a significant landslide on the north side of the station grounds. While there was no damage to equipment or buildings, several sampling systems had to be relocated from the unstable soil.
  - » The emergency generator at the station ran for five days, minimizing instrument downtime and allowing data acquisition during and after the storm.

- March: Thieves broke into the Tafuna facility and stole lawn care equipment. Station personnel were unsuccessful in locating the stolen items with local law enforcement.
- June: The NOAA Ship Hi'ialakai docked in Pago Pago and brought supplies needed to recover from Tropical Storm Gita: pressure-treated wood and residential emergency generators that could not be found on island in the storm's wake. The NOAA offices in Hawaii and ship's crew supported the station's recovery.

- **OUTREACH**

2015
- Jesse Milton worked with other NOAA staff on the island to create a "One NOAA" community, including monthly meetings to share what other NOAA staff were doing and how each line office could better support one another.

2016
- Multiple tours were held, including Coral Research group, Climate Teacher Workshop participants, ASCC Oceanography class, and private citizens

2017
- February: The station hosted tours for the NOAA Ship Okeanos Explorer officers and science party , a local 3rd grade class, a homeschool field trip, and 12 local visitors.
- The National Park Superintendent and his friends and family visited the station for a science tour.
- Station staff participated in the Samoa ozone summit meeting on Tutuila and attended a local high school STEM event.
- The Ofu National Park ranger and National Park head of outreach visited the station.
- August: Visitors included a local high school group, Walt Oeschel and his colleague, and a private family.
- November: The American Samoa Community College Oceanography class toured the station.

2018
- March: Vai demonstrated ozonesonde prep procedures at the Lakina High School.
- 16 April: Assistant Secretary of Insular and International Affairs for the United States Department of Interior, Doug Domenech, and various officials toured the station.
- 12 June: The NOAA NWS held the first Federal Pathways Open House for high school seniors, introducing island high school students to careers in the federal workplace. Station personnel were at the open house to demonstrate a balloon launch and talk about the observatory.
- 19 June: Local USCG personnel toured the station.
- 22 June: Three individuals who sailed from Hawaii on a personal yacht toured the station.
- 5 July: Approximately 40 teachers toured the station to learn how atmospheric research could be incorporated into their curriculum.
- 16 July: Eight high school students from the Western Pacific Regional Fishery Management Council's High School Fisheries and Resource Management course toured the station.
- 20 July: 16 crewmembers from NOAA Ship Hi'ialakai toured the station.
- 24 August: 14 EPA employees toured the station.
- 17 August: 12 members of the NWS Pacific International Training Desk toured the station as a supplement to their tropical weather forecast training.
- 9 November: Two cruise ship visitors toured the station.
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2.6 SOUTH POLE, ANTARCTICA

BACKGROUND

The South Pole Atmospheric Baseline Observatory (SPO) is located at the geographic South Pole on the Antarctic plateau at 2837 m above sea level. The South Pole Station was established 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, including nine months of isolation and six months of darkness. The ARO facility is approximately 500 m east-northeast of the elevated station. This location is generally separated from and upwind of the station operations. A Clean Air Sector (CAS) is defined as the area beyond the ARO facility from grid 340° to grid 110° grid 110°. The prevailing winds at the South Pole are from the CAS nearly 90 precent of the time. Thus, the CAS preserves the unique atmospheric and terrestrial conditions without influences from South Pole Station. Except for special circumstances, access, including foot and vehicle traffic, to the CAS is prohibited. Aircraft activity is limited in the CAS, and strict guidelines for scientific or other activities ensure that the pristine nature of the CAS is meticulously preserved, not just for current scientific activities but also for future science conducted at the South Pole.

Figure 2.14: South Pole Atmospheric Research Observatory facility beneath the Milky Way and the aerosol lidar beam pointing toward the South Polar Star cluster.

Due to annual snow accumulation at South Pole, the ARO facility, once on a berm and elevated high above the snow, began suffering from critical inundation. The building was designed to accelerate wind blowing under the building to keep snow from accumulating there. During the 2014- 2018 period, the snow level reached nearly to ARO's second story. Although the building still scoured, the drifting upwind and downwind of the facility grew significantly. A great deal of snow removal was needed to keep the cargo bay accessible by heavy equipment. In 2018, snow was removed upwind of ARO, as well as downwind—a first for the research site.

The Balloon Inflation Facility (BIF) was also deteriorating from age, location, and the pressure of increasing snow depth. Located downwind of the main elevated station and the arches, and directly behind the large Cryo facility, the BIF began to be buried, was no longer level and no longer square. Because of these structural stresses, the BIF was replaced in the 2015-2016 summer season. The Cryo facility was relocated due grid east of its original position and converted into the new BIF. The new facility also included a small office for prepping radiosondes and ozonesondes and also had a large bay for plastic balloon inflation. The doors from the original BIF were repurposed and hung on the inflation bay of the new BIF. The facility was occupied and used for launches at the end of the 2015-2016 summer season, with finishing touches applied during the 2016-2017 summer season.

STAFF

Year	Station Chief	Technician
2013-2014	Joseph Phillips	Johan Booth Lance Roth (Nov - Jan)
2014-2015	Jesse Milton	Johan Booth Andy Clarke (Nov - Jan)
2015-2016	Refael Klein	Johan Booth Christine Schultz (Nov - Jan) Andy Clarke (Jan - Feb)
2016-2017	Gavin Chensue	David Riebel
2017-2018	Cherisa Friedlander	Sabrina Shemet
2018-2019	Benjamin Kaiser	Johan Booth
2019-2020	Marisa Gedney	Johan Booth
2020-2021	Tim Holland	Joseph Samaniego

FACILITIES

2014

- Evaporation was building up in the NASA vertical micropulse lidar (MPL) tube. Evaporated liquid nitrogen exhaust and blankets did not dispel the ice accumulating on the inside portion of the outside window when temperatures dropped below -50●C. Heat trace was applied to the outside of the tube in April. Several adjustments to the wattage kept the ice at bay.
  - » While troubleshooting the lidar window, technicians discovered the thermostat in the lidar room pulled cold air into the room when it got too hot. Since keeping the room warm was an issue, they used a space heater and worked with station personnel to get the heating/cooling back to its original design (auxiliary heater connected and online).
  - » In December a flue pipe was installed between the inside and outside lens. However, the ice returned in March. A slow flow of nitrogen began to be pumped into the lens for the rest of the year.
- July: The BIF's deck was damaged when a loader ran over the grating during snow removal. The damage initially prevented the doors from opening, but once the damaged grating was removed the doors could again be opened.
- October: The thermostat in ARO's UV penthouse was found stuck in the on position, likely due to a power brownout. The thermostat was replaced.
- December: During UPS maintenance, the power to ARO's second floor was accidentally shut off, causing a hard shutdown to most of the second floor instruments (MPL, aethalometers, NIPR all-sky camera, UV instruments, aerosol suite, Brewer, and TEI). Some instruments experienced minor issues, and the station was fully operational again after 24 hours.

2015

- March – April: In late March, ice built up again on the NASA MPL top lens (the bottom surface). A slow flow of nitrogen was again established in the lens housing to mitigate ice formation. In April, the heat trace temperature was increased to prevent ice buildup. Later, in May, the nitrogen feed ceased and there was no additional ice buildup.

- April: The ARO penthouse thermostat was replaced in an attempt to more tightly control the temperature of the UV Monitor instrumentation's roof box. In October, the penthouse thermostat malfunctioned again, causing the penthouse to drastically overheat. Temperatures stabilized after the thermostat was replaced.
- November: Betsy Andrews visited SPO to upgrade the nephelometer's connection to the aerosol stack. With the assistance of station plumbers, a section of the copper piping that connected the nephelometer to the stack was removed and upgraded. A large valve was removed, and a joint that split the flow of sample air to the nephelometer and excess stack air was installed. A copper fitting was added to the end of the pipe, allowing flexible piping to be fitted directly into the nephelometer.

Figure 2.15: Halocarbon instrument room in the South Pole Observatory with an identical gas chromatograph as shown for Mauna Loa in Figure 2.9.

- November: Construction of the new Balloon Inflation Facility (BIF) began. The Cryo facility had been relocated, and most of the building was converted into an office/laboratory space for prepping radiosondes and ozonesondes and a large inflation room. The doors from the deteriorating BIF were removed and mounted to the new BIF in December, but launches were still held from the old BIF through the summer months. The building was habitable by the end of the summer, with finishing touches completed in Summer 2016/2017.
- December: In preparation for a new NSF upper atmospheric project installation where Gonzolo's project used to be housed, station carpenters removed ARO's two small northeast penthouses and expanded the size of the upwind penthouse. Carpenters were careful to operate within the height limitations/restrictions and not block existing solar instrument views.

2016

- March: Frost began to develop again on the NASA MPL upper window. The heat trace around the tube was powered on, eliminating the problem.
- April: The ARO penthouse thermometer was replaced.
- November: The Interplanetary Dust Sampling project was installed adjacent to ARO on the border of the Clean Air Sector (CAS):
    - » During installation there was a communication error between ASC science support and the heavy equipment operators. On 24 November, the operator drove a bulldozer into the CAS and built a berm for the Interplanetary Dust Sampling project. During this installation, the bulldozer entered approximately 20 meters into the CAS. The bulldozer also ran over the firn air sampling lines, destroying them.
    - » On 25 November, the bulldozer had to re-enter the CAS to remove the improperly placed berm.
    - » The science and logistical support crew did not purchase enough power cable to allow the new sampling building to be placed outside ARO's clean air buffer zone. It was placed exactly along the CAS delineation line and within 100 meters of ARO.
    - » The sampling system ran a very powerful motor pump, and there were concerns that the pump would impact aerosol data.
- December: The demolition of the old BIF was completed.

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- December: The albedo rack was raised. Approximately 10 feet of mounting pole was dug out of the snow.
- December: New HATS air lines were installed on the 30 m tower on 10 December. The GC sampling switched over to the new lines on 11 December, and the old lines were removed from the tower and the building. On 12 December a new HATS flask sample inlet line was installed on the 340° line of the CAS.

2017

- Januar: Additional work on the new BIF inflation room occurred in January. The floor of the facility was repainted 24-30 January. In addition, the interior walls were finished, exterior siding completed, and additional shelving installed. Balloon flight procedures were only slightly affected, and all flights were completed without issues.
- December: A power outage damaged the webcam, but no other instrumentation was affected.

2018

- January 22-23: Riggers adjusted the tension on the 30 m tower wires.
- With an unusually windy winter and the snow accumulating around ARO, there was a significant amount of drifting throughout the year. NOAA staff had the downwind drift cleared from ARO several times throughout the winter, in an effort to keep the building entrance and cargo area mostly open. A group of volunteers helped clear the stairs and porch in September.
- June: The station electrician replaced the starter/contactor in the control cabinets for the first and third stages of ARO's main heater. The internal contacts on the starter/contactors had burned out from long-term use. This may have been contributing to the heating control circuit issues, which resulted in frequent breaker resets.
  - » ohe second starter/contactor was not replaced because it was in the best shape of the three, and there were only two spare starter/contactors available.
  - » The South Pole crew recommended to ASC to replace these components on a biannual basis.
- The water and sewage tanks from ARO's mechanical room were removed, freeing up a significant amount of space.

COOPERATIVE PROJECTS

2014 - 2015

No cooperative project changes.

2016

- August: The Coherent laser supply on the legacy NASA MPL ceased working. With no replacement available, and NASA's intent to retire the instrument at the end of the winter, no efforts were made to repair the instrument. Instead, it was removed and shipped back to NASA over the summer.
- January: A new project was moved into the small dark room on ARO's 2nd floor (previously Gonzolo's interferometer space). The NSF-backed Conde project required modifications to the roof penthouses, and needed a crane for installation. This project was maintained by ASC Research Assistants.

Figure 2:16: South Pole Atmospheric Research Observatory in a hollow of drifted snow in late winter viewed from the meteorological and sampling tower.

2017

- January: Significant troubleshooting was necessary for the Scripps Institution of Oceanography 30 m tower inlet line. The line was frozen over and had zero flow. Back pressure, heat, and electrician's fish tape were used in an attempt to clear an apparent blockage in the line. Finally it was determined a blockage had been formed at the warm/cold boundary where the tubing exits the ARO. The tubing was separated midway between ARO and tower, and the line was pulled back inside to thaw. After two hours, the line was thawed and clear. It was reconnected outside, and normal operations continued.
- March: The NIPR All Sky camera was removed from the roof. With the project's completion, it was shipped back to Japan in November.

SPECIAL EVENTS

2014

- March: Began upgrades to Windows 7.

2015

- During the trade out between Dobson D042 and D082 in December, it was determined the M2 mirror for D082 had shifted during transport. Glen McConville spent three days adjusting the mirror but decided to leave both instruments on station for the 2016 winter to compare them under a wider variety of conditions, including sun-focused images and lunar observations.
- A new Balloon Inflation Facility (BIF) was constructed during 2015-2016 summer. The new BIF re-used the freezer doors and converted a portion of the Cryo facility into the inflation and lab area.

2016

- January: New HATS inlet lines were installed on the tower. After the installation, the air sampled through the new lines exhibited elevated levels of CFC-11. A spare pump was set up to flush the new Synflex lines independently. The new Synflex lines were placed in operation in April 2016.
- February: During the latter half of 2015-2016 summer, the doors to the new BIF were installed, and the facility was officially occupied and used for daily radiosonde and weekly ozonesonde launches in February.
- 9 May: ARO's in-situ CO2 analyzer recorded its first data point over 400 ppm.
- 21 June: The first mid-winter medevac mission was successful. A Ken Borek Air Twin Otter safely arrived at South Pole during a period of clear skies, a full moon, and relatively "warm" temperatures to evacuate critically-ill winter-over staff members. The ARO meteorology tower was lit up as a beacon and served as a navigation aid for the flight crew.
- December: Data transfer from South Pole was upgraded. The new data transfer system discontinued the direct FTP method and began to use bulk transfer using the science-only service on the SPTR satellite.

2017

- The arrival of LT Cherisa Friedlander and Sabrina Shemet on the station marked the first all-female NOAA crew at ARO.

2018

- January: The USAP survey team reported the NGO camp was placed in violation of the CAS.
  - It was determined there were not enough flags near the camp, and the CAS boundary sign was situated at an angle which may have led the NGO camp management to believe the boundary extended farther.
  - There was a total of 11 tent sites found past the NGO camp boundary. Of those, approximatel

3.5 sites extended past the 340° azimuth line. The edge of camp encroachment was determined by the extent of snowmobile tracks and footprints visible in the snow. Distances for the length and width of the encroachment were 69 ft and 239 ft, respectively.
    - ARO crew and the survey team added red flags to mark the NGO camp boundary (every 50 ft) and black flags for the CAS boundary (every 50 ft). The CAS sign was also relocated for additional clarity, placing it just past and parallel to the camp boundary line.
- 10 May: An ozonesonde launch was coordinated to coincide with the NASA ATom-4 DC-8 flight. The closest point of approach to the South Pole was 80°S

Figure 2:17: South Pole Atmospheric Research Observatory instrument rack and gas calibration tanks.

OUTREACH

2014

- January: Lance Roth and Joe Phillips spoke to an elementary school class at the Connecticut New Canaan Country School, answering questions about life at South Pole Station.
- January: Renowned atmospheric scientist Dr. Roger Wakimoto and NSF's Kelly Falkner toured ARO.
- Ranking members of the House Committee on Science, Space, and Technology visited South Pole Station

2015

- LTJG Refael Klein started writing monthly entries for the Voice of America "Science World" blog. His blog posts focused on life and personal impressions of conducting science at the South Pole: https://blogs.voanews.com/science-world/author/rklein/

2016

29 November: The Deputy Administrator of NASA visited the South Pole. NOAA personnel gave a short presentation about ARO science in the B2 science laboratory.

- LTJG Gavin Chensue presented a Sunday Science Lecture about ozone depletion.

2017

- No significant outreach events.

2018

- 11 May: The NOAA crew showed a station-wide screening of the movie "Ozone Hole: How We Saved the Planet."
- 20 September: The NOAA crew participated in a video call with an eighth-grade class from LaFayette JR/SR High School in LaFayette, New York. The students, who had been learning about ozone using GMD's educational videos, followed the development of the 2018 ozone hole.
- 30 September: ARO held an open house with tours for station personnel.
- 11 October: LT Cherisa Friedlander gave a presentation about the NOAA Corps.
- December: ARO hosted a group of six distinguished visitors from the National Science Board and the U.S. Air Force, including former astronaut Dr. Ellen Ochoa.

2.7 METEOROLOGY PROGRAM

PROGRAM OVERVIEW

The surface weather observations at the Atmospheric Baseline Observatories (ABOs) record the wind speed and direction, atmospheric pressure, air and dewpoint temperatures, and precipitation amounts each minute. Hourly averages and one-minute resolution data are available on GMD's FTP. The meteorological sensors in use were selected for their high accuracy and ability to withstand the extreme conditions of polar and tropical regions.

DATA ACQUISITION SUITE UPGRADES

As of 1 January 2014, the meteorological data acquisition system acquired atmospheric data using the 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. The data were transmitted via RS-232 communications to a remote computer, which collected data in real time and transmitted the data to Boulder each day for processing.

Beginning in 2016, the meteorology team started designing and assembling a new data acquisition system and updated instrumentation at all ABOs. The new system focused on precision and accuracy, flexibility, and interchangeability with other GMD Divisions. The Campbell Scientific CR1000 datalogger and Loggernet software replaced the Zeno-3200. The CR1000 datalogger is easily programmable using the included Loggernet software, supports a wide variety of instrumentation, and is also used by the GMD GRAD Division.

In the new systems, data are recorded by CR1000 data loggers, output as RS232, and converted to digital by a Digi-1 serial server. Every 1-3 minutes, the SMO, SUM, BRW, and MLO CR1000's are queried by a computer in Boulder, and data are downloaded in real time. The real-time data are uploaded to the ABO webpages and are available to the public and ABO staff. Every 15 minutes, the SMO, SUM, BRW, and MLO CR1000's are queried by a Boulder computer—raw, processed, and quality control (QC) data are saved to daily files on the GMD network. Because SPO does not have the same internet connectivity as the other ABOs, real-time data are sent from SPO to Boulder every 15 minutes when a satellite connection is available. Complete SPO raw, processed, and QC daily data files are sent via satellite each day.

INSTRUMENT CHANGES

Wind Speed and Direction

The R.M. Young anemometers were replaced with Lufft Ventus UMB 2D sonic anemometers. After being tested at Summit Camp for several seasons, the instruments proved to be accurate, robust, and relatively maintenance-free. No frost forms on them because the units are heated. There are no moving components that can wear out. Calculations for wind speed and direction are made using the laws of physics, so they never require calibration. The drawbacks are that the units are almost impossible to troubleshoot locally; in most cases, they must be returned to Lufft technicians.

R.M. Young anemometers were kept online at SUM and SPO at the 10m level to serve as backup instruments in case the sonic anemometers failed during critical flight operations. Backup wind measurements from the R.M. Young instruments are not reported in the official records.

Dewpoint Temperature

The new systems measure dewpoint temperature with a Vaisala HMP155 RH sensor. This instrument detects a range of -60C to +60C. Although dewpoint temperatures regularly drop below -60C over the winter months at SPO and SUM, the GMD scientists agreed the dewpoint was not a critical measurement during the winter.

Temperature
All temperature measurements were changed to Logan Enterprises series 4150 resistance temperature detectors (RTD).

No changes were made to the barometric pressure (Setra 270) or the National Weather Service (NWS) standard tipping bucket precipitation gauge (only operational at MLO and SMO).

Table 2.1: Sensor deployment and changes made from 1 January 2014 through 31 December 2018.

Barrow Meteorology System				
	Legacy Zeno System Sensor (Prior to Jan 2014 - Sep 2017)		Upgraded CR1000 System (Sep 2017 - ongoing)	
Measurement	**Manufacturer**	**Model**	**Manufacturer**	**Model**
2m Pressure	Setra Systems, Inc. 270	270 pressure sensor	Setra Systems, Inc. 270	270 pressure sensor
2m Temperature	Logan Enterprises	4150 Series RTD	Logan Enterprises	4150 Series RTD
2m Dewpoint	Technical Services Laboratory	1088-400	Vaisala	HMP155
10m Temperature	Logan Enterprises	4150 Series RTD	Logan Enterprises	4150 Series RTD
10m Wind	R.M. Young Company	5103 anemometer	Lufft (OTT Hydromet)	Ventus UMB
16m Temperature	Logan Enterprises	4150 Series RTD	Logan Enterprises	4150 Series RTD
16m Wind	R.M. Young Company	5103 anemometer	Lufft (OTT Hydromet)	Ventus UMB

Trinidad Head Meteorology System				
	Legacy Zeno System Sensor (Prior to Jan 2014 - Jun 2017)			
Measurement	**Manufacturer**	**Model**		
2m Pressure	Setra Systems, Inc 270	270 pressure sensor		
2m Temperature	Logan Enterprises	4150 Series RTD		
2m Dewpoint	R.M. Young Company	41382		
10m Temperature	Logan Enterprises	4150 Series RTD		
10m Wind	R.M. Young Company	5103 anemometer		
16m Wind	R.M. Young Company	5103 anemometer		

Summit Meteorology System				
	Legacy Zeno System Sensor (Prior to Jan 2014 - Jul 2016)		Upgraded CR1000 System (Jul 2016 - Dec 2016 on Swiss Tower, Aug 2017 - ongoing on TAWO Tower)	
Measurement	**Manufacturer**	**Model**	**Manufacturer**	**Model**
2m Pressure	Setra Systems, Inc 270	270 pressure sensor	Setra Systems, Inc 270	270 pressure sensor
2m Temperature	Logan Enterprises	4150 Series RTD	Logan Enterprises	4150 Series RTD
2m Dewpoint	Vaisala	HMP45DU	Vaisala	HMP155
10m Temperature	Vaisala	HMP45A	Logan Enterprises	4150 Series RTD
10m Wind	R.M. Young Company	5103 anemometer	R.M. Young Company	5103 anemometer
16m Wind	R.M. Young Company	5103 anemometer	R.M. Young Company	5103 anemometer
16m Wind	R.M. Young Company	5103 anemometer	Lufft (OTT Hydromet)	Ventus UMB

Mauna Loa Meteorology System				
	Legacy Zeno System Sensor (Prior to Jan 2014 - Jun 2018)		Upgraded CR1000 System (Jun 2018 - ongoing)	
Measurement	**Manufacturer**	**Model**	**Manufacturer**	**Model**
2m Pressure	Setra Systems, Inc 270	270 pressure sensor	Setra Systems, Inc 270	270 pressure sensor
2m Temperature	Logan Enterprises	4150 Series RTD	Logan Enterprises	4150 Series RTD
2m Dewpoint	Technical Services Laboratory	1088-400	Vaisala	HMP155
10m Temperature	Logan Enterprises	4150 Series RTD	Logan Enterprises	4150 Series RTD
10m Wind	R.M. Young Company	5103 anemometer	Lufft (OTT Hydromet)	Ventus UMB
38m Temperature	Logan Enterprises	4150 Series RTD	Logan Enterprises	4150 Series RTD
38m Wind	R.M. Young Company	5103 anemometer	Lufft (OTT Hydromet)	Ventus UMB

American Samoa Meteorology System				
	Legacy Zeno System Sensor (Prior to Jan 2014 - Jan 2018)		Upgraded CR1000 System (Jan 2018 - ongoing)	
Measurement	**Manufacturer**	**Model**	**Manufacturer**	**Model**
2m Pressure	Setra Systems, Inc. 270	270 pressure sensor	Setra Systems, Inc. 270	270 pressure sensor
2m Temperature	Logan Enterprises	4150 Series RTD	Logan Enterprises	4150 Series RTD
2m Dewpoint	Vaisala	HMP60	Vaisala	HMP155
17m Temperature	Logan Enterprises	4150 Series RTD	Logan Enterprises	4150 Series RTD
17m Wind	R.M. Young Company	5103	Lufft (OTT Hydromet)	Ventus UMB
Precipitation	NWS Standard	Tipping Bucket	NWS Standard	Tipping Bucket
38m Wind	R.M. Young Company	5103 anemometer	Lufft (OTT Hydromet)	Ventus UMB

South Pole Meteorology System				
	Legacy Zeno System Sensor (Prior to Jan 2014 - Jan 2018)		Upgraded CR1000 System (Jan 2018 - ongoing)	
Measurement	**Manufacturer**	**Model**	**Manufacturer**	**Model**
2m Pressure	Setra Systems, Inc	270 pressure sensor	Setra Systems, Inc 270	270 pressure sensor
2m Temperature	Logan Enterprises	4150 Series RTD	Logan Enterprises	4150 Series RTD
2m Dewpoint	Technical Services Laboratory	1088-400	Vaisala	HMP155
2m Wind	R.M. Young Company	5103 anemometer	Lufft (OTT Hydromet)	Ventus UMB
10m Temperature	Logan Enterprises	4150 Series RTD	Logan Enterprises	4150 Series RTD
10m Wind	R.M. Young Company	5103 anemometer	Lufft (OTT Hydromet)	Ventus UMB
30m Temperature	Logan Enterprises	4150 Series RTD	Logan Enterprises	4150 Series RTD

OBSERVATORY UPDATES

Barrow

The BRW Met system was upgraded in July 2017. The old system was left online and operational for instrument overlap until 24 September 2017. The Setra pressure sensor was installed inside the Observatory building to prevent it from being impacted by temperature swings, but the instrument enclosure was mounted to the tower.

Summit

Summit Station was the first ABO to be upgraded to the new CR1000 system with Lufft Ventus sonic anemometers. The new system was installed during the 2016 summer season on the Swiss tower. The system performed well until the tower suffered a catastrophic failure on 27 December 2016. The top half of the tower fell over during a severe winter storm with high winds. All power to the tower was lost, and for safety reasons, no technicians were allowed to climb the remaining lower section of the tower.
The new system was re-installed in August 2017 on a new tower constructed at the Temporary Atmospheric Watch Observatory (TAWO), upwind of the main station. During the same season, the site was downgraded from a full ABO to a GMD sampling site. Only the mandatory level instruments were installed: 2m dewpoint, 2m temperature, 2m pressure, and 10m wind. The system supported remaining GMD instruments, regular station science, and flight operations.

Trinidad Head

The Trinidad Head ABO was decommissioned in June 2017. The meteorology instrument suite ceased operation and was completely removed on 5 June 2017.

Mauna Loa

The MLO Met system was upgraded in January 2018. The Vaisala HMP155 dewpoint sensor took several months of troubleshooting to work properly. The new system was officially commissioned on 15 June 2018.

American Samoa

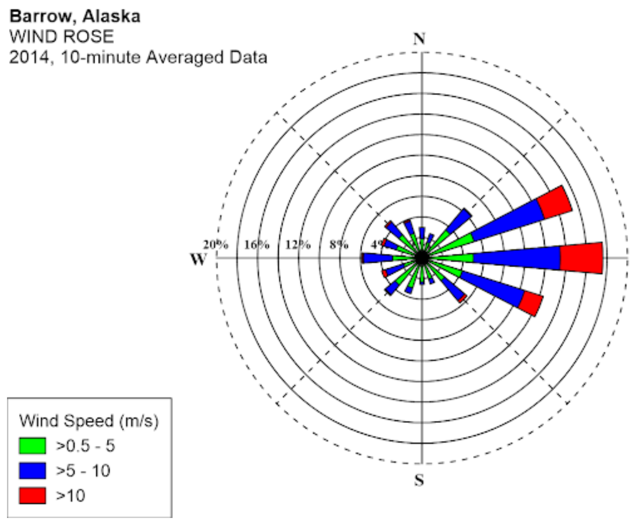
The upgraded meteorology system was installed on the new BlueSky cell tower outside the Hudson Building in January 2018. The previous tower was severely degraded and corroded due to age and salt spray, and was unsafe to climb. BlueSky, which leases the space in front of the Hudson Building, refurbished the bottom 1/3 of the tower, and replaced the corroded top • of the tower.
The Lufft Ventus sonic anemometer and tower RTD are mounted on the lower catwalk of the BlueSky tower. The top catwalk is occupied by BlueSky antennae. The 2m instruments (Vaisala HMP155, RTD, tipping bucket rain gauge) are located south of the Hudson Building. The instrument enclosure housing the Setra pressure sensor and data logger was moved from an old DOE sampling box outside and mounted on an interior wall of the Hudson Building.

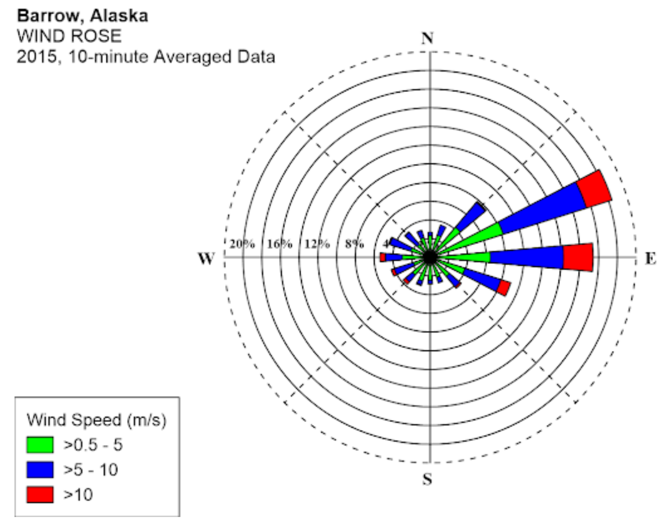
South Pole

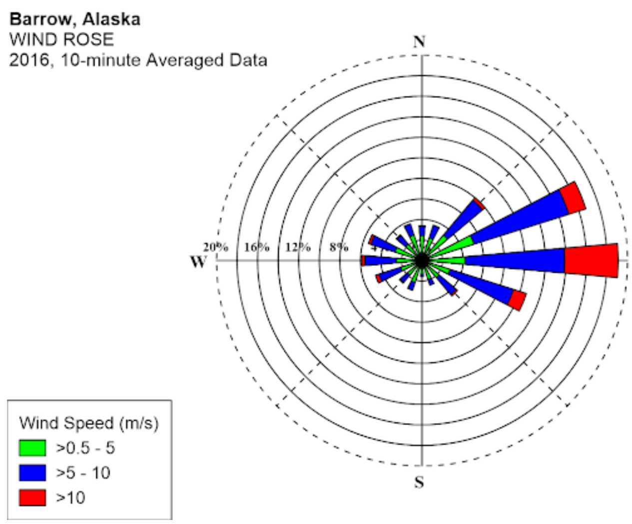
The SPO meteorology suite was upgraded during the 2016-2017 summer field season. A full set of instruments was installed and run in parallel with the Zeno system for one year. During winter 2017, minor tweaks were made to the system so it would run and collect data more efficiently. The operation of the Lufft Ventus sonic anemometers were also closely observed, since temperatures at South Pole were much colder than the test environment at Summit Station.
In the 2017-2018 summer, the sonic anemometer cables were swapped out from Lufft cables to separate power and data cables that have more flex in the cold. Additional power supplies for the sonic anemometers were added to the 10m and tower top levels to provide power closer to the instruments.

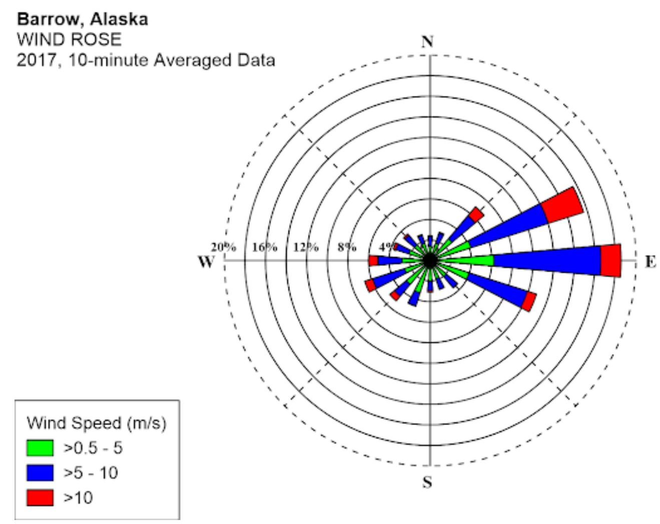
This allowed the instruments to receive enough power to run the internal heaters and continue operating in cold temperatures. With these repairs complete, the new system was finally commissioned on 1 January 2018.

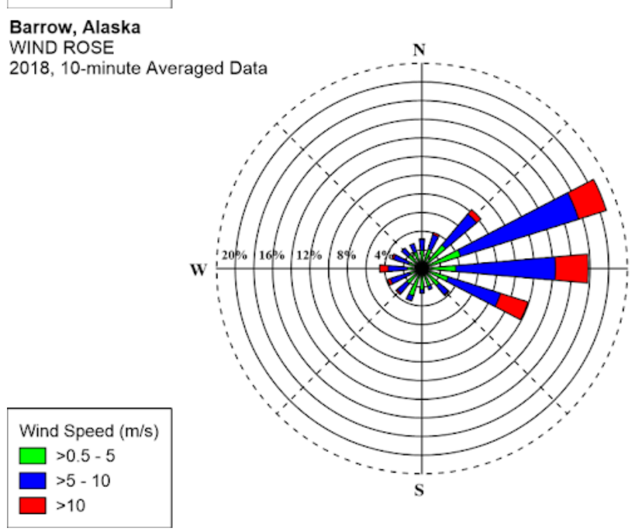
Observatory Annual Wind Roses

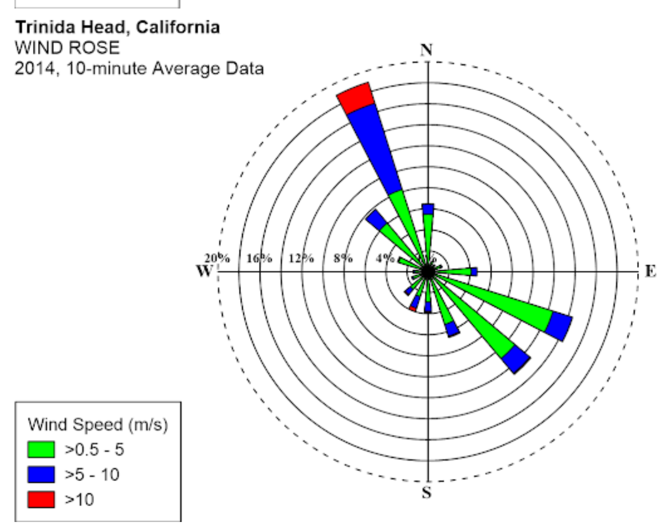


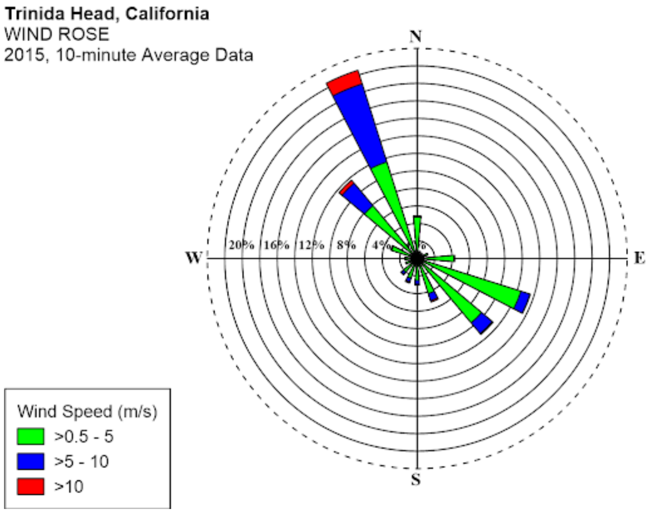








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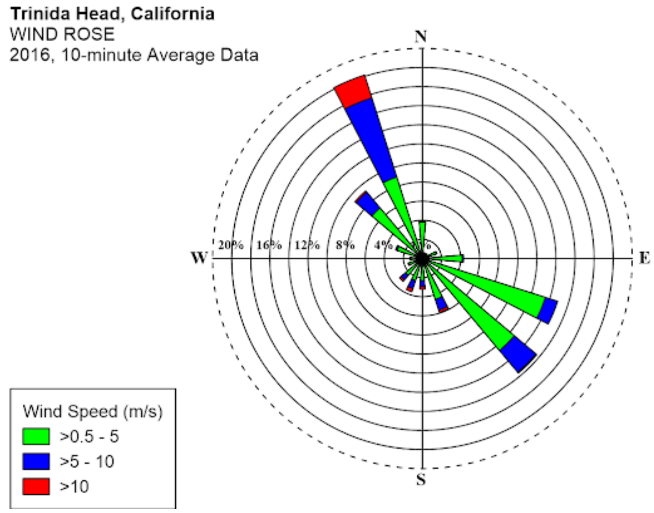
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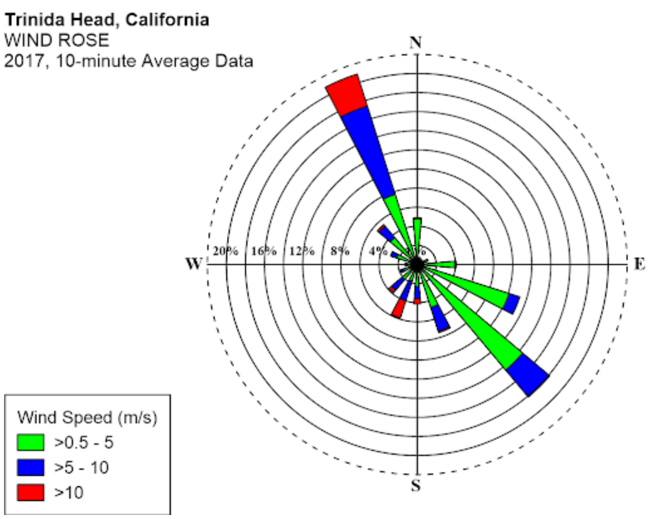
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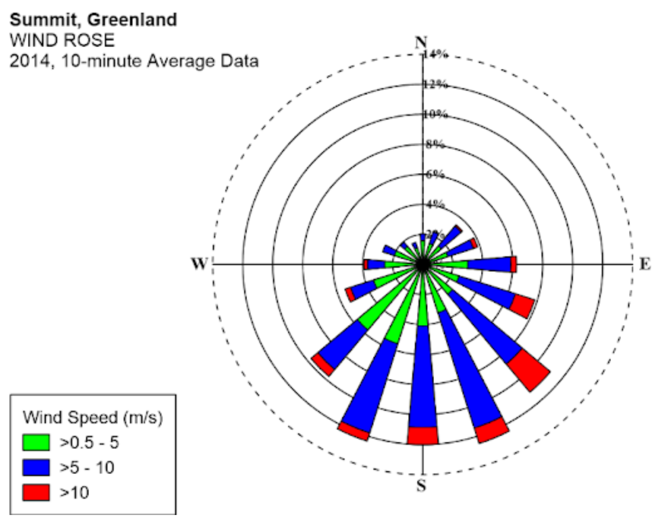
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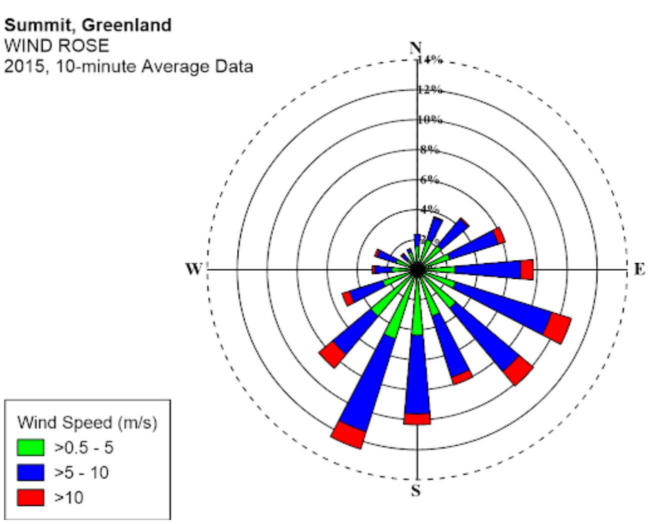
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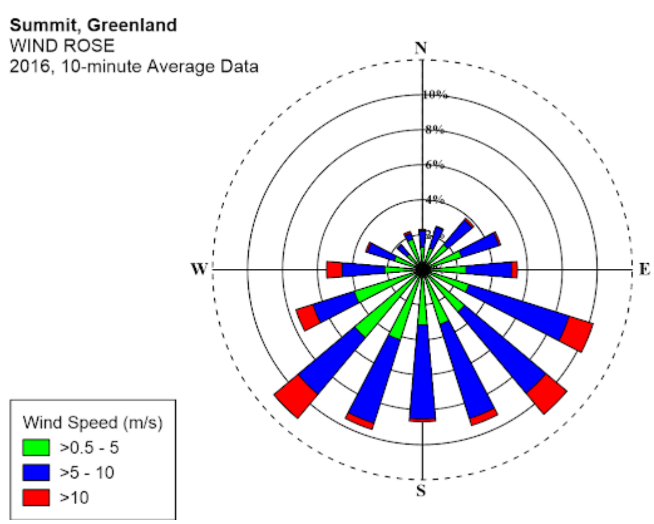
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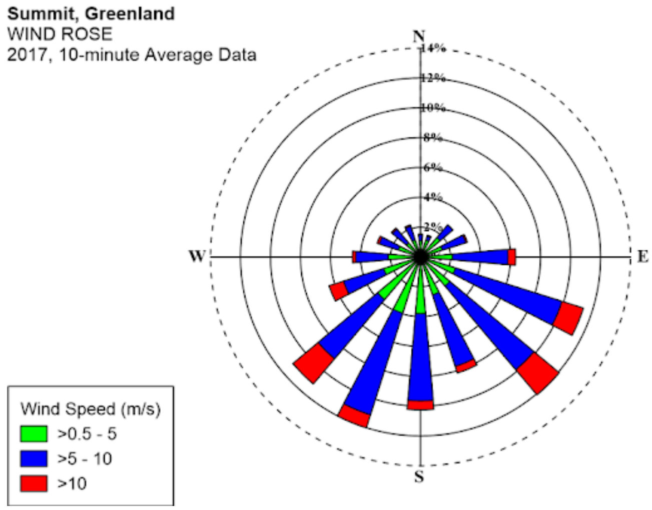
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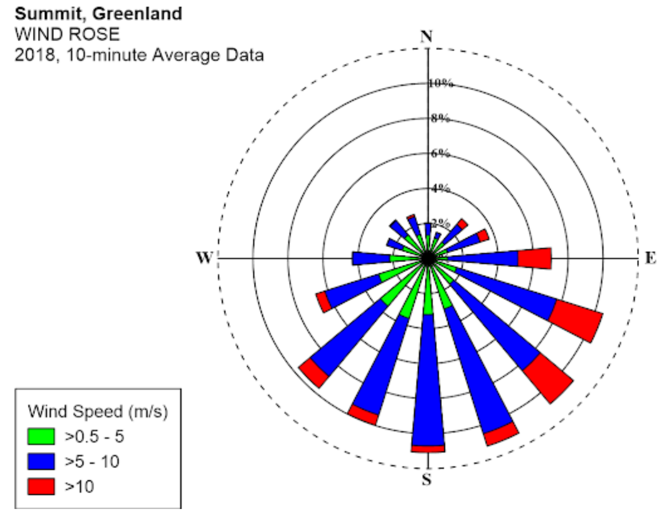
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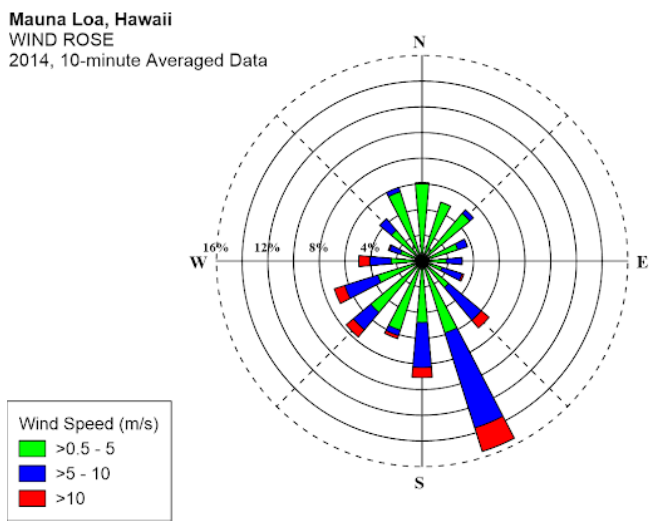
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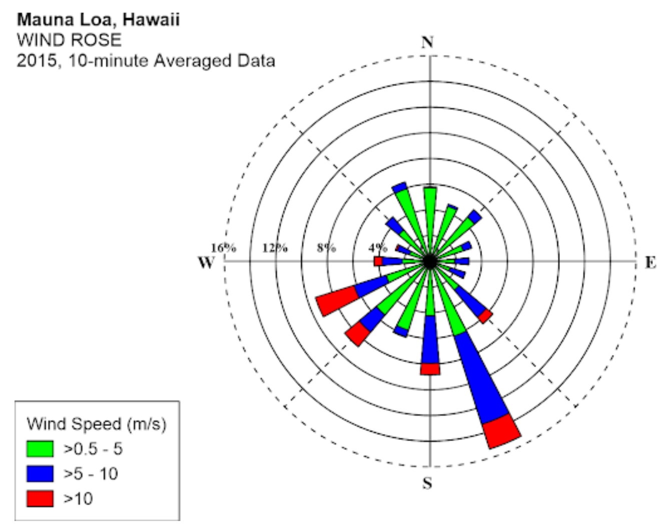
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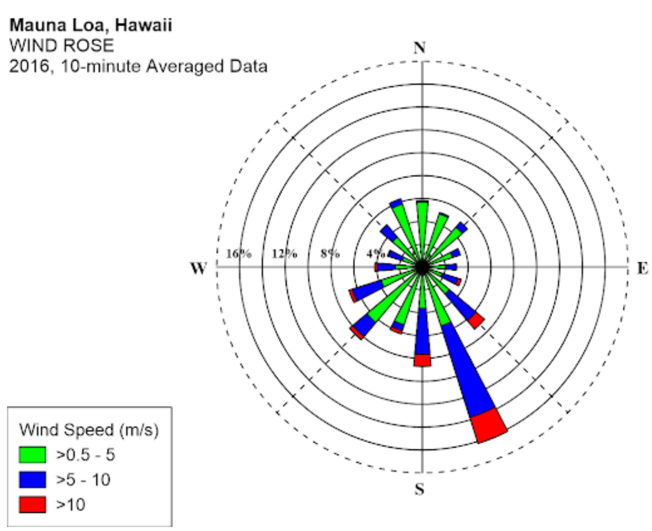
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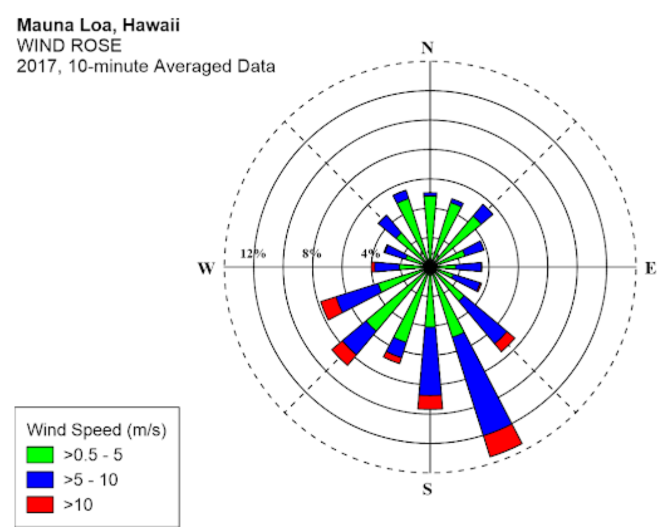
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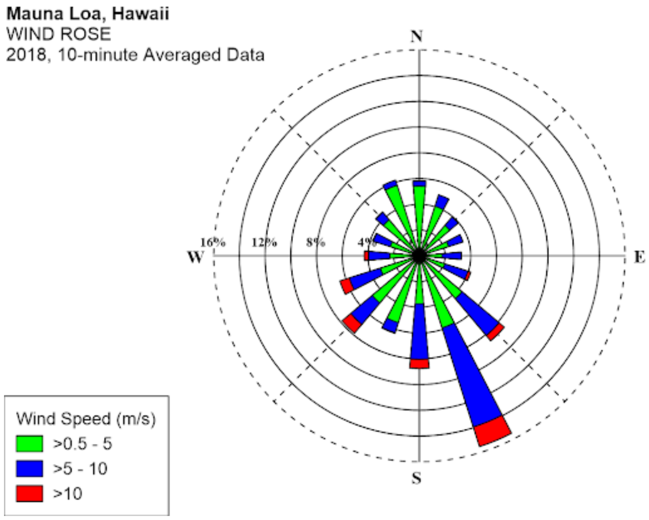
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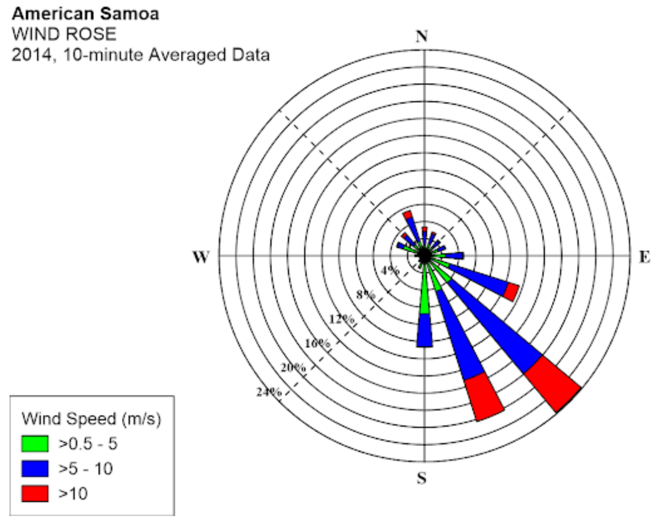
American Samoa
WIND ROSE
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12%
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24%
Wind Speed (m/s)
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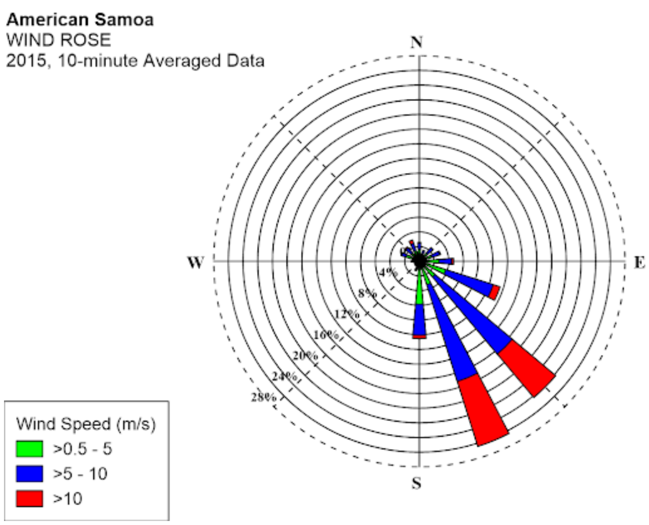
American Samoa
WIND ROSE
2015, 10-minute Averaged Data
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E
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4%
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Wind Speed (m/s)
>0.5 - 5
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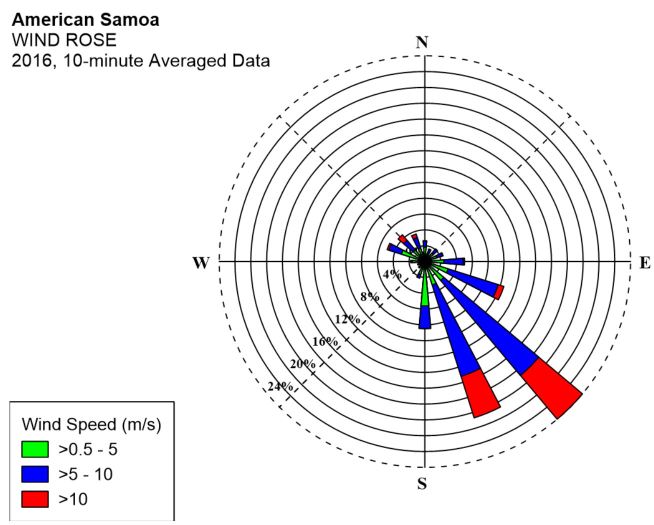
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WIND ROSE
2016, 10-minute Averaged Data
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Wind Speed (m/s)
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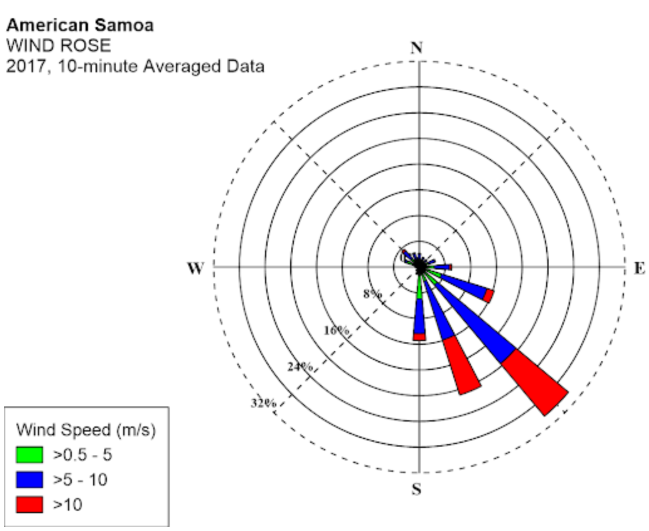
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WIND ROSE
2017, 10-minute Averaged Data
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Wind Speed (m/s)
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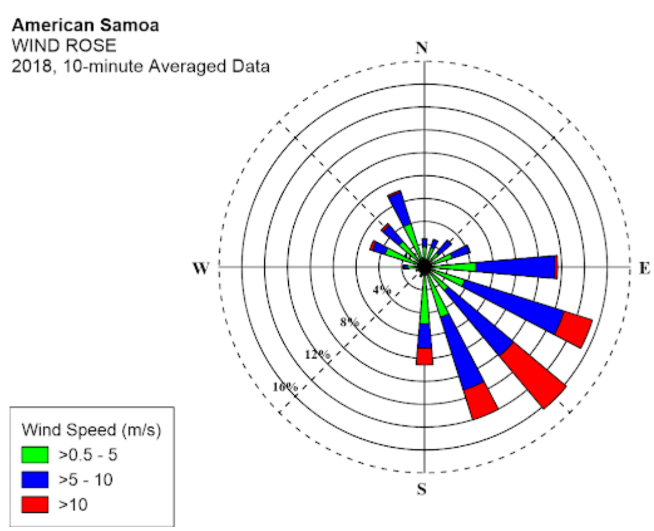
American Samoa
WIND ROSE
2018, 10-minute Averaged Data
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Wind Speed (m/s)
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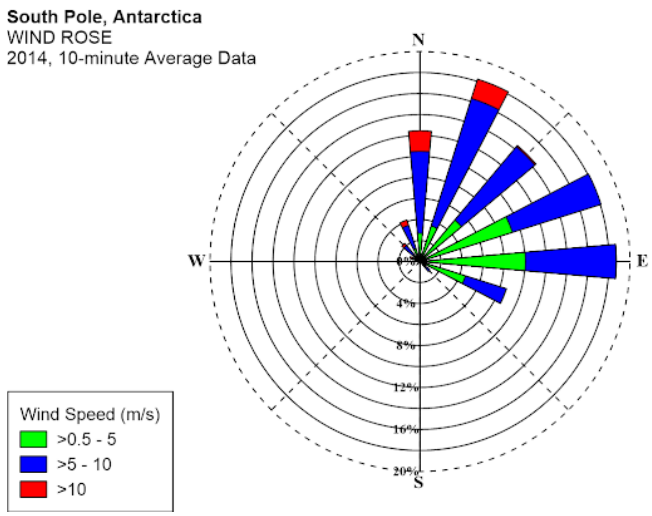
South Pole, Antarctica
WIND ROSE
2014, 10-minute Average Data
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Wind Speed (m/s)
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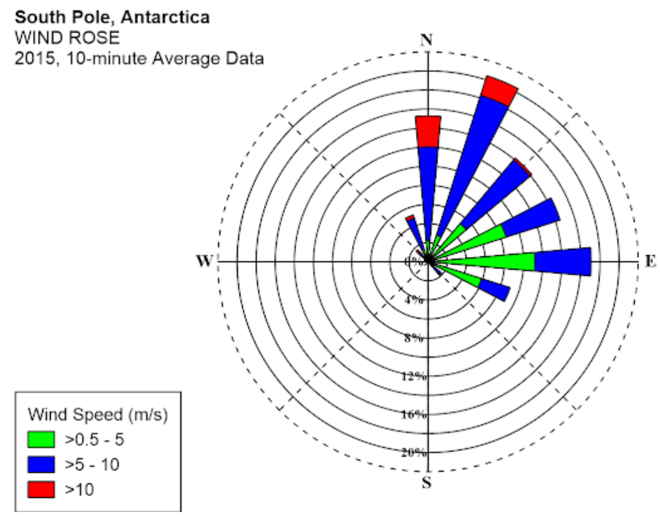
South Pole, Antarctica
WIND ROSE
2015, 10-minute Average Data
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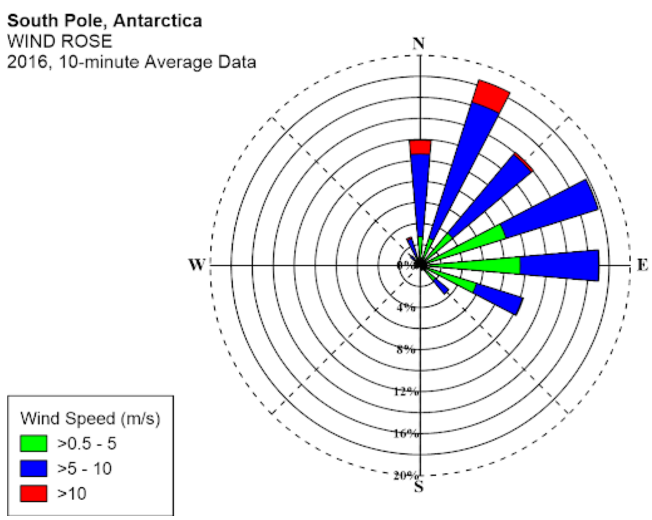
South Pole, Antarctica
WIND ROSE
2016, 10-minute Average Data
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Wind Speed (m/s)
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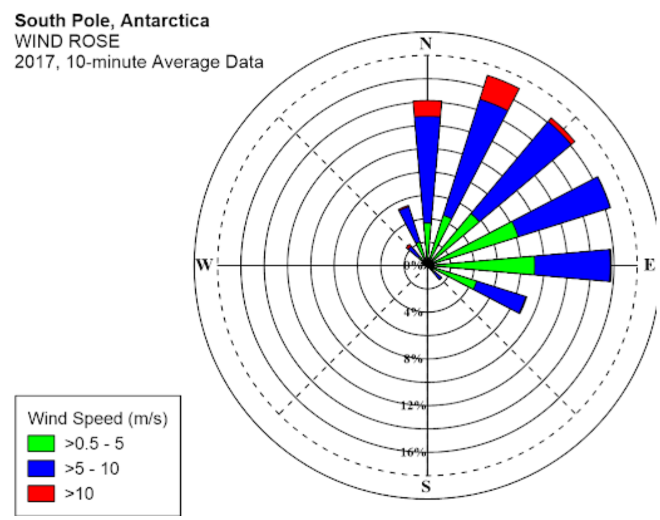
South Pole, Antarctica
WIND ROSE
2017, 10-minute Average Data
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Wind Speed (m/s)
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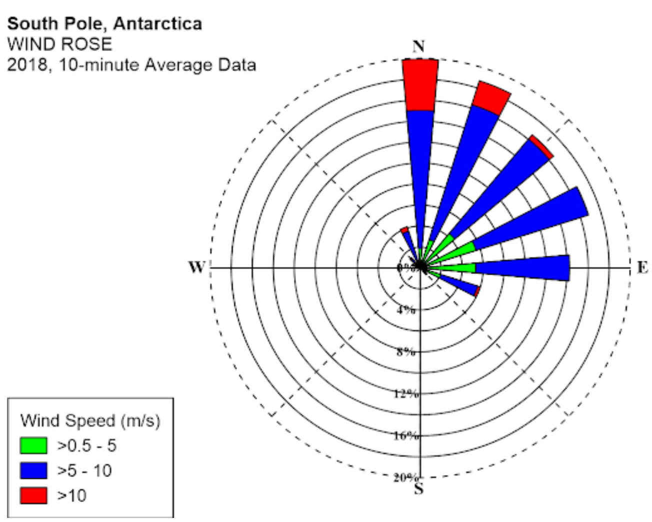
South Pole, Antarctica
WIND ROSE
2018, 10-minute Average Data
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Wind Speed (m/s)
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SECTION 3 – AEROSOLS (AERO) RESEARCH GROUP

RESEARCH OVERVIEW

The primary focus of the Aerosols Research Group is making the highest quality measurements of climate-relevant aerosol properties at locations worldwide. The predecessor organizations of GMD began making long-term measurements of surface aerosol properties at the four NOAA Atmospheric Baseline Observatories in the mid- 1970s. Since that time, scientific understanding of atmospheric aerosols has improved significantly. Aerosol particles were found to influence the radiation balance of the Earth, and substantial, although 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 so we could determine anthropogenic effects. In the early 1990s, NOAA realized 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. The 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 understand the factors that control these properties. To accomplish these goals, the GMD Aerosols Group makes collaborative measurements of aerosol properties at stations worldwide. 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, micro-physical, and hygroscopic property measurements, are made at some of these sites to better understand the optical properties and their radiative effects. For more information on GMD aerosol measurements, please visit https://gml.noaa.gov/grad/.

This report documents changes in inlet systems, operations, instruments, and the local station environments 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 THE NOAA FEDERATED AEROSOL NETWORK

THE EARLY NETWORK (1974-2003)

Aerosol measurements at the four original NOAA Atmospheric Baseline Observatories began in the mid-1970s. With the shift in focus of the Aerosols Program in the early 1990s, more monitoring stations in different parts of the world were necessary. Our goal was to accomplish this network expansion without a significant increase in the operating budget.

The solution was to organize a federated network of scientific collaborators (https://doi.org/10.1175/BAMS-D-17-0175.1) to operate regional aerosol monitoring stations using the same methods as the NOAA stations. The GMD Aerosols Program identified partners with a 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 significant. NOAA receives access to the data from collaborator stations yet does not support the major long-term costs of the stations. These costs include the purchase and maintenance of the key instrument systems, salaries for station personnel, long-term station operation costs (e.g., facility costs, site access, 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 and atmospheric measurements that are directly comparable with the other stations in the network and follow established aerosol sampling protocols (i.e., NOAA and GAW).

Table 3-1 shows the NOAA Federated Aerosol Network (NFAN) stations that were in operation at the beginning of 2014 (the start of operations reporting in this Summary Report), listed chronologically by the start date of the aerosol measurements. Through the early 1990s, the only stations in the NOAA network were the four Atmospheric Baseline Observatories. The period from the early 1990s to the early 2000s saw moderate network growth primarily through the addition of regional aerosol monitoring stations.

Sable Island, Nova Scotia (WSA), was the first GMD 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 with the University of Illinois and the Department of Energy’s Atmospheric Radiation Measurement (ARM) Program, respectively, although the BND regional aerosol monitoring station is now funded and operated solely by NOAA. In 2002, the fifth NOAA Atmospheric Baseline Observatory at Trinidad Head, California (THD) began operations.

GROWTH INTO A GLOBAL NETWORK (2004–2013)

During the period 2003–2013, the NFAN experienced rapid growth into a truly global network. The sizable growth was mainly through partnerships with scientific organizations and universities around the world. The added monitoring stations greatly improve NOAA’s ability to determine aerosol radiative forcing and its effects on regional and global climate. This growth was documented in detail in the Global Monitoring Division Summary Report #28 (2004-2013). Therefore, only a brief recap is presented here.

In 2004, the GAW Global station at Alert, Canada (ALT) joined the NOAA network. Later that year, GMD scientists helped establish the GAW Regional station at Cape San Juan, Puerto Rico, and incorporate it into the federated network. In 2005, the GAW Global stations at Mount Waliguan, China (WLG) and Cape Point, South Africa (CPT) became network members. By the end of 2013, another 13 stations in 8 countries joined the NFAN. During this growth period, shorter deployments of the ARM Mobile Facility (AMF) were also occurring. The typical AMF deployment was about a year in a given location, although these ranged from about 6-24 months. The AMF aerosol systems were managed by GMD scientists and used NOAA software, and they were operated as short-term NFAN stations in collaboration with the U.S. Department of Energy (DOE).

Table 3-1: NOAA Federated Aerosol Network (NFAN) stations at the beginning of 2014.

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	July 2017
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	September 2017
THD	Trinidad Head	USA	April 2002	June 2017
ALT	Alert	Canada	March 2004	Present
CPR	Cape San Juan	Puerto Rico	November 2004	Present
PYE	Point Reyes (AMF)	USA	March 2005	September 2005
WLG	Waliguan	China	August 2005	Present
CPT	Cape Point	South Africa	November 2005	Present
NIM	Niamey (AMF)	Niger	December 2005	December 2006
KPS	K'puszta	Hungary	May 2006	Present
FKB	Hesselbach (AMF)	Germany	March 2007	December 2007
HFE	Shouxian (AMF)	China	May 2008	December 2008
ETL	East Trout Lake	Canada	September 2008	Present
WHI	Whistler	Canada	September 2008	Present
LLN	Lulin	Taiwan	October 2008	Present
ARN	El Arenosillo	Spain	February 2009	Present
GRW	Graciosa (AMF)	Azores	April 2009	December 2010
APP	Appalachian State	USA	June 2009	Present
BEO	Moussala	Bulgaria	October 2009	Present
EGB	Egbert	Canada	November 2009	Present
AMY	Anmyeon-do	Korea	December 2009	Present
SPL	Storm Peak	USA	January 2011	Present
SUM	Summit	Greenland	May 2011	Present
PGH	Nainital (AMF)	India	June 2011	March 2012
GSN	Gosan	Korea	October 2011	Present
PVC	Cape Cod (AMF)	USA	July 2012	June 2013
UGR	University of Granada	Spain	January 2013	Present
RSL	Resolute	Canada	May 2013	June 2017
MAN	Manacapuro (AMF)	Brazil	December 2013	December 2015

NETWORK EXPANSION OVER THE LAST FIVE YEARS (2014–2018)

While the period 2014-2018 saw an overall expansion of the NFAN, several stations were closed during this time. Decisions were made to cease aerosol operations in 2017 at two of the NOAA Atmospheric Baseline Observatories (at American Samoa (SMO) and Trinidad Head (THD)) for scientific, logistical, and financial reasons. Additionally, GMD's involvement with the mentorship of the long-term collaborative station at Lamont, OK (DOE/ARM Southern Great Plains Central Facility (SGP)) was terminated in 2017.

Figure 3-1 shows the number of stations in the network by year through the end of 2018. For a station to be counted, it had to be in operation during a part of the indicated year. For example, if a station measured in part of a year before closing, it was counted in that year (e.g., THD and SGP are counted in 2017 since they closed in June and September of 2017, respectively).

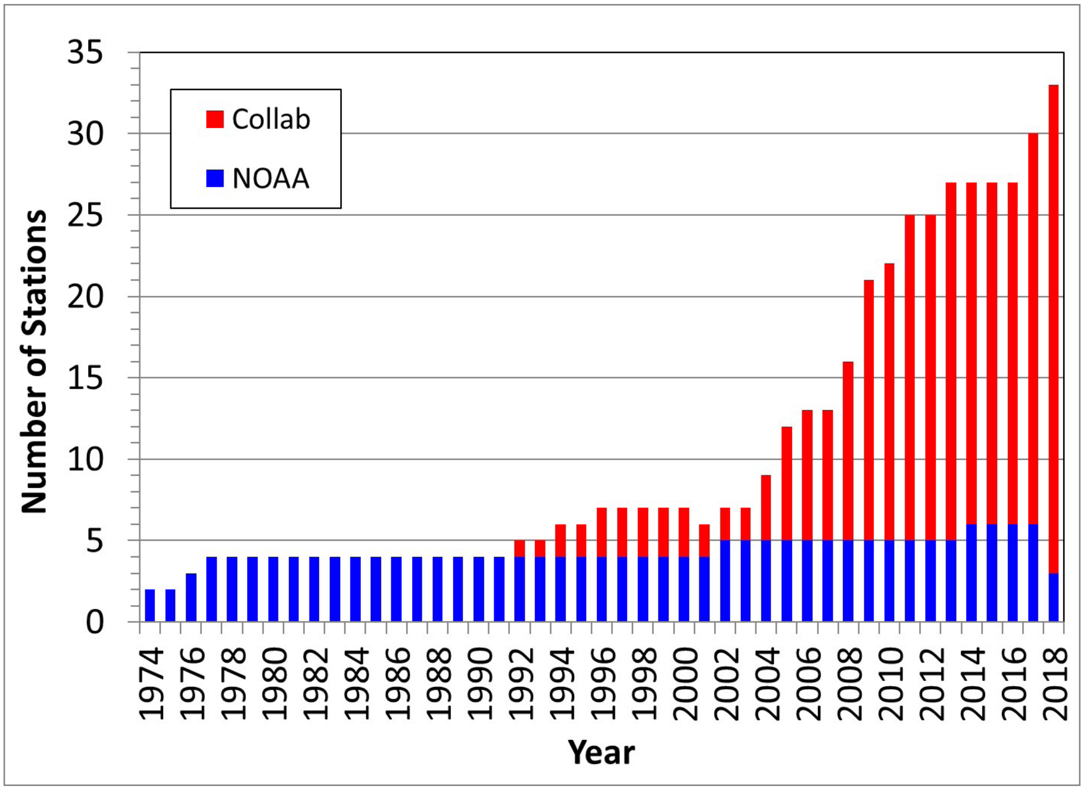

Figure 3.1: Number of stations by year in the NOAA Federated Aerosol Network.

Table 3-2 shows the stations joining the NOAA Federated Aerosol Network during the last five-year Summary Report period. Of these 12 sites, 11 are long-term monitoring stations and are in operation today. Changes in priorities of the Korea Meteorological Administration (KMA) led to the shutdown of the Anmyeon-do (AMY) network station in 2015, and the instruments were moved to the roof of the KMA building in Seoul. The measurements of the Seoul (SEL) station began in October 2015. Measurements continued there for less than a year, at which time the decision was made to discontinue operations at the SEL site there. The instruments were returned to the original site at Anmyeon-do, and measurements were resumed there in 2018. To avoid double-counting the station, only one station (SEL) was counted in 2016 in Figure 3-1.

Continuous aerosol measurements commenced at the NOAA Atmospheric Baseline Observatory at Summit, Greenland (SUM) in 2011, as a 3-year NSF-funded collaboration with the Georgia Institute of Technology. After that funding ended, GMD took over the operations of the aerosol system in 2014. As a result, the SUM station was de-commissioned as an NOAA Atmospheric Baseline Observatory in 2017. Still, the measurements continue today into collaboratione with the National Science Foundation, which manages the SUM site and provides logistical and technician support.

Table 3-2: Stations joining the NFAN during the 5-year period 2014-2018.

Station ID	Station Name	Country	Start Date	End Date
SEL	Seoul	Korea	October 2015	June 2016
SNS	Sierra Nevada Station	Spain	May 2016	Present
CGO	Cape Grim	Australia	January 2017	Present
MSA	Montsec	Spain	January 2017	Present
MSY	Montseny	Spain	January 2017	Present
SMR	Hyytiala	Finland	January 2018	Present
MBO	Mount Bachelor	USA	April 2018	Present
ZEP	Zeppelin	Norway	April 2018	Present
ZSF	Zugspitze	Germany	May 2018	Present
HAC	Mount Helmos	Greece	July 2018	Present
PON	Pond Inlet	Canada	July 2018	Present
VAR	Varrio	Finland	August 2018	Present

3.2 MEASUREMENTS

As shown in Figure 3-2, the NOAA Federated Aerosol Network had a total of 33 surface aerosol-monitoring stations in operation at the end of 2018. Of these stations, three were operated entirely by NOAA (the NOAA Atmospheric Baseline Observatories, blue stars) and 30 by collaborators with NOAA support (red stars).

In the following sections of this report, we discuss specific changes in aerosol operations over the 5-year period 2014-2018 at the NOAA-controlled stations. The discussion is limited to the NOAA stations because those are the stations where NOAA maintains complete control over all 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

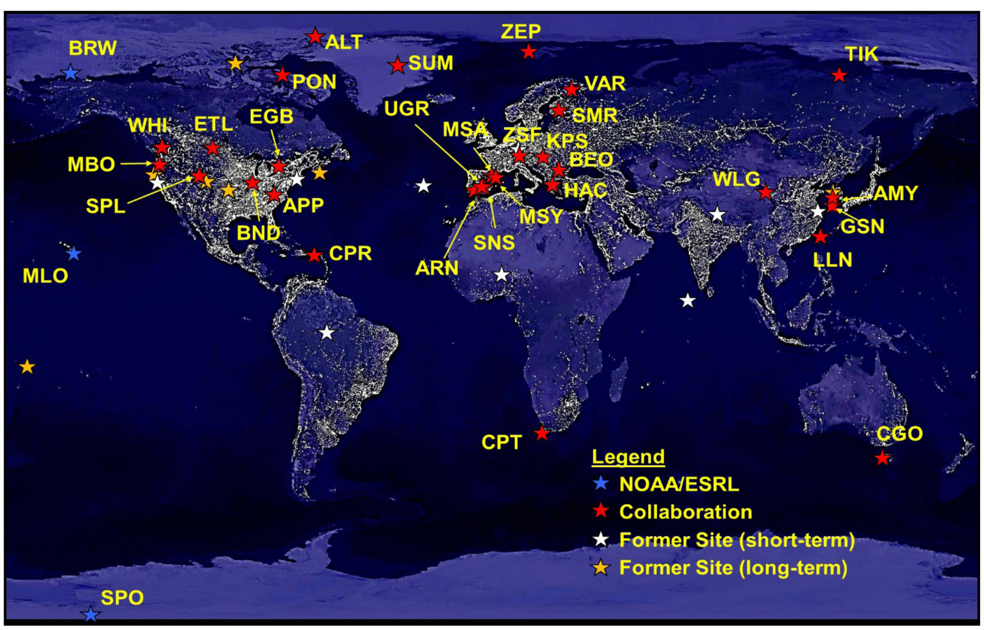

Figure 3.2: This map of the NOAA Federated Aerosol Network shows stations active in 2018 as well as former stations.

directly, whose contact information is available on the Global Monitoring Division web page at http://www.esrl.noaa.gov/gmd/aero/net/index.html.

While the Global Monitoring Division currently operates aerosol-monitoring systems at three Atmospheric Baseline Observatories (BRW, MLO, and SPO), during the Report period, it also made aerosol measurements at the current Atmospheric Baseline Observatory at SMO and the closed Observatories at THD and SUM (SUM is still operating but as a Ccollaborator Sstation). It was also directly responsible for the aerosol measurements at the Collaborator Station at Bondville, IL (BND). The start and end dates of specific aerosol measurements at these seven NOAA-controlled NFAN stations are listed in Table 3-3. 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

Table 3.3: Aerosol measurements made at the seven NOAA-operated Federated Aerosol Network stations over the 2014-2018 period.

Station ID	*Aerosol Measurement*	*Start Date*	*End Date*
MLO	*Total particle number concentration*	*January 2014*	*December 2018*
	Aerosol light scattering coefficient	*January 2014*	*December 2018*
	Aerosol hemispheric backscattering coefficient	*January 2014*	*December 2018*
	Aerosol light absorption coefficient	*January 2014*	*December 2018*
SPO	*Total particle number concentration*	*January 2014*	*December 2018*
	Aerosol light scattering coefficient	*January 2014*	*December 2018*
	Aerosol hemispheric backscattering coefficient	*January 2014*	*December 2018*
	Aerosol light absorption coefficient	*December 2017*	*December 2018*
BRW	*Total particle number concentration*	*January 2014*	*December 2018*
	Aerosol light scattering coefficient	*January 2014*	*December 2018*
	Aerosol hemispheric backscattering coefficient	*January 2014*	*December 2018*
	Aerosol light absorption coefficient	*January 2014*	*December 2018*
	Aerosol size distribution	*August 2014*	*December 2018*
SMO	*Total particle number concentration*	*January 2014*	*July 2017*
THD	*Total particle number concentration*	*January 2014*	*June 2017*
	Aerosol light scattering coefficient	*January 2014*	*June 2017*
	Aerosol hemispheric backscattering coefficient	*January 2014*	*June 2017*
	Aerosol light absorption coefficient	*January 2014*	*June 2017*

Table 3.3: Aerosol measurements made at the seven NOAA-operated Federated Aerosol Network stations over the 2014-2018 period (continued)

SUM	*Aerosol light scattering coefficient*	*January 2014*	*December 2018*
	Aerosol hemispheric backscattering coefficient	*January 2014*	*December 2018*
	Aerosol light absorption coefficient	*January 2014*	*December 2018*
BND	*Total particle number concentration*	*January 2014*	*December 2018*
	Aerosol light scattering coefficient	*January 2014*	*December 2018*
	Aerosol hemispheric backscattering coefficient	*January 2014*	*December 2018*
	Aerosol light absorption coefficient	*January 2014*	*December 2018*

changes to replace aging equipment, accommodate additional system components, or simply improve our sampling methods. Many of the Network-wide changes in our NFAN sampling methods, including the downward adjustment of the flow rates of our PSAP light absorption instruments, the change to larger rain caps on our sampling stacks, the use of dedicated higher-flow lines for our particle number concentration measurements, etc., were made prior to 2014 and thus are documented in detail in GMD Summary Report #28. No Network-wide changes in sampling strategies or inlet designs have occurred since 2014. Table 3-4 shows a listing of all site-specific inlet and/or sampling changes at the NOAA-controlled stations over the five-year period encompassing 2014-2018 and the known effect(s) (if any) of the changes on the measurements. Most of the inlet and flow rate changes did not have noticeable effects on the aerosol data based on a 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. For details as to why specific changes were necessary or performed, contact the GMD Global Radiation and Aerosols Group. Providing approximate 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.

BEGINNING AND END OF SPECIFIC MEASUREMENTS

Table 3-5 shows when specific measurements were added or removed from the aerosol systems at the NOAA-controlled 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 particle counter 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 nearly 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 acronyms used in this section and in Table 3-5 are as listed below.

- CPC – condensation particle counter
- MCPC – mixing condensation particle counter
- 1W-PSAP – single wavelength Particle Soot Absorption Photometer
- 3W-PSAP – three-wavelength Particle Soot Absorption Photometer
- CLAP – Continuous Light Absorption Photometer
- AE16 – 1 wavelength Aethalometer
- AE31 – 7 wavelength Aethalometer

- AE33 – 7 wavelength Aethalometer
- SMPS – Scanning Mobility Particle Spectrometer

The last PSAP instrument was removed from service at BRW in 2014. Light absorption measurements are currently being made in NOAA stations using the NOAA Continuous Light Absorption Photometers (CLAPs) and/or the Magee Scientific Aethalometers (AE33). CLAPs have also been deployed to many

Table 3.4: List of all inlet and/or sampling changes at the NOAA-controlled stations over the five- year period from 2014-2018, 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	New sampling stack, inlet and rain cap	6 May 2015	Lessened rain penetration into sampling stack
SPO	No changes	Not applicable	None
BRW	No Changes	Not applicable	None
SMO	Station closed	4 October 2017	End of time series
THD	Insulating jacket on nephelometer (Installed 7 December 2012)	7 December 2012	Lowered neph sample R.H., may have impacted (lowered) scattering after start of 2014
	Station closed	1 June 2017	End of time series
SUM	Moved AE31 to sample on 2.5um inlet with neph and clap	16 August 2015	No obvious effect
	Moved aerosol instruments to north side of building and moved inlet to tower on building	9 July 2016	No obvious effect
BND	New building and inlet	30 October 2017	No obvious effect

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	Installed AE33	24-Oct-14
	Remove AE-31	15-Sep-17
SPO	Removed AE31	6-Jul-17
	Installed CLAP	8-Dec-17
	Removed MCPC	3-Aug-18
BRW	Installed AE33	15-Aug-14
	Removed 3W-PSAP	21-Aug-14
SMO	None	Closed 4 October 2017
THD	None	Closed 1 June 2017
SUM	Removed 1W-PSAP	16-Aug-15
	Removed AE16	7-Jul-16
	Installed AE33	30-Oct-14
	Removed AE33	10-Jan-18
BND	Removed MCPC	27-Dec-17

of the new NFAN collaborator stations. The MCPC instruments at the NOAA-controlled stations have been phased out over this period as they were difficult to keep running. 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. Note that the light absorption measurements from the various instruments 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.

3.3 CHANGES IN THE LOCAL STATION ENVIRONMENT

Of the seven NOAA-controlled and operated stations discussed in the Aerosols section of this Summary Report, six are (or were, during the 2014-2018 reporting window) NOAA Atmospheric Baseline Observatories. Changes in these local station environments (e.g., new roads, buildings, increased activity, etc.) that could conceivably have affected measurements are documented in the Observatory Operations section (Section 2) of this document. The one NOAA-controlled station that was never an NOAA Atmospheric Baseline Observatory is the Bondville, IL (BND) station. Major aerosol sources near the BND station include the agricultural fields in all directions, the I-72 highway to the north and west, and the I-57 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. There are now some housing developments and a medical center on the west side of I-57, which are several miles away but could, under some meteorological conditions, affect the aerosols sampled at the BND station.

3.4 SPECIAL PROJECTS

The GMD Aerosols Group participated in the 2013 Studies of Emissions and Atmospheric Composition Clouds and Climate Coupling by Regional Surveys (SEAC4RS) campaign (https://www.tandfonline.com/doi/full/10.1080/02786826.2018.1500012). While the mission occurred prior to this document's reporting period, data analysis continued through 2017. A portion of the field experiment was conducted aboard the NASA DC-8 aircraft and involved the sampling of biomass and agricultural burning plumes. In collaboration with the NOAA/ESRL Chemical Sciences Division (CSD), GMD's participation in SEAC4RS focused on the comparison of multiple in-situ methods for the determination of atmospheric aerosol light absorption coefficients.

Another ongoing effort for GMD aerosol scientists involves working with colleagues to develop and improve correction schemes for the various aerosol-monitoring instruments in use in the NFAN. During the period 2014-2018, GMD scientists participated in two large studies that used NFAN aerosol data to develop aethalometer corrections for different aerosol types. One of these focused on Arctic aerosols (https://www.atmos-meas-tech.net/10/5039/2017/), while the other used aerosol data from several NFAN (East Asian and Arctic) stations (https://www.tandfonline.com/doi/full/10.1080/02786826.2018.1555368). Both of these studies led to an improved understanding of aerosol type-specific corrections required for these instruments.

Another project the GMD Aerosols Group worked on during this period was to update the wind and aerosol climatologies at South Pole Station (SPO). Before this work, the last comprehensive published study of the SPO aerosol record occurred in 1995. This paper (http://www.aaqr.org/article/detail/AAQR-15-05-SIMtS-0358) included aerosol time series and various population distribution statistics and also assessed the frequency of wind blowing from the Clean Air Sector (CAS) at SPO. One important finding was that depending on the method used and averaging time, winds blowing from the CAS occurred at SPO 88-89% of the time, which is not consistent with the earlier (1980's and 1990's) findings of 95-98% of the time. It is not known whether the earlier data were in error or if the wind direction at SPO has actually shifted over time.

The GMD Aerosols Group also participated in the 2016 Fire Influence on Regional and Global Environments Experiment (FIREX). The FIREX campaign was conducted at the USDA Fire Sciences Laboratory in Missoula, Montana. The focus of this project was to measure gas and particle-phase emissions and the processing of burning biomass in a controlled chamber environment. Components of the FIREX project of particular interest to the GMD Aerosols Group included measuring the optical properties of fresh and progressively aged particles, the intercomparison of techniques for measuring Black Carbon (B.C.) and Brown Carbon (BrC) particles, and the photochemical processing of smoke emissions, especially in regards to SOA formation and BrC evolution. Aerosols group participation included the loan of instruments to measure the emissions and data logging and visualization software. FIREX data were processed by GMD, and GMD scientists contributed to the data analysis and scientific discussions.

3.5 AEROSOL GROUP TERMINATION

On October 1, 2018, following the recommendations of the 5-Year Global Monitoring Division External Review Panel, the Aerosol Group was formally terminated and merged with the GMD Global Radiation Group, creating the Global Radiation and Aerosols Group. This recommendation was made to benefit both groups through the sharing of resources, enhanced collaboration opportunities, and other benefits. This change does not have any significant effect on how the GMD aerosol measurement program is conducted. Long-term aerosol measurements in the Global Monitoring Division continue as before, and oversight of the NOAA Federated Aerosol Network endures through the Aerosol Program in the Global Radiation and Aerosols Group.

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

4.1 OVERVIEW AND HISTORY

HISTORY

The Geophysical Monitoring for Climatic Change laboratory, the forerunner of what is now the Global Monitoring Laboratory, made its first measurements of CO_2 in 1968 using air samples collected at Niwot Ridge, Colorado. In the next few years, the measurements expanded to the four baseline stations and several "background" air 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 create 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 Boulder) as well as CO and H_2. The observed spatial and temporal distribution of the 13C:12C ratio of CO_2 (expressed as $\delta_{13}C$) 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 the $\delta_{13}C$ of CH4 were added to the flasks. A large expansion of the network took place in the early 2000s, especially in North America as part of NOAA's contribution to the inter-agency North American Carbon Program. In situ CO_2 analyzers and automated discrete air samplers (Programmable Flask Packages, or PFPs) were installed on very tall communications towers and automated PFPs were also deployed aboard small private aircraft flying one or two times per month. The main purpose was to study the dynamics of the large CO_2 sink on the continents at mid-latitudes. The number of gaseous compounds analyzed in the flask-air samples increased enormously, with low-C hydrocarbons (with INSTAAR), CFCs and HCFCs (with the HATS group), and Carbon-14 of CO_2, also with INSTAAR.

To best understand and interpret our growing set of global and North American CO_2 measurements, we launched CarbonTracker (CT) in 2007. CT is a data assimilation/inverse modeling system that uses simulated atmospheric transport to relate spatial and temporal variations in observed atmospheric CO_2 to its surface (both oceanic and terrestrial) sources and sinks. CT produces maps of estimated surface fluxes along with estimated three-dimensional (3D) CO_2 mole fractions for the entire atmosphere. CarbonTracker is run from 2000 to within a year or so of the present. Updates to CT, which have typically been full "re-analyses" covering the entire period since 2000, occur roughly every year.

CARBON CYCLE AND GREENHOUSE GASES GROUP GOALS

The Carbon Cycle and Greenhouse Gases group (CCGG) has two main guiding research questions: How will oceanic and terrestrial carbon sources and sinks influence and respond to a changing climate? and 2) What are the anthropogenic inputs of CO_2, CH_4 and other Greenhouse Gases (GHGs) into the atmosphere? Our approach to answering these questions is to make the best possible GHG measurements and then analyze those measurements using models like CT as well as other tools.

There are three crucial features of our measurements. First, they are all frequently and very carefully calibrated. We maintain the World Meteorological Organization (WMO) calibration scales for the most important GHGs and distribute calibrated mixtures of CO_2 CH_4, N_2O, CO, and SF6 in dry natural air to GHG measurement laboratories throughout the world. This is the foundation for international quality control of measurements made under the umbrella of the WMO's Global Atmosphere Watch (GAW) program. However, calibration by itself is not enough for complete quality control. Errors, such as drying, can still occur during atmospheric sampling and sample handling. 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 other laboratories. Finally, efficient data and operations management enable quality control, efficient operation, and easy data availability. We strive to make as much data as possible, accompanied by quality control flags and documentation, freely available online. Additionally, data products such as GLOBALVIEW+, CO_2, and CH_4 trends web pages, CarbonTracker-inferred fluxes, 3D atmospheric CO_2 fields, and the Annual GHG Index (AGGI) are updated regularly and made publicly available.

Collectively, our GHG and isotope ratio measurements from the aircraft (discrete air samples), in situ, and Cooperative Global Air Sampling (discrete) programs form the Global Greenhouse Gas Reference Network (GGGRN), a name adopted in 2013. This name reflects both the global span of our measurements and the central role we play in calibrating measurements from laboratories throughout the world. In addition to the GGGRN, we measure atmospheric GHG concentrations (formally "mole fractions") and isotope ratios as part of numerous local- to global- scale field campaigns, lasting from a few days to a decade. Examples in the 2014-2018 period include the CARVE (Alaska) and ATom (up and down the Pacific and Atlantic Basins in multiple seasons) airborne campaigns, urban studies in Los Angeles and Indianapolis, and airborne campaigns in and around numerous oil- and gas- producing regions throughout the United States. Calibrated measurements using AirCore are also not part of the GGGRN but allow us to measure detailed vertical atmospheric profiles of CO_2 and CH4 in an effort to "ground-truth" remote-sensing measurements of atmospheric column CO_2 such as those from ground-based TCCON sites and the OCO-2 satellite. We also continue to engage in a long-standing measurement collaboration with Dr. Luciana Gatti of Brazil's National Institute for Space Research (INPE), focusing on vertical aircraft profiles of GHGs above the Amazon Basin.

As with campaigns, we also have modeling efforts apart from the routine CT. Such projects include specialized inverse modeling projects to estimate North American fluxes of CO_2 and other GHGs using a regionally focused approach (CT-Lagrange), and separate estimation of fossil fuel and biospheric fluxes of CO_2 over the United States using atmospheric CO_2 and Carbon-14 observations. For both routine (GGGRN and CT) and special modeling or measurement projects, our objective is to use the highest quality data and analysis tools to answer critical questions about the carbon cycle and greenhouse gas budgets, more generally.

4.2 CCGG MEASUREMENTS – THE GGGRN

IN SITU MEASUREMENTS

CCGG makes quasi-continuous in situ measurements of the dry air mole fraction of CO_2, CH4, and CO at GMD baseline observatories (four sites), and tall (> 100 m), and shorter tower sites (12 sites). CO_2 measurements are made at all sites except Cherskii, Rusia (CHS; CH_4 only), and at most of the tower sites, measurements are made at more than one vertical level. Tall and short tower measurements are generally in the continental U.S. and are meant to provide signals that are representative of regional-scale (~100 – 1000 km) processes, generally in the terrestrial biosphere, but these measurements can also be sensitive to urban and industrial activity. On the other hand, baseline observatory measurements are located in more remote regions and typically represent oceanic and terrestrial processes occurring on larger spatial scales. In all cases, the high frequency of in situ data provides important carbon cycle budget constraints when used in data analysis and inverse modeling such as CarbonTracker. Measurements of CO_2 and other gases are carefully calibrated relative to a suite of natural air reference gases. "Target" gas (i.e. natural air from a reference tank with a known mole fraction but treated as an unknown) is also measured at all in situ sites as a way of checking the quality of the calibration. The airstream entering the continuous analyzers is also dried (except at CRV), to a dew point temperature of ~ - 70˚C at observatory sites and ~ -30˚C at tower sites. CO_2 is measured using either NDIR (three observatories and eight tower sites) or laser absorption spectroscopy (one observatory and three tower sites). At the observatories, CO is only measured in situ at BRW, which also measures N_2O, in situ. Most of the tower sites measure CO mole fraction in situ using a NDIR approach, with two instead using laser absorption spectroscopy. We also make in situ measurements of CH_4 at six sites, always using laser absorption spectroscopy. In 2016, measurements at the Erie, Colorado tall tower (BAO) and the short tower CHS stopped. Additionally, measurements of stable isotope ratios of CO_2 ($\delta_{13}C$ and $\delta_{18}O$) at SCT started using a laser spectroscopic approach in January 2018.

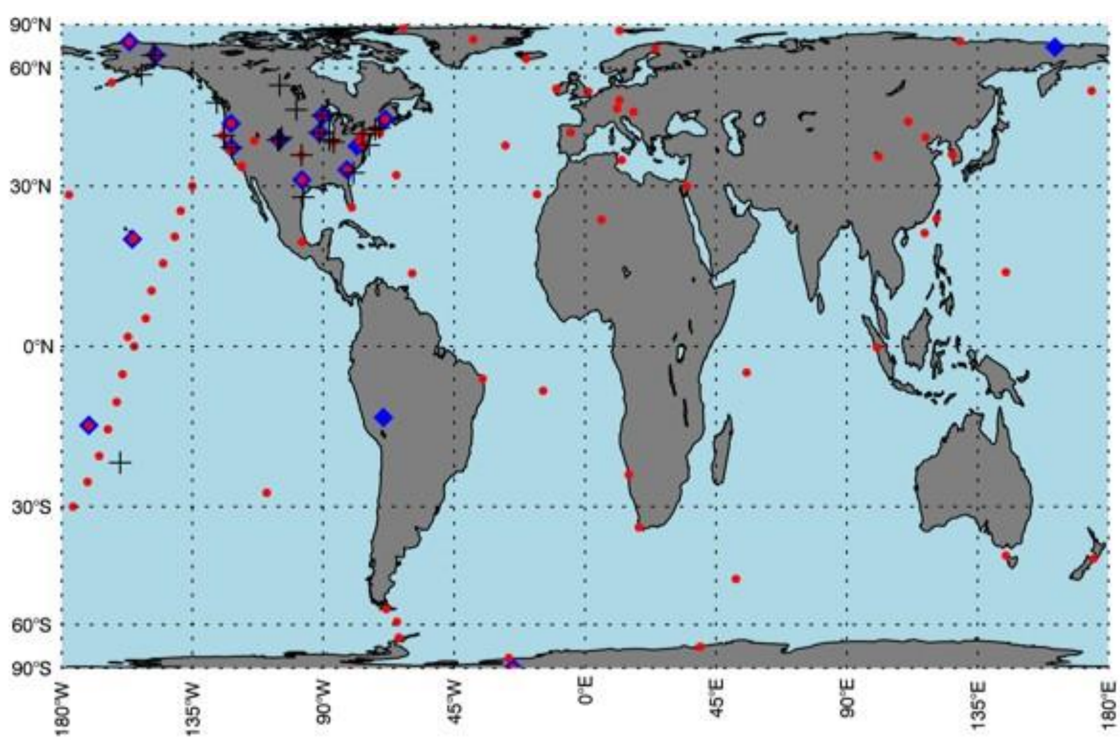

Figure 4.1: Network Map. Red symbols represent surface flask sampling sites; black crosses represent aircraft flask sampling locations; blue diamonds represent in situ measurement locations.

SURFACE DISCRETE MEASUREMENTS

Measurement of trace gas mole fractions and isotope ratios from air samples in glass flasks occurs at surface sites that are part of the Global Cooperative Air Sampling Network (using 2.2 L flasks) and at other tower and surface sites (using PFPs). Between 2014 through 2018, there were 75 located throughout the world (see Figure 4.1 and Table 4.1). This part of the GGGRN was relatively stable over 2014-2018, with eight new sites coming into the network and measurements and seven sites stopping. Air sampling at Global Cooperative Air Sampling Network sites is typically accomplished by using a Portable Sampling Unit (PSU), which is composed of a rigid plastic suitcase containing batteries, a small pump, a thermo-electric drier, flow control, and a 4 m-tall extendable mast with a polyethylene inlet tube. A pair of 2.2 L glass (boro-silicate) flasks are connected in series inside the PSU, flushed with ambient air, and then filled to an overpressure of a few psig. Flasks are returned to Boulder and then analyzed for trace gas mole fractions on the MAGICC system (for the GHGs CO_2, CH_4, N_2O, and SF_6, as well as CO and H_2; all sites); $\delta_{13}C$ and $\delta_{18}O$ of CO_2, (all sites); $\delta_{13}C$ of CH_4 (~ 30 sites); non-methane VOCs (~ 50 sites); and 14C:C of CO_2

Table 4.1: Surface-based flask-air measurement sites

Site	Country	Lat (N)	Lon (E)	Alt (m)	Start Date	Stop Date	Projects
ACG	United States	58	-153	6	4/30/2009	10/21/2017	A.F.
ALT	Canada	82	-63	190	6/10/1985	-	S.F.
AMT	United States	45	-69	53	9/18/2003	-	I.S.;S.F.
AMY	Republic of Korea	37	126	47	12/3/2013	-	S.F.
ASC	United Kingdom	-8	-14	85	8/27/1979	-	S.F.
ASK	Algeria	23	6	2710	9/12/1995	-	S.F.
AZR	Portugal	39	-27	19	12/26/1979	-	S.F.
BAO	United States	40	-105	1584	5/5/2007	7/26/2016	I.S.;A.F.; S.F.
BHD	New Zealand	-41	175	85	10/14/1999	-	S.F.
BKT	Indonesia	0	100	845	1/8/2004	-	S.F.
BMW	United Kingdom	32	-65	30	5/11/1989	-	S.F.
BRW	United States	71	-157	11	4/25/1971	-	I.S.;S.F.
BWD	United States	39	-77	17	9/25/2018	-	S.F.
CAR	United States	41	-104	1488	11/9/1992	-	A.F.
CBA	United States	55	-163	21	8/21/1978	-	S.F.
CGO	Australia	-41	145	94	4/19/1984	-	S.F.
CHR	Republic of Kiribati	2	-157	0	3/8/1984	-	S.F.
CHS	Russia	69	162	30	7/22/2008	2/12/2016	I.S.
CIB	Spain	42	-5	845	5/5/2009	-	S.F.
CMA	United States	39	-74	0	8/17/2005	-	A.F.
CPT	South Africa	-34	18	230	2/11/2010	-	S.F.
CRV	United States	65	-148	611	3/29/2011	-	I.S.;A.F.; S.F.
CRZ	France	-46	52	197	3/3/1991	-	S.F.
DND	United States	48	-99	472	9/21/2004	11/15/2016	A.F.

Table 4.1: Surface-based flask-air measurement sites (continue)

DRP	N/A	-59	-65	0	4/7/2003	-	S.F.
DSI	Taiwan	21	117	3	3/5/2010	-	S.F.
EIC	Chile	-27	-109	47	1/4/1994	-	S.F.
ESP	Canada	49	-127	7	11/22/2002	-	A.F.
ETL	Canada	54	-105	492	10/15/2005	-	A.F.
GMI	Guam	13	145	0	9/24/1978	-	S.F.
HBA	United Kingdom	-76	-26	30	1/17/1983	-	S.F.
HFM	United States	43	-72	340	11/11/1999	8/7/2016	A.F.;S.F.
HIL	United States	40	-88	202	9/16/2004	-	A.F.
HPB	Germany	48	11	936	4/6/2006	-	S.F.
HSU	United States	41	-125	0	5/17/2008	5/31/2017	S.F.
HUN	Hungary	47	17	248	3/2/1993	-	S.F.
ICE	Iceland	63	-20	118	10/2/1992	-	S.F.
INX	United States	40	-86	-10000	10/9/2010	-	A.F.;S.F.
IZO	Spain	28	-16	2373	11/16/1991	-	S.F.
KEY	United States	26	-80	1	12/13/1972	-	S.F.
KUM	United States	20	-155	0	1/12/1971	-	S.F.
LAC	United States	34	-118	100	11/5/2014	10/8/2017	S.F.
LEF	United States	46	-90	472	11/29/1994	-	I.S.;A.F.; S.F.
LEW	United States	41	-77	161	2/28/2013	-	S.F.
LLN	Taiwan	23	121	2862	8/1/2006	-	S.F.
LMP	Italy	36	13	45	10/12/2006	-	S.F.
MBO	United States	44	-122	2731	10/14/2011	-	I.S.;S.F.
MEX	Mexico	19	-97	4464	1/9/2009	-	S.F.
MHD	Ireland	53	-10	5	6/3/1991	-	S.F.
MID	United States	28	-177	11	5/3/1985	-	S.F.
MLO	United States	20	-156	3397	8/20/1969	-	I.S.;S.F.
MRC	United States	41	-76	592	5/21/2015	-	A.F.;S.F.
MSH	United States	42	-70	32	5/11/2016	-	S.F.
MWO	United States	34	-118	1728	4/30/2010	-	S.F.
NAT	Brazil	-6	-35	50	9/12/2010	-	S.F.
NEB	United States	39	-77	44	4/4/2018	-	S.F.
NHA	United States	43	-71	0	9/12/2003	-	A.F.
NMB	Namibia	-24	15	456	1/13/1997	-	S.F.
NWB	United States	39	-77	135	4/17/2018	-	S.F.
NWR	United States	40	-106	3523	5/18/1967	-	A.F.;S.F.
OXK	Germany	50	12	1022	3/13/2003	-	S.F.
PAL	Finland	68	24	565	12/21/2001	-	S.F.
PFA	United States	65	-149	210	6/27/1999	-	A.F.

Table 4.1: Surface-based flask-air measurement sites (continued)

POC	N/A	Pacific Ocean		10	12/20/1986	7/10/2017	S.F.
PSA	N/A	-65	-64	10	1/27/1978	-	S.F.
RPB	Barbados	13	-59	15	11/14/1987	-	S.F.
RTA	Cook Islands	-21	-160	3	4/16/2000	-	A.F.
SCA	United States	33	-80	0	8/22/2003	-	A.F.
SCT	United States	33	-82	115	8/14/2008	-	I.S.;S.F.
SDZ	China	41	117	293	9/3/2009	9/2/2015	S.F.
SEY	Seychelles	-5	56	2	1/15/1980	-	S.F.
SGP	United States	37	-97	314	3/2/1998	-	A.F.;S.F.
SHM	United States	53	174	23	9/4/1985	-	S.F.
SMO	American Samoa	-14	-171	42	1/15/1972	-	I.S.;S.F.
SNP	United States	39	-78	1008	8/26/2008	-	I.S.
SPO	United States	-90	-25	2810	1/21/1975	-	I.S.;S.F.
STR	United States	38	-122	254	10/2/2007	-	S.F.
SUM	Greenland	73	-38	3210	6/23/1997	-	S.F.
SYO	Japan	-69	40	14	1/25/1986	-	S.F.
TAC	United Kingdom	53	1	56	6/6/2014	1/4/2016	S.F.
TAP	Republic of Korea	37	126	16	11/24/1990	-	S.F.
TBP	Peru	-13	-69	200	12/9/2015	-	I.S.
TGC	United States	28	-97	0	9/9/2003	-	A.F.
THD	United States	41	-124	107	4/19/2002	-	A.F.;S.F.
TIK	Russia	72	129	19	8/15/2011	-	S.F.
TMD	United States	40	-77	561	8/1/2017	-	S.F.
USH	Argentina	-55	-68	12	9/14/1994	-	S.F.
UTA	United States	40	-114	1327	5/6/1993	-	S.F.
UUM	Mongolia	44	111	1007	1/1/1992	-	S.F.
WBI	United States	42	-91	242	9/14/2004	-	I.S.;A.F.; S.F.
WGC	United States	38	-121	0	8/25/2007	-	I.S.;A.F.; S.F.
WIS	Israel	30	35	151	11/27/1995	-	S.F.
WKT	United States	31	-97	251	2/11/2001	-	I.S.;S.F.
WLG	China	36	101	3810	8/5/1990	-	S.F.
ZEP	Norway	79	12	474	2/11/1994	-	S.F.

A.F. Airborne flasks

S.F. Surface flasks

I.S. In situ

(expressed as Δ14C; 23 sites). At most of the other sites (e.g. at tower locations), PFP flasks are used to hold air. In this case, air is pumped into 0.7 L flasks using a Programmable Compressor Package (PCP) to a pressure of 40 psia. PFPs contain 12 flasks and can be programmed to collect either single or paired air samples. Depending on the site, air samples from PFPs are measured for many of the same mole fractions and isotope ratios as the larger flasks (always the basic six trace gases), but they are most often additionally analyzed for ~50 halo- and hydro-carbon trace gases in cooperation with the HATS group. Starting in 2012, we also began collecting large volume (~400 L) samples in high-pressure cylinders for analysis of Δ14C of CH_4 at two sites in Alaska (BRW and CRV).

Table 4.2: Aircraft Missions

Mission Name	Location	Period	PFP samples	In Situ Properties Measured	Flight hours/ flights	Purpose
CARVE	Alaska	2014-2015 (2 missions)	1301	CO2, CO, O3, CH4, H2O, T	~690/138	Arctic Carbon Cycle
Bakken Shale Study	North Dakota	May-14	72	CO2, CO, O3, CH4, H2O, T	~35/~7	Oil and Gas
TOP-DOWN	NM, CO	Jun 2014; Apr 2015	23	CO2, CO, O3, CH4, C2H6, H2O, T	~10/2	Oil and Gas
North Slope Alaska	Alaska	May-Sep 2015; Jul-Aug 2016	380	CO2, CO, O3, CH4, C2H6, H2O, T	~115/23	Arctic Carbon Cycle
RPSEA-Fayetteville Shale	Arkansas	Sep-Nov 2015; Apr 2017	129	CO2, CH4, H2O	107/~15	Oil and Gas
ORCAS	Southern Ocean	Jan-Feb 2016	0	CO2, CO, O3, CH4, C2H6, H2O, T	98/19	Southern Ocean Carbon Cycle
ATom	Global	2016 - 2018 (4 missions)	1246	CO2, CO, CH4, H2O, PFPs	~100/12	Global Atmospheric Composition
ACT	Eastern half of US	2016-2018 (4 missions)	1551	CO2, CO, CH4	~120/~24	US carbon cycle
Alberta Tar Sands	Alberta, Canada	Oct-17	47	None	~20/4	Oil and Gas
ABoVE	Alaska	Apr-Nov 2017	410	CO2, CO, O3, CH4, H2O, T, winds	360/56	Arctic
ECO	East Coast, US	Apr-May 2018	332	CO2, CO, O3, CH4, H2O, T, winds	100/17	Urban Emissions

AIRBORNE DISCRETE MEASUREMENTS

Since its inception in 1992, the Global Greenhouse Gas Reference Network's aircraft program has been dedicated to collecting vertical profiles of air samples over North America. The program's mission is to capture seasonal and inter-annual changes in trace gas mixing ratios throughout the boundary layer and free troposphere (up to 8000m/26,000 ft). Vertical profiles of air samples are collected monthly or twice per month aboard contracted private light aircraft at 13 sites throughout North America and one site in the South Pacific (Rarotonga, RTA) (see Table: 4.2 Airecraft Missions). One site in North Dakota was lost in December 2016 and has not been replaced. The aircraft sites are typically relatively remote from strong anthropogenic sources, although in some cases, the lower part of the vertical profile that samples the planetary boundary layer (PBL) contains clear anthropogenic signals. Generally, the PBL portion of the vertical profile (which is sampled more densely) is more sensitive to local- to regional-scale sources and sinks, while the upper, free troposphere portion of the profile is sensitive only to continental- to hemispheric-scale processes.

In addition to regular profiling sites, samples have been collected as part of numerous field campaigns (as discussed below), not always in the form of profiles. As with most tower samples, aircraft samples are collected using PFPs and PCPs, typically as individual samples so that a single vertical profile is composed of 12 samples. For the five profiling sites where samples are collected for Δ14C analysis, vertical profiles typically consist of nine levels, with three levels having paired samples to allow for the larger volume of air required for Δ14C measurement. As with all other air samples collected in the GGGRN, aircraft PFP samples are always measured on the MAGICC system for the primary GHGs; samples are also typically analyzed for halo- and hydro-carbon mole fractions as well as carbon stable isotope ratios of CO_2 (14 sites) and CH_4 (two sites). Since the start of 2014, the aircraft program has generated more than 36 peer-reviewed papers. Because the aircraft program is one of the only programs of its kind that has routinely measured vertical profiles at remote sites over the last 15 years, it has been frequently used as a tool to evaluate forward and inversion models of CO_2 and CH_4 as well as satellite measurements for CO_2, CO, and CH_4. For regional inverse model studies, aircraft data has provided estimates of both background and enhancements. This has been done in studies used to estimate emissions of CO_2, CH_4, N_2O, CCl_4, and HFC-134a.

MEASUREMENT OF DISCRETE AIR SAMPLES

Table 4.3: Analytical methods used on MAGICC-1 and MAGICC-2

Species	Date	Method	Repeatability (68%CI)
CO2	1997-2019	NDIR	0.04 ppm
CH4	1997-2019	GC-FID	0.5 ppb
N2O	1997-2019	GC-ECD	0.3 ppb (0.5 ppb after ~2015)
SF6	1997- 2019	GC-ECD	0.04 ppt
CO	1997-2008	GC HgO reduction	1.0 ppb
CO	2008-2019	VURF	0.3 ppb
H2	1997-2010	GC HgO reduction	3 ppb

Since 1997, discrete air samples collected through the GGGRN have been measured for CO_2, CH_4, N_2O, SF_6, CO, and H_2 on one of two measurement systems. These systems (MAGICC-1, in service from 1997 – 2019 and MAGICC-2, in service 2008-2017) were essentially duplicate measurement systems using the same analytical techniques (see Table 4.3). The duplicate systems increased measurement capacity and served as backups to ensure continuity of operations. The analytical methods and typical analytical repeatability used are shown in Table AMC-1.

Since the original development of MAGICC-1, there have been significant improvements in analytical techniques for measuring several of the core species measured by CCGG. In particular rapid advances in laser spectroscopic techniques for CO_2, CH_4, N_2O, and CO now offer advantages over the techniques previously available. In 2017, CCGG began development of a new analytical system (MAGICC-3) for measurement of CO_2, CH_4, N_2O, SF_6, CO, and H_2 in the discrete air samples that takes advantage of the new laser spectroscopic techniques. Core goals of the new measurement system were to: 1) Improve the analytical performance, especially for N_2O where atmospheric gradients are small relative to measurement

Table 4.4: Analytical methods used on MAGICC-3

Species	Method	Repeatability (68%CI)	Calibrated_range
CO2	CRDS	0	340-550 ppm
CH4	CRDS	0	1000 – 4200 ppb
N2O	QC-TILDAS	0	275 – 370 ppb
SF6	GC-ECD	0	5 – 17 ppt
CO	QC-TILDAS	0	20 – 500 ppb
H2	GC-HePDD	0	225 – 600 ppb

noise on older techniques; 2) Minimize gas usage to allow the flasks to be measured for more species; 3) Expand the measurement ranges to allow samples collected in areas of higher emissions to be measured on the same system as the background network samples; 4) Shorten the measurement cycle to improve sample throughput. Analytical methods used on MAGICC-3 are listed in Table 4.4 along with expected analytical repeatability and the calibrated ranges. As with all the MAGICC systems, the very high accuracy of the data it produces is made possible by the extensive use of carefully calibrated reference gases for each compound we measure.

4.3 QUALITY ASSURANCE AND CONTROL

Quality assurance (QA) in our processes and quality control (QC) of our data and data products is a critical aspect of the CCGG group's operations. QA/ QC starts with extensive use of well-calibrated reference gases in all of our measurements, to ensure maximum consistency between every measurement we make and international trace gas reference scales—this is what allows us to produce highly accurate measurements. Carefully linking measurements to trace gas reference scales is necessary, but not sufficient, to ensure data of the highest quality. There are many points along the way from collecting a sample and analyzing it for trace gas mole fractions where problems can occur—e.g., sampling materials interacting with trace gases and H2O contamination. Over the years, the CCGG group has developed methods to check for the presence of possible errors in both sampling and analysis. Several methods are employed to assess the quality of our air sampling.

In the case of flask-air sampling, we often collect air in pairs of flasks (always in individual flasks, rarely for PFPs). Mole fraction differences between the pair members above a certain threshold can result from contamination (or possibly from high natural variability) and are flagged in our database. Before being sent into the field, flasks are typically filled with "fill gas," which is artificial air containing no CH4.

Thus, when sample analysis reveals lower- than-physical CH_4 values, we conclude that the flasks were incompletely flushed and these samples are flagged as untrustworthy. At a subset

of our sites, we compare measurements made in more than one way, including measurements made by other research groups. Measurements made at the same time, but through different air inlets and into different flasks or in situ instruments can be compared. For example, Mauna Loa Observatory (MLO) has in situ CO_2 systems from CCGG and the Scripps Institution of Oceanography and flask-air samples from CCGG, Scripps, CSIRO, and NIES.

For MLO and 43 additional sites where there are co-located flask and/or in situ measurements either within CCGG or across laboratories, we have developed a web-based Inter-comparison Project (ICP) tool to examine differences between measurement approaches and/or laboratories. Data ingest is automated for NOAA sites, which helps us detect problems as soon as possible. For external partners, we encourage them to transfer data to us on a regular basis to accelerate the comparison process. The differences we find help us assess the quality of our measurements, and in some cases have helped us identify problems with our sampling

We measure previously calibrated natural air in high-pressure cylinders as a way of assessing how well we have implemented reference scales for particular gases. One of the most important ways we do this is through the use of "target" or "surveillance" gases, in which air of known composition is introduced into the analyzer, but otherwise treated as an unknown. From repeated measurements, we can help determine "repeatability" (short-term precision), "reproducibility" (long-term precision), and mean bias of our analytical systems. We also measure air from high-pressure cylinders as part of international inter-laboratory activities such as "round-robins" that we organize and BIPM "Key Comparisons," which involve national meteorology laboratories. Finally, we perform "test flask" analyses in which flasks are filled with the air of a known composition, stored for a brief time, and analyzed as any other flask on a given measurement system. While test flasks analyses will not reveal all problems associated with flask sampling (such as problems with PCPs and PSUs), they represent an independent means of assessing system performance that should indicate problems with both the analysis system and flask contamination.

Although there are significant advantages to using PFPs, such as ease of deployment on multiple platforms (tower, aircraft, automobile) and ease of operator use, two major drawbacks in the current PFP system have come to light over the last five years. First, to minimize the size of the PFP and maximize the number of trace gases analyzed, the sampling system requires that the 0.7 L flasks be pressurized to 2.7 atmospheres (to achieve roughly the same amount of air as a "standard" 2.2 L flask). Second, because of the high cost resulting from the technical challenge of drying a sample stream flowing at ~10-15 L/min, samples are often undried. These design aspects of the PFPs appear to lead to two sources of CO_2 bias, both relating to water. First, positive but variable CO_2 biases up to ~1 ppm can appear when the ambient air is pressurized into PFP flasks that have been filled with "bone-dry" fill gas. Second, when ambient water vapor is high enough to produce liquid water upon compression to 2.7 atmospheres, negative CO_2 biases (ranging roughly from 0-2 ppm) arise that appear to be roughly proportional to the ambient water vapor mole fraction. These biases were identified where in situ and flask CO_2 measurements had been extensively compared during sampling on tall towers and aircraft campaigns. There is little evidence that other ~50 trace gases measured in PFP samples are significantly affected; however, more comparisons are needed to evaluate this. It is clear from the tests done so far that several changes need to be done to the flask system to correct this bias:

1. "Pre-fill" samples. To deal with the dry bias problem, we continue to investigate, at both surface and aircraft sites, replacing the bone- dry fill gas in the PFP flasks with ambient air prior to final sampling. There is some indication that such "conditioning" of the flask walls with relatively humid air

ameliorates the dry (negative) bias issues. Variables such as the time required for conditioning are still under investigation.

2. Clean the flasks/filter the air. Especially with the negative bias issue, there is a tendency for some flasks to be repeatedly worse than others, indicating that clean flasks are less likely to be sensitive to the high storage pressure or changes in water content of the flasks. Therefore, it is essential to keep the flask systems as clean as possible with frequent cleaning and air filters to prevent contamination.
3. Dry the sample. While driers are generally not used for aircraft systems (except in some campaigns), they are typically used at surface sites. This has resulted in less bias at surface sites; however, some sites have not dried the samples enough, leading to bias. Thoroughly drying PFP samples at tower sites and developing drying technology for aircraft sites is actively being researched.

Work is being done to bias-correct affected PFP data, but this is non-trivial because there are multiple sources of bias, with the possibility for cancellation. Moreover, the magnitude of biases is not consistent across flasks (dry bias issue), and the relationship between ambient water vapor and bias is very noisy (wet bias issue). Until a time when a bias correction may be developed, aircraft data where the measured or model- estimated ambient humidity is above a certain threshold have been flagged in our database. In addition to field and laboratory tests relating to water vapor, PFP flasks are also regularly tested for storage effects. After PFP flasks are filled with an air of known composition, they are analyzed for a wide variety of trace gas mole fractions for either a short (1-7 days) or long (~28 days) period. There are noticeable offsets of order a few tenths of a ppm for CO_2, but at present, these offsets are not corrected for. The final note on QA/QC is that data analysis and modeling represent a critical activity in maintaining high-quality measurements. These processes allow us to ask whether measurements make sense scientifically, and in the past, have been useful in identifying problematic observations.

4.4 MODELING AND DATA ANALYSIS

To extract as much information as possible from our measurements, the CCGG group analyzes its data using a variety of approaches, including numerical atmospheric transport modeling, in both forward and inverse modes. (An inverse model estimates surface fluxes given atmospheric mole fractions and atmospheric transport; a forward model estimates atmospheric mole fractions given surface fluxes and transport.) CCGG has developed a broad set of modeling tools that produce both regularly updated estimates of CO_2 sources and known as CarbonTracker Near-Real-Time (CT-NRT).

4.5 CARBONTRACKER

CarbonTracker is CCGG's quasi-operational CO_2 inverse modeling framework. Using an Ensemble Kalman Filter (EnKF) approach, it estimates atmosphere-surface fluxes (sources and sinks) of CO_2 from the global oceans and terrestrial biosphere, optimized to agree with CO_2 measurements, given fixed emissions from fossil fuel and biomass combustion. From these surface fluxes, we produce associated three-dimensional (3D) atmospheric distributions of CO_2 at any given point in time (at three-hourly resolution). The period of analysis for CarbonTracker begins in 2000 and extends through the end of the most recent full year of quality-controlled measurements as published by the GLOBALVIEW+ effort. This means that CarbonTracker is often more than a full year behind real-time, and in an effort to mitigate this latency, we also extend the CO_2 analysis using provisional measurements. This extension is known as CarbonTracker Near-Real-Time (CT-NRT). Due to the density of measurements available, CarbonTracker employs a nested zoom (1˚x1˚) over North America, and this is the main focus of its flux analysis. One prominent result is that fluxes over the temperate part of North America appear to be related to the continental drought status, with the sink strength reduced during high drought years (Figure 4.2).

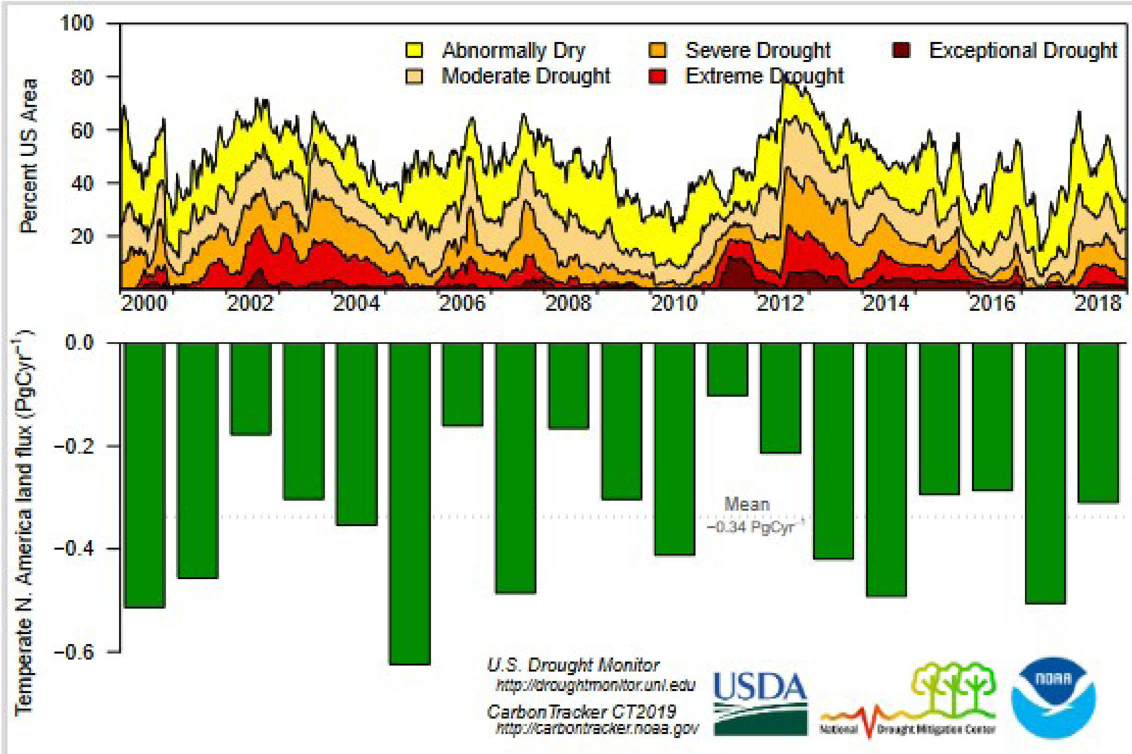

Figure 4.2: Top Panel: Percent of US surface area affected by droughts of different intensities, as defined by the U.S. Drought Monitor. Bottom Panel: Annual net ecosystem flux for the CarbonTracker region "Temperate North America."

Over the period 2014-2018, there were five major releases of CarbonTracker and six updates of CT-NRT. Each release introduced a set of improvements, including the use of ObsPack data format, significant improvements to atmospheric transport, statistical optimization of model-data mismatch errors, exploration of the use of multiple Bayesian priors, and the extension of the EnKF assimilation window from five to 12 weeks. Model-data mismatch errors (derived from the scheme in CT developed to optimize model performance for matching CO_2 measurements) are now included with recent GLOBALVIEW+ releases and have been widely adopted for use by modelers around the world.

CarbonTracker's surface fluxes and 3D CO_2 mole fraction fields are extensively used in carbon cycle science, as boundary conditions for regional analyses, exploration of satellite CO_2 retrieval biases, and studies of terrestrial and oceanic carbon cycling. These uses are revealed by tracking CarbonTracker citations in the scientific literature. Over the period 2014-2018, there were 299 citations of the Peters et al. (2007) PNAS paper which introduced CarbonTracker, and 73 acknowledgments for the use of products ranging from the CT2013 through the CT2017 releases. CarbonTracker is supported in part by NASA OCO 2 science team grants, and CT-NRT is funded by NASA's OCO-2 and ACT-America programs.

4.6 CARBONTRACKER-LAGRANGE

CarbonTracker-Lagrange (CT-L) is a regional inverse modeling framework designed primarily for estimating North American greenhouse gas sources and sinks. CT-L uses surface sensitivity footprints from Lagrangian particle dispersion models (LPDMs) driven by high-resolution (~ 10 km) meteorological simulations. Using Bayesian and geostatistical inverse modeling (GIM) techniques, surface fluxes are optimized to be consistent with atmospheric measurements of CO_2 and other gases.

CT-L mainly uses high-resolution transport fields derived from the WRF-STILT atmospheric transport model customized for Lagrangian simulations. Footprints for use in some of our regional inversions have also been calculated using NOAA ARL's HYSPLIT trajectory model, using input from high-resolution meteorological analyses. 10-day surface footprints are computed and stored for each measurement along with back-trajectories. Note that footprints and trajectories are trace gas- independent as long as the compound of interest is long-lived relative to ten days, as are the GHGs we study.

In collaboration with the University of Colorado Boulder, we have used the CT-L framework to estimate N2O emissions for North America and found large emissions from agricultural regions. We have also estimated North American CO_2 surface fluxes for 2007-2015 and found strong correlations with humidity and temperature anomalies associated with ENSO. And in collaboration with the Carnegie Institution for Science, we have used the CT-L footprint library with a GIM optimization scheme informed by in situ and discrete CO_2 measurements and satellite retrievals of solar- induced fluorescence to show that forested regions dominate the interannual variability of North American CO2 uptake. In a study focusing on halocarbons, we used a predecessor of CT- L to estimate U.S emissions for a comprehensive suite of ozone-depleting substances and their substitutes, hydrofluorocarbons, that are regulated under the Montreal Protocol.

The STILT model was derived from HYSPLIT, and we are working to create an operational implementation of CT-L using HYSPLIT driven by operational NOAA meteorological analysis products such as from the North American Mesoscale (NAM) model. In the future, we also aim to use CT-L to produce annually updated estimates of North American surface fluxes of CO_2, CH_4, N_2O, SF_6, and a suite of halocarbons and other gases of interest.

4.7 OTHER MODELING AND DATA ANALYSIS

In addition to CT and CT-L, during 2014-2018 we have focused on other more experimental modeling analyses. Two projects of note focused on inverse modeling of CO2 with the additional atmospheric constraint of either Δ14C or δ13C. The δ13C, CO2 inverse model, a collaboration with Wageningen University, the Netherlands, was a global inversion similar to CT. However, in addition to optimizing surface fluxes, this inverse model also optimized the isotopic fractionation factor during photosynthesis. This parameter is related to how ecosystems respond to water stress, and it was shown that models of the terrestrial biosphere did not exhibit as much response to drought as the atmospheric data suggest. Global inverse modeling (with a North American zoom, like CT) of CO2 and Δ14C is meant to optimize biospheric sources and sinks and fossil fuel sources of CO2, simultaneously. A synthetic data study showed that with the network density of 2010, we could estimate fossil fuel-CO2 emissions with a precision of approximately 5 percent. Preliminary results of the same analysis using actual CO2 and Δ14C data show that inventories of fossil fuel-CO2 emissions for the United States tend to be low by at least several percent. We also use δ13C of CH4 to constrain components of the global CH4 budget in both box and 3D models. CH4 sources can be divided into different categories (i.e., microbial, biomass combustion, and fossil fuel) each having a characteristic δ13C source "signature". When combined with gradients of atmospheric δ13C of CH4 over time and/or space, we can optimize the source strengths, given some assumptions about the sink magnitude and isotopic fractionation..

4.8 DATA PRODUCTS

OBSPACK

Observation Package (ObsPack) data products are collections of raw or averaged GHG data from one or more measurement laboratories combined in a consistent format with metadata necessary for intelligent use in various GHG data analysis and modeling activities. The flagship ObsPack product is named GLOBALVIEW+ and was first released for CO2 measurements in 2015. GLOBALVIEW+ is different from its predecessor GLOBALVIEW in that it contains actual measurements rather than smoothed averages. The GLOBALVIEW+ CO2 product is updated annually and has grown from 6 million measurements in 205 distinct datasets with 25 contributing institutions in the first release to over 29 million measurements in 411 datasets with 50 contributing institutions, as of the fourth version update in 2018. Since the first GLOBALVIEW+ release, we have expanded the availability of different products each year. A version for sulfur hexafluoride (SF6) measurements was added in 2017 and has version updates as needed. The SF6 ObsPack product is the only globally collaborative collection of SF6 measurements available in once place. As of 2018, the SF6 product contained just under 1 million measurements in 224 datasets from 13 institutions. For research applications that demand access to data at Near Real-Time (NRT), an NRT CO2 ObsPack product that is released roughly quarterly was developed. This product contains CO2 measurements from the end of the last GLOBALVIEW+ release up to no more than a month prior to the release of the NRT product. The ObsPack format is also used as a means to distribute CarbonTracker model input and results. The CARBONTRACKER ObsPacks have been released alongside CarbonTracker starting with version CT2013 in the year 2014. The last type of ObsPack produced is different from the GLOBALVIEW+ style of ObsPack. Multi-species ObsPacks are a set of products that are intended to release all Carbon Cycle and Greenhouse Gases (CCGG) group reference network measurements from all project types and gas species. All ObsPacks are available via the CCGG group website. In addition, all official ObsPack product releases now contain a Digital Object Identifier (DOI) to track usage through a citation. These features help to ensure that data providers receive credit for their contributions.

TRENDS WEB PAGES

We maintain several web pages to summarize and communicate our findings in timely manner to scientists, the general public, the news media, and politicians. "Current trends in CO2" was initiated in 2007, presenting both Mauna Loa and globally averaged monthly and annual mean CO2 values, with downloadable graphs and data tables, and also annually averaged growth estimates. See, for example, https://gml.noaa.gov/ccgg/trends/.

In March 2018, we added daily updated estimates of global average CO2, smoothed over one month, calculated as the average of continuous measurements at the four background stations of Barrow, Mauna Loa, Samoa, and the South Pole. This record shows that global CO2, after removal of the (repeating) seasonal cycle, keeps increasing every single day at a pace of 0.006 to 0.008 ppm per day. During 2018, the CO2 trends pages had 1.25 million separate page views.

In February 2015, we added "Current trends in CH4," which presents globally averaged monthly and annual values and annual growth rates. See https://gml.noaa.gov/ccgg/trends_ch4/.
During 2018, the CH4 trends web pages had 41,000 separate page views.

4.9 SPECIAL PROJECTS

FIELD CAMPAIGNS

With limited resources and sampling sites, CCGG has had to take advantage of external funding to extend our coverage and advance our measurement techniques. Over the last five years, there have been four major foci: 1) CH4 emissions from oil and gas; 2) Arctic emissions of CH4 and CO2; 3) urban emissions, and

4) global mapping of vertical and latitudinal gradients in GHGs. With outside support from NASA, DOE, EDF, NIST, and NSF, these projects have enabled us to explore new sampling techniques and emissions quantification methodologies that have helped change policy and also provided pathways for emissions quantification that are being implemented by oil and gas producers and cities to better understand and control emissions of GHGs. This was accomplished with more than 70 peer-reviewed papers and several thousand hours of aircraft- and ground- based sampling, along with more than 6000 PFP flask samples (Table Y). One of the most significant gains from these special projects has been the development of an in situ system that can be deployed for six month-periods on commercial aircraft without the need for human interaction. This advance is a critical step in our plan to expand our aircraft sampling network on commercial aircraft, where we plan to continuously measure CO2, CO, CH4, and H2O. Ten aircraft will allow a 2-3 order-of-magnitude increase in sampling frequency, as well as insight into the role that urban centers play in the GHG emissions.

1. Oil and gas production studies. Over the last five years, studies focused on oil and gas production have been the biggest focus. This work has led to significant changes in the methods that EPA uses to calculate emissions from oil and gas production. CCGG led the technology development needed to not only quantify regional CH4 emissions from oil and gas producing regions, but also distinguish these oil and gas emissions from other sources of CH4. We flew over production fields in Fayetteville Shale Basin; Alberta Tar Sands; North Slope, AK; Bakken Shale Basin, ND; San Juan Basin, NM; and Marcellus Shale Basin, PA, adding to data from Barnett Basin, TX; Denver Julesburg, CO; and Uinta Basin, UT.
2. Arctic Studies. Ongoing collaborations with the Coast Guard and NASA continue to fund a mountain site just north of Fairbanks, AK, in addition to more than 900 hours of aircraftflights during the spring-summer-fall seasons of 2014, 2015, 2016, and 2017. These studies helped us confirm that oil and gas production only contributes a small fraction of the CH4 emissions in the Arctic. The majority of the CH4 emissions are coming from lowland regions (most likely wetlands). These studies also confirmed that fluxes of CH4 and CO2 continuewell after snow cover throughout the Arcticregion and do not cease until the ground below the snow is completely frozen in December. According to the analysis of data collected at BRW, the shutdown in emissions happens later and later each year, due to the enhanced warming.
3. Urban Studies. Urban emissions account for as much as 70 percent of total GHG emissions globally. It is therefore imperative that we understand how to track these emissions as cities figure out ways to control them. CCGG continues to play an important role in these studies by deploying PFPs to measure Δ14C of CO2 and many other tracers that enable us to attribute the sources of these emissions. In studies done in Los Angeles, CA and Indianapolis, IN, measurements of Δ14C of CO2 have played a critical role in our success separating emissions from biological processes and fossil sources. More measurements have been started in the Baltimore/Washington, DC region, but no results have been published yet. In addition to the long-term measurements made in these three cities, CCGG also led the East Coast Outflow (ECO) Study in spring of 2018 that showed that methane emissions from natural gas leaks in Boston, New York, Philadelphia, Baltimore and Washington, DC were almost an order of magnitude more than those estimated by the EPA
4. Global and U.S. GHG studies. The ATom and O2/ N2 Ratio and CO2 Airborne Southern Ocean (ORCAS) aircraft missions provided another level of detail to the earlier HIAPER Pole-to-Pole Observations (HIPPO) mission, which mapped out large-scale gradients in GHGs from the Arctic Ocean to the Antarctic. CCGG contributed both in situ CO2, CH4, and CO measurements to these campaigns, as well as PFP flask measurements. More than a dozen publications have been generated from these campaigns, with more to follow. ORCAS data have been instrumental in understanding the impact of Southern Ocean air-sea gas exchange of many trace gases, with a particular focus on O2 and CO2. Atom has contributed to our understanding of the role that OH plays in the oxidation of reactive trace

gases, as well as distributions of the long-lived gases like CH_4, CO_2, and CO. The recently completed airborne Atmospheric Carbon Transport (ACT) - America mission was done over three different regions based in Lincoln, NE; Wallops Is, VA; and Shreveport, LA over four seasons. CCGG was involved in both the in situ flask and modelling components of this mission. This mission focused on measuring carbon transport at frontal boundaries, which most studies avoid, because making aircraft measurements in poor weather conditions is risky.

4.10 AIRCORE

The AirCore is a unique sampling system patented by CCGG to make GHG measurements to altitudes of 30 km using balloon launched sampling systems similar to a radiosonde, allowing for frequent and relatively low cost deployments. In its simplest form, the AirCore is a long tube (~100m) that is launched with one end open and the other end closed. As the AirCore rises, air flows out of the tube. By the time it reaches altitudes of 30km, all but 1 percent of the air in the tube has escaped due to low pressure at that altitude. When the balloon is cut, the AirCore falls to the ground at a speed controlled by a parachute. As the AirCores falls, surrounding air flows back into the AirCore, capturing a profile of the air for later analysis. By capturing the air in a small diameter tube (1/8"), most turbulent mixing is eliminated, allowing mainly molecular diffusion to smear the resolution of the sampled air.

Over the last five years, CCGG has worked with groups outside the United States to expand regular measurement sites. These sites include Sodankylä, Finland; Lauder, New Zealand, and Orléans, France. In addition to the monthly flights in Boulder, CO, CCGG continues to travel to Lamont, OK to conduct launches near the Total Carbon Column Observing Network (TCCON) site, to evaluate the greenhouse gas measurements made there. During summer 2018, a campaign was conducted to make AirCore measurements at three different TCCON sites (Rosamond, CA; Lamont, OK; and Park Falls, WI) along with four lightweight upward-looking Fourier Transform Spectrometers (FTSs) to test their stability and comparability. The last decade of measurements (~140 profiles) is now available (ftp://aftp.cmdl.noaa.gov/data/AirCore) in multiple formats as well as the Python version of the processing code.

Significant improvements have been made to the AirCore design and applications over the last five years. Each AirCore launch now includes two separate sampling tubes to provide duplicate measurements. It has also been demonstrated that it is possible to make measurements of N_2O in addition to CO_2, CH_4, and CO. The AirCore team has also designed, built, and deployed a drone- based "active" AirCore that allows 30 minutes of sample air to be actively pumped into an AirCore tube during a flight of any "shape" (i.e., not necessarily a vertical profile). This provides a high-resolution recording of CO_2, CH_4, and CO mixing ratios over the course of a drone flight. A new tall tower site for CO_2, CH_4 and CO measurements is being constructed to house an upward-looking FTS. This site will be used to compare measurements of the total column of CO_2, CH_4, and CO from FTS, satellite, and (WMO-calibrated) AirCore measurements. Because of the weather and infrequent satellite overpasses, this new site will become a "transfer standard," whereby the AirCore will "calibrate" the FTS, which will then be compared to satellite retrievals, allowing us to link satellite measurements to the WMO mole fraction scales. Finally, progress is underway to build a balloon- launched AirCore system using an auto-piloted glider that is capable of returning the AirCore to the launch location under many wind conditions.

Section 5 - Halocarbons and Other Trace Atmospheric Species (HATS) Research Division

ACTIVITIES OVERVIEW

In the late 1970s, predecessors at the Geophysical Monitoring for Climatic Change (GMCC) began making measurements of atmospheric trace gases, such as halogenated gases and nitrous oxide, that influence stratospheric ozone and climate. What started as weekly air samples collected at four GMD Atmospheric Baseline Observatories plus Niwot Ridge, Colorado, and analyzed for three gases, has grown into a multi-faceted endeavor consisting of ongoing flask and in situ sampling of both the surface and vertical dimension of the atmosphere along with periodic focused field campaigns. Many of these measurements complement those obtained by other GMD research efforts, including the Carbon Cycle and Greenhouse Gases (CCGG) and Ozone and Water Vapor (OZWV) divisions.

The HATS division's primary objective is to characterize and understand trends and distributions of atmospheric abundances of trace gases that influence stratospheric ozone and climate, and to a lesser degree, air quality. Topics of focus during 2014-2018 have included documenting and understanding changes in atmospheric abundances of a) ozone-depleting gases and their substitutes, on both global and regional scales; b) very short-lived halogenated gases, which influence stratospheric ozone; atmospheric hydroxyl radical, which acts to remove pollutants from the atmosphere; an carbonyl sulfide, which contributes to sulfur in the stratosphere and provides insights into terrestrial carbon uptake during photosynthesis. HATS division members have also collaborated to validate results from satellites; made progress developing halocarbon sampling and analysis by AirCore™; improved the understanding of methane and hydrocarbon emissions from urban areas and oil and gas operations throughout the U.S.; and improved our understanding of calibration consistency among organizations making measurements of halocarbons and hydrocarbons. Division members also developed inverse modeling capabilities that translate atmospheric abundance measurements directly into regional fluxes. This modeling provides observation-constrained emissions estimates that are policy relevant for evaluating the effectiveness of mitigation strategies and potential climate feedbacks. HATS data have been used in international assessments, reports, and reviews.

Finally, many scientists outside of NOAA GMD have found GMD data invaluable for addressing many additional scientific and policy-relevant questions regarding atmospheric processes and human impacts on the chemical and physical state of the atmosphere. For a complete list of publications related to these and other topics, see https://gml.noaa.gov/publications/browse.php. Below, we describe how many facets of GMD operations, including measurement systems, sampling, analysis, data processing, modeling, and standardization changed during 2014-2018.

5.1 FLASK AND IN SITU PROGRAMS

The flask program is one of the cornerstones of the HATS sampling efforts. Sampling using flasks (grab samples) in collaboration with CCGG enables ongoing surface measurements at sites across much of the Western Hemisphere and through much of the troposphere above North America, with additional sites in Australia, the South Pacific, South Korea, and Israel. Samples are analyzed on dedicated instruments under controlled conditions, thus limiting calibration and inter-instrument issues that can influence in situ measurements under field conditions. By combining efforts with other research divisions in GMD, approximately 60 compounds are measured from most flask samples.

In addition to routine sampling within the global network (see 5.5.1), samples were also collected and analyzed during 2014-2018 as part of several special projects, such as NASA's Atmospheric Tomography mission (ATom), which sampled the

whole troposphere in both the Pacific and Atlantic basins over all four seasons in four deployments during 2016-2018; and the analysis of firn-air samples collected from South Pole (December 2015) and at sites in Greenland in 2015 (Rennland) and 2018 (EGRIP). Atmospheric histories were also reconstructed via HATS analyses of a subset of samples from the Cape Grim Air Archive, which was facilitated by M. Vollmer of the Swiss Federal Laboratories for Materials Science and Technology (Empa) and scientists at the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia.

The in situ program was started in the late 1980s to complement the flask program by providing high-frequency measurements of select compounds at a relatively small number of sites using custom- built gas chromatographs with electron capture detectors (GC-ECDs). In the late 1990s, the original instruments were upgraded with second-generation GC-ECDs.

The combination of surface in situ measurements and flask sampling from a variety of platforms allows us to obtain a comprehensive view of atmospheric trace gas mole fractions and distributions and provides insight into the natural and anthropogenic processes controlling changes in the chemical composition of the atmosphere over seasonal to decadal periods. Data are used in indices created and maintained by GMD, such as the NOAA Annual Greenhouse Gas Index (AGGI) and Ozone Depleting Gas Index (ODGI), which are reposted by other U.S. Agencies (U.S. EPA's climate indicator: https://www.epa.gov/climate-indicators/climate-change-indicators-climate-forcing; and the U.S. EPA's Report on the Environment Indicator: https://cfpub.epa.gov/roe/indicator.cfm?i=11).

5.1.1 FLASK SAMPLING AND MEASUREMENTSCURRENT OPERATIONS.

A number of changes occurred to the flask collection and analysis program during 2014-2018. The HATS global flask sampling network continues to consist of sixteen ground-based sites, with flask sampling initiated at one new site (AMY) and terminated at another (WLG) (Table 5.1). At PSA, a new flask pump dedicated to sampling HATS flasks was installed in the spring of 2018. This dedicated pump allows higher flask fill pressures and improved results for many gases, in particular CH3CCl3. At Cape Kumukahi (KUM), a volcanic eruption in May 2018 resulted in a lava flow that cut off access to the tower at our regular flask sampling location. Sampling at the original site (19.516°N, 154.811°W) was moved to a more northerly point (19.737°N, 155°W). Unfortunately, a tower was not available at this new site, sosamples have been affected more strongly by local marine and tidal-zone sources and other processes, which has led to elevated levels of a number of different gases (e.g., CHBr3) in the sampling flasks. Work continues to appropriately flag the anomalous results and to devise a long-term solution for the resumption of artifact-free sampling at KUM, potentially via a drone. At the South Pole Atmospheric Baseline Observatory (SPO) during 2014 to 2018, the sampling pumps and inlet tubing suffered a number of unforeseenproblems related to contamination and anomalous removal of some of the more reactive gases in the sampled air stream. Improvements were made during each winter in an attempt to enable a long-term solution. Lastly, sampling at a site in eastern New Zealand is being considered and there are plans to add flask sampling at Ragged Point, Barbados, to expand the tropical coverage of the network in the near future.

Paired flask samples are collected weekly or biweekly at all sites. The total number of flask sample pairs collected per year has ranged between 580 and 615 over the period 2014 to 2018 (Figure 5.1); the number of samples collected at the 12 remote sites has ranged between 491 and 514, which amounts to an average of 0.78-0.85 sample pairs per site per week. Sampling frequencies are sometimes below 1.0/week at the remote baseline sites because of out-of-sector wind conditions, flask shortages, and pump malfunctions. HATS paired flasks are routinely analyzed on two to three instruments in the laboratory: a GC-ECD and one or two gas chromatographs with mass spectrometry detection (GC-MS).

Table 5.1: Ground-based HATS sampling sites, global network. Remote sites designated by *; S.S. = stainless steel For site locations see https://gml.noaa.gov/dv/site/.

Site	Flask Type	Frequency	Status
ALT*	SS	1/wk	ongoing
SUM*	glass	0.5 to 1/wk	ongoing
BRW*	SS	1/wk	ongoing
MHD*	SS	1/wk	ongoing
LEF	SS, glass	1/wk	ongoing
HFM	SS	1/wk	ongoing
THD*	SS	1/wk	ongoing
NWR*	SS	1/wk	ongoing
AMY	glass	0.5 to 1/wk	started in 2018
WLG	glass	1/wk	terminated
WIS	glass	0.5/wk	ongoing
KUM*	SS	1/wk	ongoing
MLO*	SS	1/wk	ongoing
SMO*	SS, glass	1/wk	ongoing
CGA*	SS, glass	1/wk	ongoing
PSA*	glass	1/wk	ongoing
SPO*	SS, glass	1-2/month	ongoing

Table 5.2: Ground-based tower network (CCGG) sites with flasks analyzed by GC-MS instruments in HATS

Site	Lat	Long	Alt. (m)	Start - End
AMT	45	69	February 1900	Nov. 2008 - present
BWD	39	77	January 1900	Dec. 2018 - present
CRV	65	148	September 1901	Mar. 2011 - present
LEF	46	90	December 1901	Oct. 2006 - present
INX	40	86	February 1901	Oct. 2010 - present
LEW	41	77	September 1900	Jun. 2013 - present
MBO	44	122	July 1907	Apr. 2010 - present
MWO	34	118	November 1904	Feb. 2006 - present
MSH	42	71	February 1900	May 2016 - present
NWR	40	106	August 1909	Apr 2012 - present
SGP	40	97	September 1900	Mar. 2016 - present
STR	38	122	April 1901	Oct. 2007 - present
SCT	33	82	February 1901	Aug. 2008 - present
TMD	40	77	July 1901	Aug. 2017 - present
WBI	42	91	September 1901	Jun. 2007 - present
WGC	38	121	91 or 483	Sep. 2007 - present
WKT	31	97	708	Aug. 2006 - present

The analysis is conducted with two aliquots from each flask surrounded by reference gas injections on GC-MS instruments and three aliquots per flask on the GC-ECD instrument. Both stainless steel (S.S.) and glass flasks are used for sampling air at HATS sites (Table 5.1). Since the early 2000s, both glass and S.S. flasks have been collected at SPO, Cape Grim Observatory (CGO), American Samoa Atmospheric Baseline Observatory (SMO), and the WLEF TV Tower Observatory (LEF) near Park Falls, Wisconsin. Unlike the other sites where the same equipment (pump, inlet line) is used to sample the different flask types, at LEF the sampling of glass flasks is done automatically with a separate pump and inlet line using a Programmable Flask Package (PFP). At the southern hemisphere sites, the different flask types are filled from the same pumping apparatus. These procedures have allowed us to identify flask artifacts associated with sampling containers for some sensitive chemicals in dry air (e.g., at SPO), and they have prompted the use of glass flasks exclusively at low humidity sites associated with long storage times (e.g., at Summit (SUM), Palmer Station, Antarctica (PSA), and Weizmann Institute of Science at the Arava Institute, Ketura, Israel (WIS)).

Data for chemicals measured in this program and for which data records have been documented in peer-reviewed articles are updated approximately monthly on the web at https://gml.noaa.gov/aftp/data/hats/. These compounds include: N_2O, SF_6, CFC-11, CFC-12, CFC-113, CCl4, CH_3CCl_3, HCFC-22, HCFC-142b, HCFC-141b, H-1211, H-1301, H-2402, HFC-134a, HFC-125, HFC-143a, HFC-32, HFC-152a, HFC-365mfc, HFC-227ea, CH3Cl, CH3Br, COS, CH2Cl2, and C2Cl4. Results for these gases are available on the web at: https://gml.noaa.gov/dv/iadv/.

Higher-frequency flask measurements (i.e., approximately daily) are also made at 17 U.S. sites in collaboration with the CCGG tall tower network (Table 5.2) and semi- monthly to monthly at 19 sites as 12-flask aircraft profiles also as part of the CCGG aircraft network (Figure 5.1, lower panel) (Table 5.3). Owing to flask and air availability and instrument time constraints, these samples are collected as single

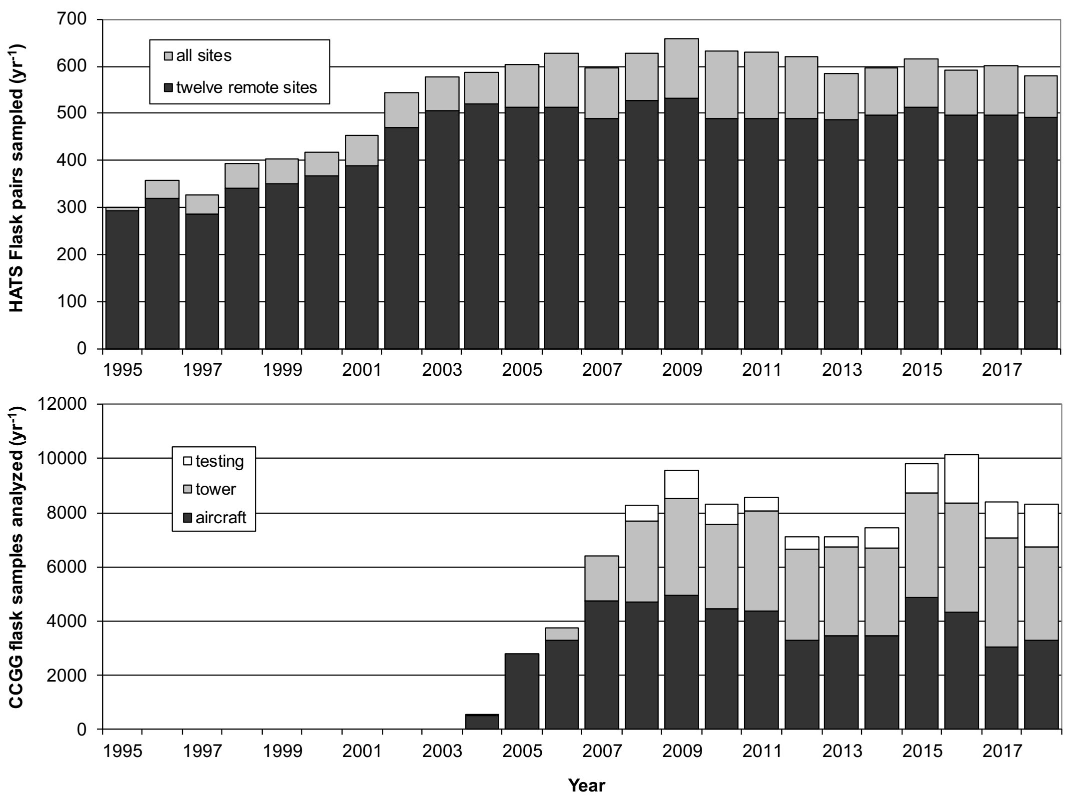

Figure 5.1: Top panel: Number of paired glass or stainless-steel flask samples collected yearly from HATS ground-based sampling locations (see Table 5.1). Bottom panel: Number of flasks collected by the GMD CCGG division and analyzed on GC-MS instrumentation. The CCGG samples are typically single flasks collected from tower and aircraft platforms in North America and over the Pacific Ocean.

Table 5.3: Profiling aircraft network (CCGG) sites with flasks analyzed by GC-MS

Site	Lat	Long	Start - End
AAO*	40	89	Jun. 2006 - Sep. 2009
ACG**	87 to 86	130 to 170	Apr. 2009 (no winter samples) - present
BGI	43	94	Sep. 2004 - Nov. 2005
BNE	41	97	Sep. 2004 - Apr. 2011
CAR	40	104	Jan. 2005 - present
CMA	39	74	Sep. 2005 - present
CRV**	60 to 71	144 to 164	Mar. 2011 - Nov. 2017
DND	48	98	Sep. 2004 - Nov. 2016
ESP	50	126	Mar. 2005 - present
ETL	54	105	Oct. 2005 - Mar. 2020
FWI	45	91	Sep. 2004 - Nov. 2005
HAA	21	159	Aug. 2006 - Apr. 2008
HIL	40	88	Sep. 2004 - present
INX	40	86	Oct. 2010 - May 2016
LEF*	46	90	Jun. 2005 - present
NHA	43	71	Oct. 2005 - present
OIL	41	89	Sep. 2004 - Nov. 2005
PFA	65	147	Apr. 2009 - present
RTA	20.96 S	160	Sep. 2007 - present
SCA	33	80	Oct. 2005 - present
SGP*	37	98	Mar. 2006 - present
TGC	28	97	Feb. 2005 - present
THD	41	124	Nov. 2004 - present
ULB*	47	106 E	Nov. 2004 - Nov. 2005
WBI	42	91	Sep. 2004 - present

* maximum altitude routinely < 25000 ft

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

flasks, and they are analyzed on the GC-MS with a single injection. These automated sampling and analysis protocols have enabled the collection of thousands of samples per year across the United States. These data are regularly updated on internal NOAA GMD databases and are available on request.

5.1.2 FLASK ANALYSIS BY GC-MS: INSTRUMENT UPDATES

The original H.P. 5971A GC-MS instrument (M1), used since 1991, was replaced in 2009 with an Agilent 5973 GC-MS (M3). This change was necessary as the performance of the original instrument had deteriorated, and dramatically improved results were obtained after the change (Figure 5.2). In November of 2015, the detector element for M3 was upgraded to a triple axis detector (Agilent) of the model that is used in the newer Agilent 5975 and 5977 quadrupole mass spectrometers. Here again, the change resulted in significant improvements in measurement precision for nearly all gases. Since that time, replicate injection precision for the most abundant chemicals measured (CFC-11, 12, -13, HCFC-22,

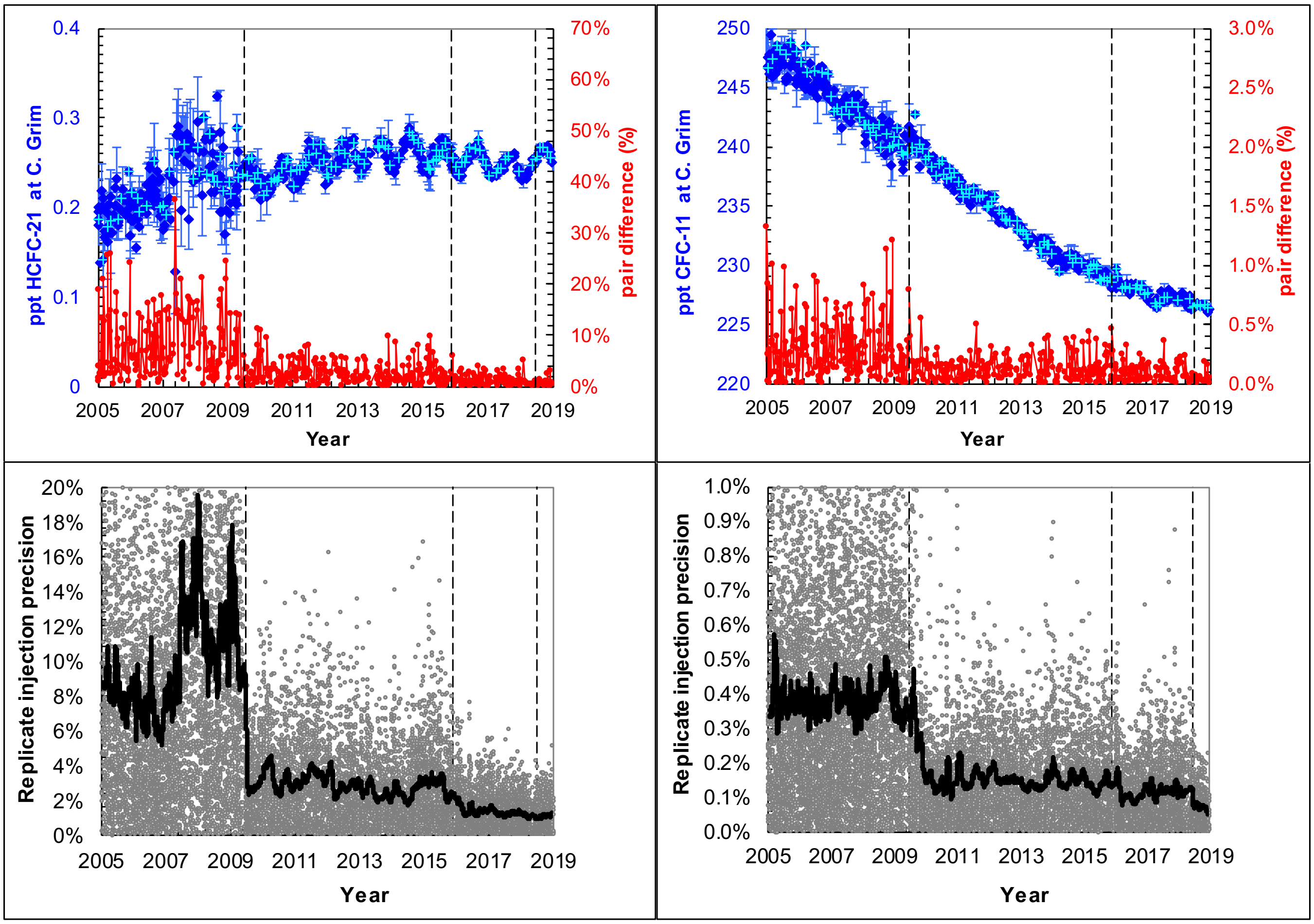

Figure 5.2: Measured mixing ratios, pair agreement, and replicate injection precision for HCFC-21 and CFC-11 from the M1 & M3 instruments in recent years (the M1 to M3 transition was in mid-2009). Top panels: Flask pair means collected at Cape Grim, Australia, from stainless steel (blue diamonds) or glass (light blue plusses) flask pairs. Pair agreement (red, as a percent of measured mean) in these results is plotted on the right-hand axis. Bottom panel: replicate injection precision for all flasks measured by M1 and M3 over time. Points indicate individual flask results, and dark lines represent 100-point running means. The dashed lines in all panels indicate the dates associated with instrument modifications: in 2009, flask analysis was shifted from M1 to M3, which included upgrading the mass spectrometer to a 5973 Agilent mass spectrometer; in 2015, the detector element for the mass spectrometer was upgraded to a triple axis detector (Agilent); in 2018, the sample pressure sensor was upgraded to a new temperature-controlled capacitance manometer (MKS).

-141b, HFC-134a, methyl chloride and carbonyl sulfide) is typically 0.1%. Flask pair agreement for these chemicals is also typically 0.1%, with the exception being carbonyl sulfide, whose pairs typically agree to only within 0.3% (median value). Instrument precision has been further improved since mid-June of 2018, when a new capacitance manometer with internal temperature control was installed for more precisely measuring air mass volumes injected into the GCMS. The improvement arising from this change was most notable for the more highly abundant gases such as CFC-11, CFC- 12, and others (Figure 5.2).

Other M3-specific changes include the installation of a new capillary column in August of 2016. This change was made to avoid the long-term degradation observed with the last column, which was replaced in 2009 during the transition from M1 to M3. The column type was unchanged and remains a 60 m long, 0.25 mm I.D. column, with a 1µm thick internal film of 5% phenyl methyl silicone.

NEW GCMS INSTRUMENT: "PERSEUS" OR PR1

An additional GC-MS instrument (Perseus) was built in 2014 to replace the aging M2 instrument and to handle the additional samples collected from the CCGG's tower and aircraft networks. Currently,

Table 5.4: Chemicals measured in flask air by GC-MS or GC-ECD, or in situ by GC-ECD

Chemical	Instrument	Notes
N2O	Otto, CATS	6
SF6	PR1, Otto, CATS	6
CFC-11	M2, M3, PR1, Otto, CATS	
CFC-12	M2, M3, PR1, Otto, CATS	6
CFC-13	PR1	1
CFC-113	M2, M3, PR1, Otto, CATS	
CFC-112	M3	2, 7
CFC-114	M3, PR1	4
CFC-115	M2, PR1	
HCFC-22	M2, M3, PR1	
HCFC-141b	M2, M3, PR1	
HCFC-142b	M2, M3, PR1	
HCFC-21	M3	7
HCFC-123	PR1	1
HCFC-133a	M3, PR1	1
HFC-134a	M2, M3, PR1	
HFC-152a	M2, M3, PR1	
HFC-23	M2, PR1	7
HFC-32	M2, PR1	
HFC-125	M2, PR1	
HFC-143a	M2, PR1	
HFC-365mfc	M2, M3, PR1	
HFC-236fa	PR1	1
HFC-227ea	M2, M3, PR1	
H-1211	M2, M3, PR1	
H-1301	M2, PR1	
H-2402	M2, M3, PR1	
HFO-1234yf	PR1	1, 2
HFO-1234ze	PR1	1, 2
CCl4	M2, M3, PR1, Otto, CATS	
CH3CCl3	M2, M3, PR1, Otto, CATS	
CH3Cl	M2, M3, PR1	
CH3Br	M2, M3, PR1	
CH3I	M2, M3, PR1	7
CH2Cl2	M2, M3, PR1	
CHCl3	M2, M3, PR1, CATS	5, 7

Table 5.4: Chemicals measured in flask air by GC-MS or GC-ECD, or in situ by GC-ECD (continued)

C2Cl4	M2, M3, PR1	
CH2ClCH2Cl	M3, PR1	2, 7
CH2Br2	M2, M3, PR1	7
CHBr3	M2, M3, PR1	7
CH2BrCl	M3	7
CHBrCl2	M3	7
CHBr2Cl	M3	7
CH2ClI	M3	7
CH2I2	M3	7
COS	M2, M3, PR1	
C2H2	M2, PR1	
C2H6	M2, PR1	
C3H4	M3	1, 7
C3H8	M2, M3, PR1	3
n-C4H10	M2, M3, PR1	3
i-C4H10	M3, PR1	3
n-C5H12	M2, M3, PR1	
i-C5H12	M2, M3, PR1	3
n-C6H14	M2, M3, PR1	
C6H6	M2, M3, PR1	
NF3	PR1	1
CF4	PR1	1
C2F6	PR1	1
C3F8	PR1	1
SO2F2	PR1	1

Notes: Instrument M2 was replaced by PR1.
1: new since 2013
2: calibration scale not fully developed
3: M3 results are only from the subset of CCGG PFP flasks that are analyzed on M3
4: mixture of isomers CFC-114 and CFC-114a
5: CATS measurement under development
6: measurement no longer possible on the Otto system as of 2013 for SF6 and N2O and 2017 for CFC-12
7: preliminary results that are not currently posted publicly, but may be available upon request

nearly all HATS ground-based, non-tower network flasks are analyzed on the M3 GC-MS, whereas the Perseus instrument analyzes these flasks plus the CCGG flasks collected in programmable flask packages. M3 and Perseus measure a similar but not identical suite of gases (see Table 5.4).

The Perseus GC-MS ('PR1') was developed as a joint effort between the CCGG and HATS divisions in 2014. This instrument is used to analyze PFP flasks from CCGG and flask pairs from the HATS networks for 60

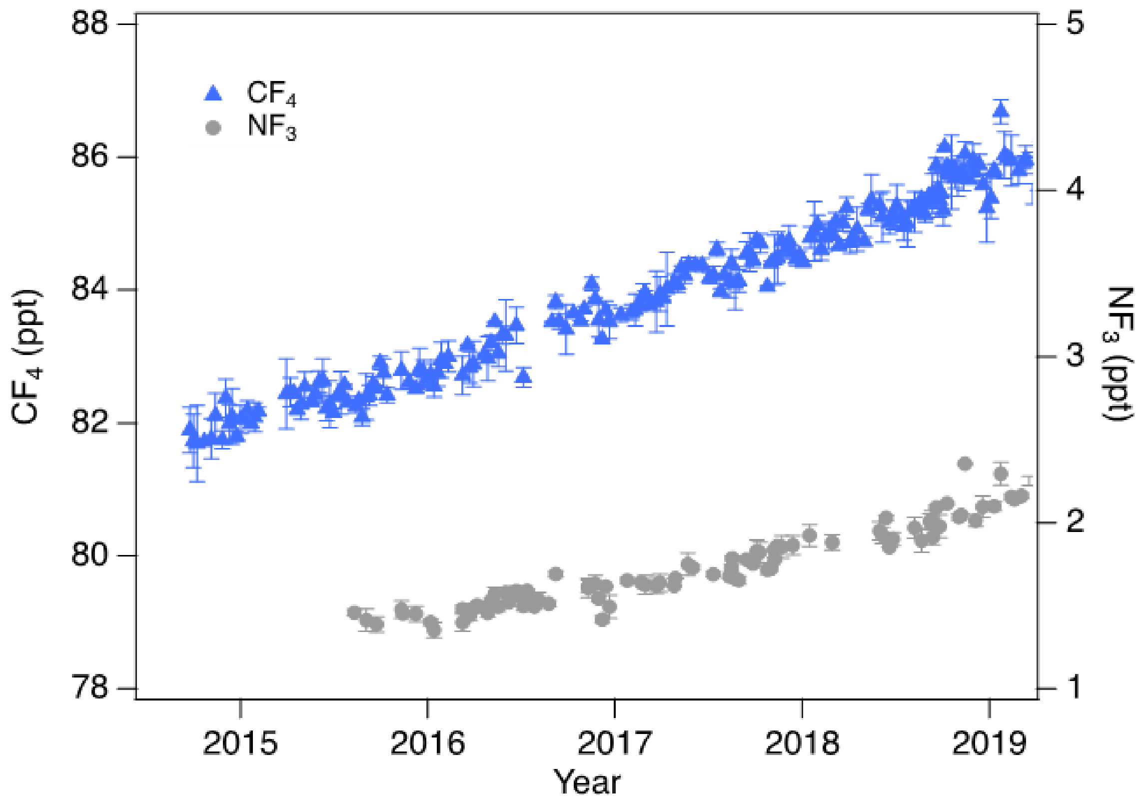

Figure 5.3: Results for CF4 (blue triangles) and NF3 (grey circles) measured on PR1 from HATS flasks collected at MLO from 2014-2018. Note that we have temporarily adopted AGAGE calibration scales for these measurements.

gases present in the atmosphere in mole fractions ranging from 10s of parts-per-quadrillion (ppq) up to 10s of part-per-billion (ppb) (Table 5.4). As a replacement for M2, Perseus was designed to measure all the gases measured by M2 plus certain highly volatile gases, such as CF4 and NF3 (Figure 5.3), which were not measured by M2.

In Perseus, a nominal 500 cc air sample is dried using a Nafion counter-purge drier before pre-concentration on 50 mg of divinyl benzene chromatographic adsorbent (100/120 mesh) maintained at -165˚C. A post-trapping flush with helium carrier gas of the adsorbent at -60˚C moves CF4, NF3 and CO2 from this first stage trap onto a molecular sieve 4A column at 40˚C, where CO2 is removed, and the CF4 and NF3 pass onto a second stage adsorbent trap (5 mg divinyl benzene) at -165˚C. The remaining 58 analytes plus residual water are then desorbed at +100˚C and pushed with helium through a second Nafion dryer before pre-concentration on the second trap. These analytes, along with CF4 and NF3, are then desorbed at +100˚C and pushed with helium onto 5m of PoraBond Q capillary precolumn (0.32mm I.D.), which leads to 25m of GasPro capillary column and the mass selective detector. Backflush of the precolumn after elution of CHBr3 prevents heavier, undesirable compounds from reaching the main chromatographic column. The total sample analysis time is 22.5 min. The first stage trap allows samples of pressures ranging from sub-ambient to ~40 psia to be analyzed without regulators. Approximately weekly mapping of the instrument's nonlinearities is performed by injection of different volumes of a single standard gas over a range of approximately 10% to 500% of the nominal 500 cc standard injection. 'System blanks' (non-sample injections) are performed approximately twice daily to correct all other samples for any trace contamination from system hardware. Long-term reproducibility of analytes ranges from 0.1% to several percent relative standard deviations depending on analyte abundance. All field sample measurements are made relative to ambient whole air standards collected at Niwot Ridge and stored in either Aculife- treated aluminum or Essex stainless steel cylinders. Periodic comparison of standards allows detection and correction of any analyte drift within the tanks.

5.1.3 FLASK ANALYSIS BY GC-ECD:

Analysis of flask samples with the electron capture gas chromatograph known as "Otto" continued from 2014-2018. However, the performance of this system has deteriorated significantly for some gases. N2O and SF6 are no longer measured on this system, and data quality for CFC-12 has suffered.

The Shimadzu GC-ECD used to measure N2O and SF6 quit working just prior to the onset of 2014. We were unable to repair or replace this aging sub-system. In early 2015, a mysterious instability appeared in the baseline signal near the CFC-12 peak on the Porasil A channel. This degraded the analysis of that peak and increased the noise of the measurement to a very significant degree. Efforts to diagnose and rectify the problem were unproductive. In the spring of 2017, the baseline problem worsened to the point that the CFC-12 peak could not be integrated using standard methods. It is hoped that through the future development of a special post-processing method designed to overcome the problematic characteristics of the affected chromatograms, we will ultimately be able to recover some CFC-12 data. In the meantime, we have not reported any CFC-12 results from ECD analysis of flask samples since March of 2017.

The OV-101 channel continues to produce high- quality measurements of CFC-11, CFC-113, and CCl4. We also continue to report measurements of CH3CCl3 from this channel, although atmospheric background concentrations of this molecule are now very close to Otto's minimum detectable limit, and relative measurement precision has deteriorated accordingly. Precisions on the remaining molecules (i.e., CFC-11, CFC-113, and CCl4) have modestly worsened by factors of 2 or less, while still remaining fairly close to the

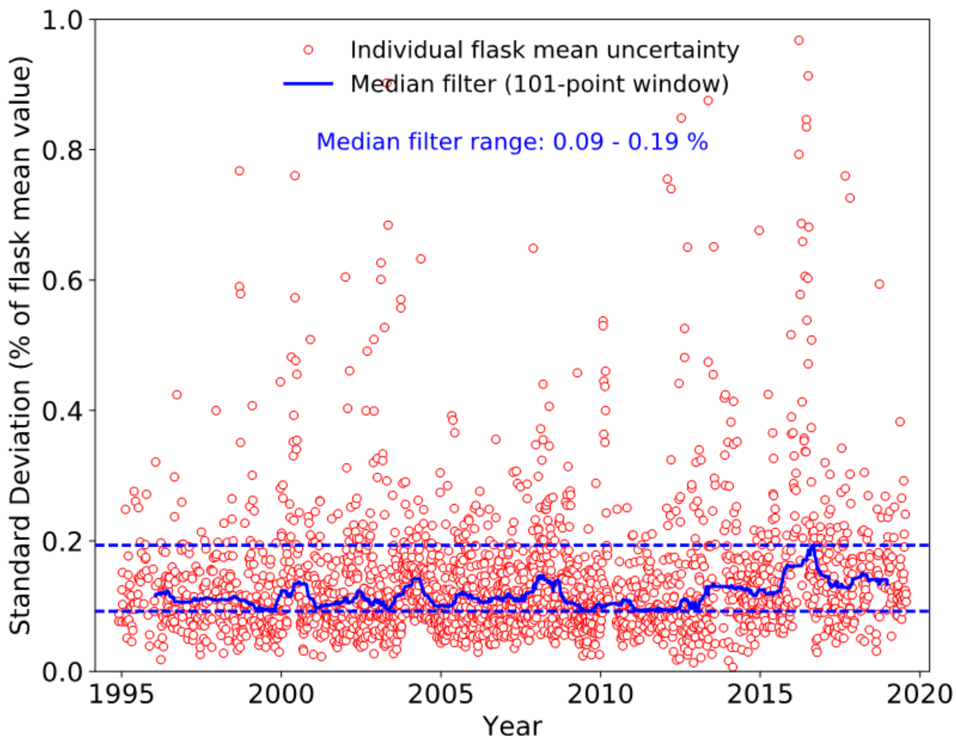

Figure 5.4: CFC-11 standard deviations from Otto measurements of flasks. Red circles are individual flask mean standard deviations based on multiple injections (aliquots) from each flask sample. The solid blue line is a median filter applied to the data with a 101- point window. 101 is approximately the number of flasks filled at SMO in one year. The dashed blue lines mark the lower and upper extremes of the running median standard deviations, 0.09% and 0.20%, respectively.

historic peak performance of this system (Figure 5.4). In the late fall of 2018, work began on a replacement gas chromatograph based on an Agilent 7890 GC. The new system will allow measurement of most of the same gases as Otto, at higher throughput. We are not planning to measure CH3CCl3 with the new system, but measurement of H-1211 and CHCl3 should be possible.
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5.1.4 IN SITU SURFACE MEASUREMENTS (CATS)

The HATS in situ program started in the 1980s and continues today with five GC-ECD systems at NOAA baseline observatories (BRW, MLO, SMO, and SPO) as well as a cooperative site in Colorado (NWR). The current set of instruments (known as CATS: Chromatograph for Atmospheric Trace Species) were deployed in at BRW, MLO, SMO, and SPO in 1998; NWR in 2000, and SUM in 2007. However, the CATS instrument located at SUM and several other GMD instruments were removed from the site in July of 2017 due to funding shortfalls. 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). CATS

Table 5.5: Significant events and changes to CATS instruments.

Site	Date	Comment
BRW	5/30/2013	Significant improvements to ECD temp control affecting N2O/SF6.
BRW	2/22/2018	Changed N2O/SF6 chromatography to use N2 carrier gas and CO2 doping.
MLO	7/27/2014	Changed N2O/SF6 chromatography to use N2 carrier gas and CO2 doping.
MLO	10/22/2018	An audit of the SF6 measurement was performed by Korea Meteorological Admin.
NWR	7/28/2014	Replaced N2O/SF6 ECD.
NWR	7/24/2018	Replaced wall-mounted room air conditioner.
SMO	11/2017-7/2018	New tower and sample lines installed. Tower painted in 2018.
SMO	9/18/2018	Changed N2O/SF6 chromatography to use N2 carrier gas and CO2 doping.
SPO	1/1/2014	No significant changes during 2014-2018.
SUM	7/31/2015	Building raised again. Air inlets moved to top of building.
SUM	4/30/2016	Changed N2O/SF6 chromatography to use N2 carrier gas and CO2 doping.
SUM	7/24/2017	Instrument shutdown and removed from station.

instruments were custom-built in the 1990s and have since undergone field maintenance, repairs, and upgrades. Table 5.5 expands on the previous GMD summary report documenting many of the significant changes to each CATS instrument.

CHANGES AND IMPROVEMENTS TO CATS INSTRUMENTS

The original configuration of the CATS instruments used three different carrier gases: nitrogen (N2), helium (He), and P-5 (95% argon and 5% methane). The methane (CH4) in the P-5 carrier gas acts as a dopant to enhance the response of N2O in an electron capture detector. To reduce operational costs and simplify shipping and handling of carrier gas cylinders to observatories, the CATS systems were transitioned from P-5 to N2 with an addition of carbon dioxide (CO2) as the dopant. The instrument at NWR was refurbished in 2007 after sustaining damage from rainwater and has demonstrated the N2/CO2 doping system's use and reliability. All of the CATS GCs have been reconfigured to the N2/CO2 doping system except for SPO where there is an abundance of P-5 onsite for the next few years. Air is sampled from four ports; two calibration cylinders and two airlines with constant flow delivered by diaphragm pumps. The pump manufacture, KNF Neuberger Inc. (Trenton, New Jersey), discontinued the model of the pump (N05) used by the in situ and flask programs. The replacement pump (N86) is nearly identical in shape and size; however, the valve flap is slightly smaller, and the diaphragm is molded and now attached to a threaded stem. N86 pumps have been installed at all stations (BRW, NWR, SMO, and SPO) except MLO, where the last remaining N05 pumps are in use.

DATA ARCHIVING

In 2016 GMD was awarded a grant associated with the Big Earth Data Initiative (BEDI) to archive and improve the discoverability of some of the division's important data sets. As a part of the BEDI work, the CATS and its predecessor program (known as RITS: Radiatively Important Trace Species) have been published and received a Digital Object Identifier (DOI). Both of these data sets are available on the GMD ftp site in text format and net-CDF format at the NCEI archive (RITS: http://doi.org/10.7289/V51N7ZDK and CATS: http://doi.org/10.7289/V5X0659V).

AUDIT OF THE MLO SF6 MEASUREMENT

In late October 2018, the WMO World Calibration Center for SF6 operated by the Korea Meteorological Administration (KMA), sent three
scientists to MLO to conduct a formal audit of the CATS SF_6 measurement system. Four calibrated cylinders were analyzed on the CATS instrument and processed through custom CATS software. The results were mixed. The CATS SF_6 measurement agreed with the KMA values on 3 of the four cylinders, however, the precision of the CATS system was poor. After the audit, it was determined that the ECD on the N_2O/SF_6 channel was failing. A replacement ECD was installed in April 2019.

5.2 HATS INVERSE MODELING

Variability in atmospheric trace gas concentrations measured in air in the mid-continental United States primarily reflects spatial gradients and temporal changes in human emissions and the climate response of natural ecosystems. The ability to accurately extract this information from our atmospheric measurements and provide estimates of emissions of trace gases affecting climate, stratospheric ozone, air quality, and insights into climate feedbacks adds to the societal value of the measurements being made in NOAA GMD.

The development of HATS regional inverse modeling capability was first initiated in 2012 as a collaborative effort with CCGG's CarbonTracker- Lagrange (CT-L) project. The initial inverse modeling framework was coded using MATLAB, with an objective for deriving U.S. national and regional emissions of ozone-depleting substances, which are also potent greenhouse gases. In 2016, we started to incorporate inverse modeling algorithms specific to the HATS MATLAB inverse modeling system (e.g., Maximum Likelihood Estimation, optimizing scaling factors of surface fluxes) into the CT-L core modeling framework.
We also derived new algorithms to optimize the diurnal cycle of CO2 on a weekly basis in CT-L.

The inference of surface fluxes from atmospheric observations assumes that the measured enhancement (or reduction) of trace gas mixing ratios relative to those measured in the background atmosphere correlates linearly with regional fluxes. Using Bayesian methods, a mathematical representation of surface fluxes as a function of observed mixing ratio enhancement or deviation (relative to background atmosphere), atmospheric transport, an a priori flux estimate is developed. In the current inverse model system for halocarbons, posterior emissions are derived on a monthly timescale and with a 1o × 1o spatial resolution in a 15- to 18-month batch inversion.

We are operationalizing the regional inverse modeling framework so that we can provide annual or biennial updates on atmosphere-based (top-down) U.S. national and regional emission and uptake estimates for gases measured by GMD. While the focus has been on gases measured by the HATS group, we are working with the CCGG group to bring this modeling capability into a GMD-wide regional modeling product. Further, we plan to transition our MATLAB-based modeling framework to a PYTHON-based model framework, where we will derive surface fluxes at weekly resolution to reduce temporal aggregation errors in the optimized fluxes. We are also exploring the robustness of our emissions estimates at the state level.

5.3 AIRBORNE PROJECTS

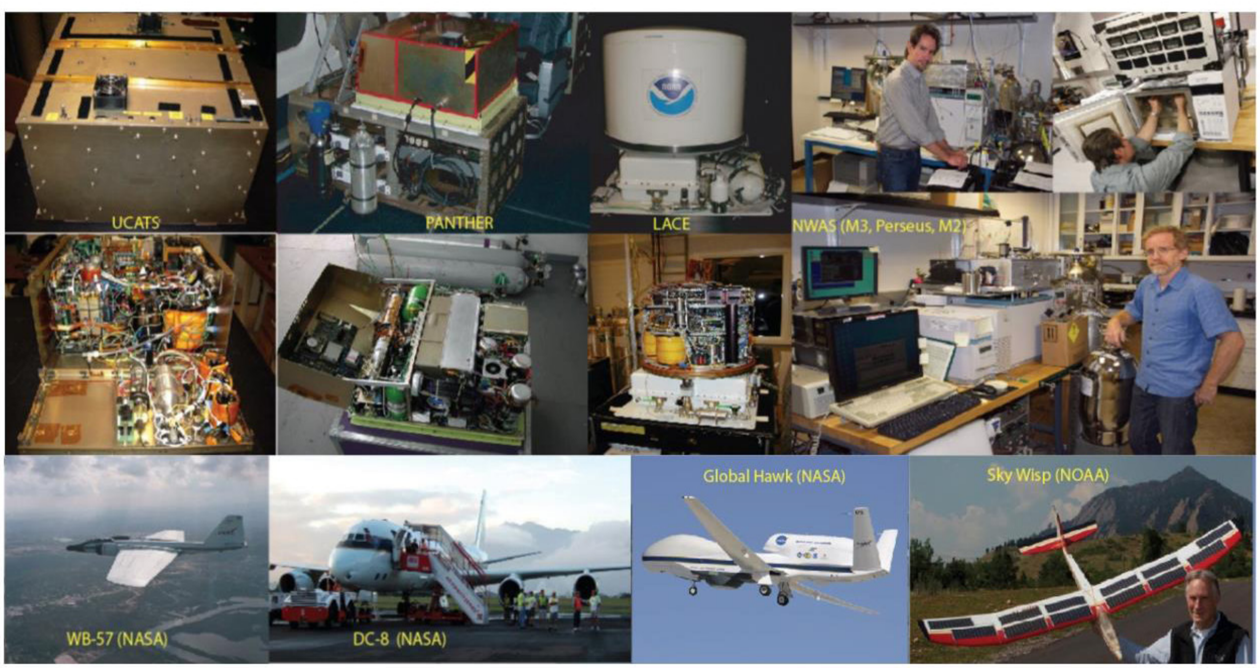

Figure 5.5: Photos of instrumentation and platforms associated with airborne and special projects from 2014-2018.

Table 5.6: Science missions from 2014-2018 involving HATS airborne instruments.

Date	Mission Name	Location	Platform	Instrument Used
2016-2018	ATom 1-4, Atmospheric Tomography Mission	Open Pacific and Atlantic, Antarctica, and the Arctic	NASA DC-8	PANTHER, UCATS, NWAS
2016	POSIDON	Guam	NASA WB-57	PANTHER
2011-2014	ATTREX 1-3, Airborne Tropical Tropopause Experiment	NASA DFRC (CA); Guam	NASA Global Hawk	UCATS (O3, H2O)
2013-2014	Sky Wisp - NOAA	Boulder, CO	Balloon, Sky Wisp	O3 sonde

Measurements of trace gases in the free troposphere and lower stratosphere are an important part of HATS division activities. We have developed several custom instruments (Figure 5.5) to measure halocarbons, nitrous oxide, sulfur hexafluoride, ozone, water vapor, peroxyacetyl nitrate (PAN), methane, and molecular hydrogen (H2) aboard aircraft and balloons, and we have deployed these instruments on various platforms in numerous campaigns (Table 5.6).

INSTRUMENTATION

LACE

Lightweight Airborne Chromatograph Experiment (LACE) is a high-altitude, three-channel GC-ECD 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-ECD capable of measuring gases listed for LACE, plus PAN, selected HCFCs and HFCs, methyl halides, COS, and H2O. A tunable diode laser spectrometer to measure water vapor can also be included in the package.

UCATS

Unmanned aircraft systems Chromatograph for Atmospheric Trace Species (UCATS) is a two- channel GC-ECD instrument capable of measuring SF_6, N_2O, CH_4, CO, H_2, O_3, and H2O. Measurements of CFCs and Halon-1211 can be substituted for CH_4 CO, and H_2. An ozone photometer and water vapor TDL have also been included in UCATS.

NWAS

NOAA Whole Air Sampler (NWAS) is a flask-sampling system that uses the CCGG Programmable Flask Packages to collect flask samples onboard aircraft.

StratCoreGC

This laboratory instrument is a two-channel GC- ECD capable of measuring halon-1211, CFCs, SF6, and N_2O from AirCores collected primarily for characterizing the composition of stratospheric air.

5.3.1 DEPLOYMENTS AND ADVANCEMENTS 2014- 2018

The NASA Airborne Tropical Tropopause Experiment (ATTREX) mission was designed to study the transport of water vapor and other trace gases in the tropical tropopause layer (TTL) over the Pacific Ocean, to better understand how dehydration occurs and how ozone-depleting gases reach the lower stratosphere. UCATS was installed on the NASA Global Hawk unmanned aircraft system (UAS) for flights over the western tropical Pacific from Guam in January-March 2014 (ATTREX-3). This followed two previous deployments with flights from California to the central and eastern tropical Pacific (ATTREX-1 and 2).

The NASA Pacific Oxidants, Sulfur, Ice, Dehydration, and Convection (POSIDON) Experiment was a brief airborne mission to study oxidation and sulfur chemistry, cirrus clouds, and dehydration in the TTL over the western Pacific. The NASA WB-57F aircraft flew out of Guam in October 2016, with a payload including PANTHER. The focus was on providing data to better evaluate the hypothesis of a minimum in O3 (and possibly OH) in the upper troposphere and its possible impact on short-lived halogenated species and sulfur, over a geographic region with intense convection driving rapid transport from the lower and mid-troposphere to the TTL. Other goals were to test global chemistry transport model simulations of anthropogenic and natural sulfur species, and to obtain additional data on microphysical properties and water vapor in anvil cirrus detrained from deep convection as well as thin cirrus near the tropopause that regulate water vapor entering the stratosphere. Data from all of our airborne missions are available on the NASA Earth Science Project Office site at https://espoarchive.nasa.gov.

PANTHER, UCATS, and the NWAS system were deployed on the NASA DC-8 aircraft during the NASA Atmospheric Tomography (ATom) mission from 2016-1018. Trace gases, aerosols, and reactive gases were measured during all four seasons above the Pacific and Atlantic Oceans, with excursions over Antarctica and the Arctic. These data will be used in studies of ozone and oxidant distributions over the oceans; the reactive nitrogen budget of the remote troposphere; the global distribution of SF6; and tropospheric age-of-air.

The last LACE balloon flight to sample the lower and middle stratosphere occurred in 2004. We are currently working to extend in time our measurement records of halocarbon concentrations at these altitudes because of their importance for diagnosing anticipated climate- driven changes in stratospheric circulation which, in turn, could induce strong feedbacks on tropospheric climate. There is a growing understanding that climate models will be of limited value if they do not incorporate a realistic representation of this changing stratospheric circulation. To that end, we have proposed an affordable long-term stratospheric circulation- monitoring program using AirCore technology. We constructed and tested a gas chromatograph (StratCore GC) capable of measuring N2O, SF6, CFC-11 CFC-12, CFC-113, halon-1211, and CCl4 invery small samples of air (a few cm3) which could be sampled from an AirCore. In addition, we have been developing new techniques to interpret stratospheric data that provide information on age-of-air and photolytic loss. These data will allow us 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.

We performed feasibility studies using small, fixed-wing, remotely piloted or autonomous UAS and balloons to loft an instrument package (e.g. AirCore) to stratospheric altitudes and return to a pre-determined ground location. In tests, a Sky Wisp aircraft was used to carry an ozone sonde (Fig. 5.5).

5.4 HATS STANDARDS PROJECT

The ability to prepare custom gas mixtures for calibration purposes is an important part of the HATS overall program. Methods for preparing gravimetric standards were developed in the 1980s and have continued to be improved upon. We also prepare working standards and archive samples by filling cylinders with whole air at a facility in the Colorado mountains west of Boulder (C-1 facility, Niwot Ridge, Colorado). Specific activities related to gas standards are discussed in a separate chapter (8.0).

SECTION 6 - OZONE AND WATER VAPOR (OZWV) GROUP

RESEARCH OVERVIEW

The Ozone and Water Vapor Research Group conducts long-term observations and intensive field campaigns 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 and column - (Balloon-borne Frost Point Hygrometer and radiosondes)
- Ground-level ozone - (UV surface ozone monitor)
- Aircraft ozone - (UV surface ozone monitor)

Measurements of the thickness of the ozone layer began with the establishment of the Dobson spectrophotometer global network in the early 1960s. We maintain Instrument #83, which serves as the world standard for this network. Total ozone column (TOC) measurements are made three times per day during weekdays at 16 locations around the globe, with several records now surpassing 50 years. We measure Umkehr ozone profiles at six of the sites. The Umkehr profile layers fall broadly within ten standard pressure levels.

Ozonesondes provide a high-resolution measurement of ozone and temperature from the surface to 30–35 km altitude. We intermittently started the ozone profile measurements in the 1960s using the Regener chemiluminescent balloon-borne ozonesondes, which were replaced by the now commonly used electrochemical concentration cell (ECC) ozonesondes. Regular weekly ozonesonde measurements began at three GMD observatory sites in the mid-1980s: BLD, SPO, and MLO (launched from Hilo). The collocated Dobson spectrophotometers at these sites have been a valuable guide for comparison of TOC, and in turn, the ozonesonde vertical profiles complement the Dobson Umkehr profile sites. The expansion of ozonesonde launches to several tropical locations began in 1998 through the NASA SHADOZ (Southern Hemisphere Additional Ozonesondes) program (http://croc.gsfc.nasa.gov/shadow/). This NASA/NOAA collaboration expanded ozonesonde observations to under-sampled tropical and sub-tropical sites.

Balloon-borne frost point hygrometers (FPHs) built in our laboratory measure water vapor profiles from the surface to the middle stratosphere (approximately 28 km), with a focus on the upper troposphere and lower stratosphere (UTLS). FPHs are launched every 3-4 weeks at three sites: BLD, MLO (launched from Hilo), and Lauder, New Zealand. The long-term water vapor measurement records at these sites began in 1980, 2010, and 2004, respectively. In addition, since mid-2017, FPH and ECC soundings at BLD and Lauder have been coordinated with overpass measurements of stratospheric water vapor and ozone by the third generation Stratospheric Aerosol and Gas Experiment (SAGE III) aboard the International Space Station for the purpose of validating the satellite-based retrievals of these gases.

We continue to launch Vaisala radiosondes with the ECC and FPH payloads at Boulder as part of the Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN). These weekly soundings of pressure, temperature, relative humidity, and horizontal winds have been performed at Boulder since 2011. Vaisala RS92 radiosondes were launched at Boulder for GRUAN soundings until they were replaced by Vaisala RS41 radiosondes in January 2017. Boulder's weekly radiosonde sounding program was certified by GRUAN in 2014 and re-certified in 2018, indicating a high level of consistency in the site's pre-flight instrument checks and launching procedures.

We currently monitor ground-level ozone using ultraviolet (UV) absorption photometers at twelve sites that are generally representative of background atmospheric conditions. These sites, two of which have records exceeding 45 years in length, provide information on long-term changes in tropospheric ozone near the surface. In addition, since 2004 we have used UV ozone monitors onboard the CCGG sampling aircraft with small, portable 2B Technologies ozone monitors. The instruments collect ozone, temperature, humidity, and GPS data during routine vertical profiling flights at two locations.

6.1 TOTAL COLUMN OZONE

OVERVIEW

We maintain a global network of Dobson Spectrometers for measuring total column ozone (TCO) to detect and understand changes in atmospheric ozone abundance. Nine of these stations are operated by NOAA. One station is operated by NASA, one is operated by the University of Alaska at Fairbanks, and four are operated by foreign entities. Several NOAA stations have TCO measurement records exceeding 50 years in length. In addition to TCO measurements, six network stations produce ozone profiles using special measurements called the Umkehr technique. We also maintain the world standard Dobson instrument to which all others are calibrated.

DOBSON MEASUREMENTS

From 2014 to the present, we continued to make total column ozone measurements at the stations that constitute the U.S. Dobson spectrophotometer network, listed in Table 6.1. All instruments in the network are either fully automated or semi-automated, except for one manual instrument at Marcapomacocha, Peru. Instrument D042 was returned to Boulder in 2016 after deployment to our observatory at the South Pole, Antarctica. It was replaced by instrument D082 after both instruments were operated in a quasi-simultaneous manner for one year to assure consistency of observations. D042 was recalibrated against D083 in 2017, and internal heaters were added to help control humidity within the instrument. The WinDobson automation system has performed well in Boulder, Mauna Loa, and Lauder, NZ, since 2012.

Several upgrades were made to the WinDobson software, including automatic updates to the control table after monthly checks. The automation of instruments at OHP and FBK was upgraded in 2014 with systems designed by the Japan Meteorological Agency. The upgrades included replacing the instrument's internal electronics, computer interface system, and the WinDobson software package, which contains additional data analysis and quality control features. The software can also be used to more efficiently process data from non-automated machines and create informative reports. The NOAA automated Dobson at Perth, Australia (PTH) failed in 2016 and is the only instrument within the network that was not upgraded with WinDobson. We are currently seeking funding to rebuild this instrument. The Australian Bureau of Meteorology (BoM) support for the instrument at PTH is uncertain; the plan is to reduce hours for the BoM operator at the station. NASA proposed to replace the Dobson instrument with a fully automated ozone-measuring instrument (i.e., Brewer or Pandora).

Many of the NOAA operational sites transfer data electronically, allowing for access to preliminary ozone data in near real-time. GMD processes all submitted data every two weeks and submits near real-time data to the NDACC. In addition, every six months, GMD QA/QC verifies Dobson data which is archived at the WMO GAW World Ozone and Ultraviolet Data Centre (WOUDC), Canada (http://www.woudc.org).

PANDORA MEASUREMENTS

In late 2013, the Pandora instrument (#34, NASA/Goddard collaborations) was installed in Boulder next to the Dobson on the roof of the David Skaggs Research Center (DSRC) building. The Pandora spectrometer

Table 7. 1: U.S. Dobson Ozone Spectrophotometer Station Network, 2014-2018

Station	Period of Record	Instr. #	Agency	Automation Type
Bismarck, North Dakota	1963 - 2017	33	NOAA	Semi-Auto
Caribou, Maine	1 Jan 1963 - current	34	NOAA	Semi-Auto
Wallops Isl, Virginia	1 Jul 1967 - Present	38	NOAA, NASA	Semi-Auto
Samoa, American Samoa	13 Dec 1975 - Present	42	NOAA	Semi-Auto
Tallahassee, Florida	2 May 1964 - 30 Sep 2005	58	NOAA, Florida State University	1964
Boulder, Colorado	1 Sept 1966 - Present	61	NOAA	WinDobson automation in 2009, Umkehr
Fairbanks, Alaska	6 March 1984 - Present	63	NOAA, University of Alaska	WinDobson automation in 2014, Umkehr
Lauder, New Zealand	29 Jan 1987 - Present	72	NOAA, NIWA	WinDobson Automation in 2011, Umkehr
Mauna Loa, Hawaii	2 Jan 1964 - Present	76	NOAA	WinDobson automation in 2010, Umkehr
Nashville, Tennessee	2 Jan 1963 - Present	79	NOAA	Semi-Auto
Perth, Australia	30 Jul 1984 - July 2016	81	NOAA, Bureau of Meteorology	Semi-Auto Umkehr
South Pole, Antarctica	17 Nov 1961 - Present	82	NOAA	Semi-Auto
Haute Provence, France	2 Sep 1983 - Present	85	NOAA, Centre National De la Recherché Scientifique	WinDobson automation in 2014 -Umkehr
Marcapomacocha, Peru	26 Feb 2001 - Present	87	NOAA, Sevicio Nacional de Meteorologia d'Hidiologia	Manual
Barrow, Alaska	6 Jun 1986 - Present	91	NOAA	Semi-Auto
Fresno, California	22 June 1983 - 13 March 1995	94	NOAA	Semi-Auto
Hanford, California	14 March 1995 - Present	95	NOAA	Semi-Auto

system TCO algorithm is based on spectral fitting, 305–330 nm, of the attenuated solar spectrum using a modern small symmetric Czerny–Turner design spectrometer (Herman et al., 2015). From the laboratory data (NASA/Goddard), a polynomial is fitted to the results as a function of pixel column number 1–2048. Wavelength calibration is validated using comparisons with the slit function convolved with high-resolution Kurucz spectrum's solar Fraunhofer lines. Total ozone is derived with high temporal resolution (4 sec).

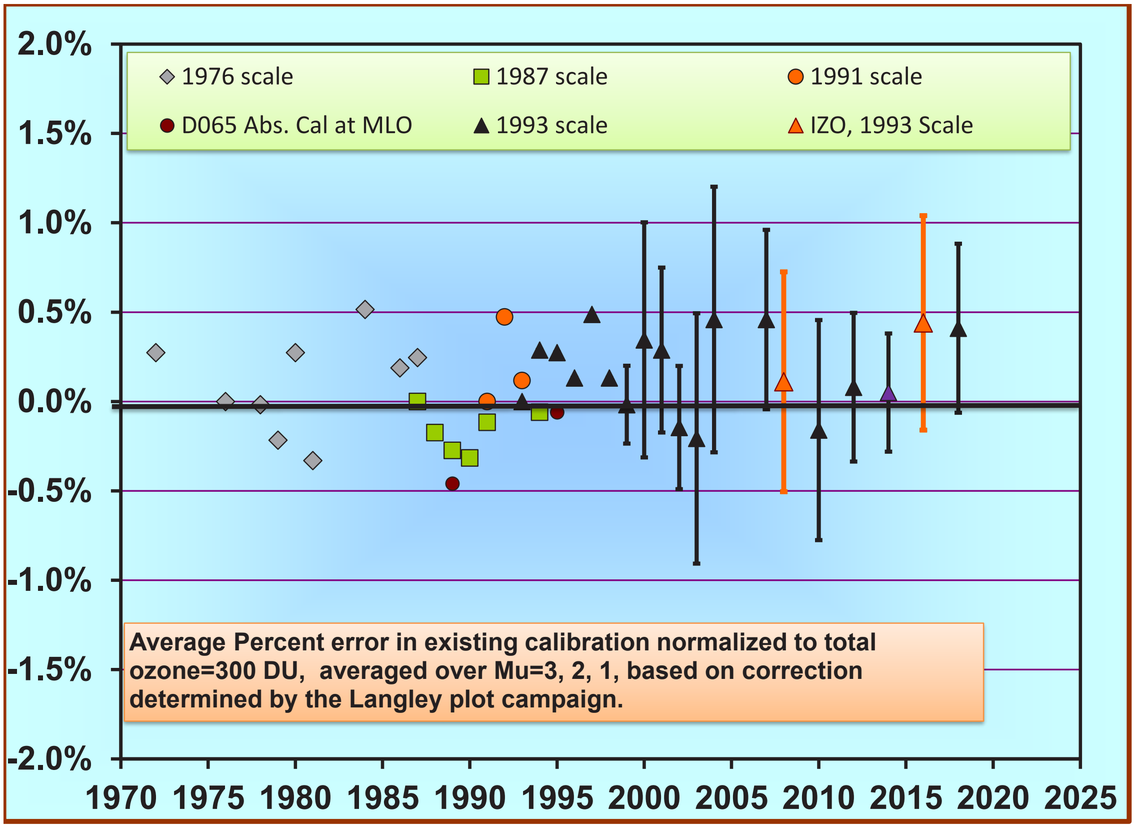

Figure. 761: This figure shows the results of Langley measurements made through 2018. They are presented as the percent error introduced to a measurement of 300 Dobson units using the existing calibration.

CALIBRATION OF DOBSON SPECTROPHOTOMETERS

GMD maintains the world standard Dobson instrument (D083). The calibration is checked during even-numbered years at our Mauna Loa Observatory (MLO) using the Langley technique. The results are displayed in Figure 6.1. In March 2016, a GMD staff member participated as the Scientific Director for the Region II Intercomparison of Dobson Instruments held in Tsukuba, Japan. Dobson D083 and GMD staff also participated in the WMO Region V intercomparison in Broadmeadows Australia in February 2017. The calibration of the region II standard (D116) and the Australian regional standard (D105) were both checked during this event. In March 2019, Dobson 065 and GMD staff members were sent to the Region III Intercomparison of Dobson Instruments held in Buenos Aires, Argentina. The South American regional standard Dobson 070 was calibrated during this event. In October 2019, GMD staff and Dobson 065 traveled to Irene, South Africa, to participate in the Region I intercomparison of Dobson instruments. The calibration of the European regional standard D064 was also checked.

The Boulder station instrument (D061) is normally compared with the primary standard (D083) during most intercomparisons at Boulder. 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 and after shipping. These instruments are maintained to within ±1% of the primary standard. Instrument D065 has maintained calibration to within ±0.5% since 1994.

In the spring of 2016, WMO World Standard Dobson 083 traveled to Physikalisch-Technische Bundesanstalt (PTB), Germany's national metrology institute (https://www.ptb.de/cms/en.html) in Braunschweig, Germany, where precise measurements of its spectral bandwidth were made using a tunable laser. D064 (European standard, Hohenpeissenberg, Germany) and D074 (secondary European standard, Prague, Czech Republic) were also characterized during this project. This work was conducted for the EU ATMOZ (TRACEABILITY FOR ATMOSPHERIC TOTAL COLUMN OZONE) collaborative project (http://projects.pmodwrc.ch/atmoz/). In September 2016, these Dobson instruments and other ozone measuring instruments participated in the ATMOZ campaign at Tenerife. Dobson D083 made eleven Langley measurements over a fourteen-day period. The results of this campaign were used to compare the performances of instruments used to measure total ozone column (TCO).

6.2 UMKEHR OBSERVATIONS

Umkehr observations are routinely performed by automated Dobson instruments at BDR, MLO, UAF, OHP, and LDR. PTH observations stopped in July 2016 due to instrument automation system failure. These observations allow us to monitor daily and long-term changes in the vertical profile of the ozone layer.

The UMK08 algorithm (Petropavlovskikh et al., 2005) was used to operationally process all NOAA Umkehr measurements in 2014-2018. GMD archives all NOAA Umkehr data (ftp://aftp.cmdl.noaa.gov/data/ozwv/Dobson/Umkehr/) and routinely deposits it at the WOUDC. A shallow python wrapper around Fortran code that executes the UMK08 ozone profile processing was developed at the end of 2018 (https://github.com/woudc/woudc-umkehr/). The generalized (instrument independent) stray light correction (SLC) procedure is routinely applied to NOAA Umkehr data processing (option in WinDobson Umkehr processing software). The SLC version of NOAA Umkehr data is archived here: (ftp://aftp.cmdl.noaa.gov/data/ozwv/DobsonUmkehr/Stray light corrected/). The method to account for optical characteristics of each individual Dobson instrument (i.e., optimized stray light contribution) is currently in development. The aim is to reduce long-standing differences (biases) between Dobson and other ozone measuring networks and homogenize the Dobson Umkehr station record (i.e., minor offsets between data collected by multiple instruments contributing to the station record). The NOAA EPA UV Brewer network (NEUBrew, http://www.esrl.noaa.gov/gmd/grad/neubrew/) was formed in 2006 and had Brewer instruments installed at six NOAA stations across the continental United States (Boulder TMTF, CO; Bonneville, IL; Ft. Peck, MT; HAO, CO; Houston, TX, and Raleigh, NC). 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 (http://www.o3soft.eu/o3bumkehr.html) were developed to derive daily ozone profiles (http://www. esrl.noaa.gov/gmd/grad/neubrew/ProductDisplays.jsp#o3profiles) in an approach similar to the method used in the Dobson Umkehr profile retrieval (i.e., UMK08, see above). Umkehr data and retrieved ozone profiles are archived at the NOAA NEUBrew site and available at an ftp access website for free download pending user registration (https://esrl.noaa.gov/gmd/grad/neubrew/Data.jsp).

6.3 OZONESONDE VERTICAL PROFILES

Table 6.2 lists the long-term NOAA GMD balloon launch sites and the number of years in operation for ECC ozonesondes and frost point hygrometer (FPH) water vapor sondes. The number of launches (i.e., profiles measured) during 2014-2018 are given in the adjacent column. The table also identifies participation in various campaigns and denotes the sites that are part of the NDACC network. Our collaboration with the NASA Southern Hemisphere Additional Ozonesondes (SHADOZ) project is currently at 22 years. The SHADOZ project began in 1998 to augment balloon-borne ozonesonde launches and provide an archive of tropical and subtropical ozonesonde profile data. The initial NASA Goddard-funded project resulted i

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, with six sites fully or partially supported by NOAA's Ozone and Water Vapor Group.

Table 7.2. Balloon Ozonesonde and Frost Point Hygrometer (FPH) Water Vapor site Network, 2014-2018

SITE	Ozone-sonde Record	Ozone Profiles	Water Vapor Record	Water Vapor Profiles	NOAA Obser-vatory	SHADOZ Site	ATom-1	ATom-2	ATom-3	ATom-4	MATCH	SAGE-III ISS Valida-tion Site	NDACC Site
		2014-2018		2014-2018									
Boulder, CO (BLD)	1979-2018	255	1980-2018	61	X*				X			X	X*
Hilo, HI (MLO)	1982-2018	253	2010-2018	55	X*	X	X	X	X	X			X*
American Samoa (SMO)	1995-2018	194			X	X	X						X
South Pole (AMS)	1986-2018	258			X				X	X			X
Trinidad Head, CA (THD)	1997-2017	223			X								
Huntsville, AL	1999-2017	213											
Summit, Greenland (SUM)	2005-2017	178					X	X			X		
Suva, Fiji	1997-2018	92				X		X		X			
San Cristobal, Galapagos	1998-2015	32				X							
Watukosek, Indonesia (supplies shipped)	1998-2013	4				X							
Ha Noi, Vietnam (supplies)	2004-2018	96				X							
La Reunion (supplies)	2003-2018	96				X							
Lauder, New Zealand			2004-2018	52								X*	X*

The high-resolution profile data from NOAA locations (for ozone and water vapor) and SHADOZ collaborative sites (for ozone) track stratospheric and upper tropospheric trends. The South Pole 34-year ozonesonde record has been an essential data set for tracking the yearly September-October Antarctic ozone hole severity through yearly minimum ozone columns and 14-21 km September ozone loss rates.

In 2017, funding ended for the observatory at Trinidad Head, CA, though ozonesonde launches continued through the California Air Resources Board while we continued to provide data editing and processing assistance. Funding reductions also ended ozonesonde observations for the observatory at Summit Station, Greenland, and the University of Alabama-Huntsville; however, UAH has obtained some NASA funding to continue with approximately 1-2 sondes per month.

ATom

The ozonesonde balloon group participated in all four of the NASA Atmospheric Tomography Mission (ATom) missions by launching coincident balloons at Hilo, Hawaii; Suva, Fiji; American Samoa; and the South Pole during takeoff, landing, or closest approach to match vertical profiles of ozone with the samples made on the DC-8 aircraft. In total, 14 ozonesondes were launched, coinciding with the ATom flights.

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. The NOAA GMD Summit, Greenland ozonesonde site participated in the January-March, 2014 and 2016 campaigns.

GALAPAGOS SITE VISIT

In 2014, a SHADOZ site visit was made to San Cristobal Island, Galapagos, to upgrade hardware, verify standard operating procedures, and meet with the leadership of the Ecuadorian National Meteorological and Hydrology Institute (INAMHI) to discuss continued funding and operation of the ozonesonde site in the Galapagos. The ozonesonde launches have been on hold since 2015.

Table 6.3 lists the short-term ozonesonde field and intercomparison campaigns. We provide a brief description of each campaign below. Participation in intercomparison campaigns (e.g., Julich Ozone Sonde Intercomparison Experiment (JOSIE) in Juelich, Germany) are important for addressing changes in ozonesonde models, sonde preparation procedures, and sensing solution used at various worldwide sites. These quality assurance (QA) campaigns, along with NOAA laboratory tests and dual ozonesonde flights, have characterized correction algorithms to maintain a homogenous data record.

NOAA FPHs were launched during NASA campaigns POSIDON and ATTREX to validate the in situ water vapor measurements of aircraft instruments. An “X” indicates campaign measurements of ozone by ECC ozonesondes while * denotes campaign measurements of water vapor by FPHs.

JOSIE-SHADOZ 2017

NOAA-GMD participated in the JOSIE-SHADOZ 2017 campaign, held during two 10-day periods in October and November of 2017 at the World Calibration Center for Ozonesondes in Juelich, Germany. A total of 20 pressure, temperature, and ozone-controlled profile simulations were run, each comparing 4 ozonesondes with a fast-response dual-beam UV-absorption photometer (OPM) reference. The simulation experiments were designed to compare the two ECC manufacturers, EN-Sci and Science Pump Corporation (SPC), and three different sensing solution compositions (see Table 6.4) used in the global ozonesonde community. The preliminary results showed that, overall, ozonesondes agreed well with the

Table 7.3 Balloon Ozonesonde and Frost Point Hygrometer (FPH) Water Vapor site Network, 2014-2018

Field Campaigns	Ozone	Water Vapor	Intercomparison	FRAPPE	BAO LIDAR	Fast-LVOS	ATTREX	POSIDON
JOSIE-SHADOZ - Juelich, DE	2017		X					
Chatfield State Park, CO	2014			X				
Denver Golf Course, CO	2014			X				
Fort Collins, CO	2014			X				
Platteville, CO	2014			X				
BAO Tower - Erie, CO	2014				X			
Joe Neal, North Las Vegas, NV	2017					X		
Guam	2014, 2016	2014, 2016					X*	X*

Table 7.4: Ozonesonde Sensor Solution Recipes Currently Used Within International Ozonesonde Community.

Cathode Sensing Solution		**(Grams per Liter Deionized Water)**		
Solution Name	KI	KBr	Na2HPO4·12H2O	NaH2PO4·H2O
(1) 1% KI, 1.0x Buffer	10	25	5	1
(2) 0.5% KI, 0.5x Buffer	5	13	3	0
(3) 1.0% KI, 0.1x Buffer	10	25	0	0

OPM reference. The SHADOZ operational methods for instrument (En-Sci and SPC) and sensor solution combinations (SHADOZ sites use the 0.5% KI recipe) showed the best results with 5% accuracy and precision.

FRAPPE

Boundary layer ozone and temperature profiles were measured during the 2014 Front Range Air Pollution and Photochemistry Experiment (FRAPPE). The profiles were measured by tethered ozonesondes at three different sites across the Colorado Front Range. Using a custom tether reel, balloons carrying ECC ozonesondes collected 344 vertical profiles over nine sampling days of the boundary layer up to approximately 500 meters above the surface to observe the progression of ozone buildup during selected summer days.

BAO Tower LIDAR Validation

Ozone profiles were measured by ozonesondes at the Boulder Atmospheric Observatory on July 10-12, 2014, for comparison with LIDAR systems that would be used for the FRAPPE campaign. Ozonesondes are released on free-flying balloons that ascended to 30-35 km altitude before bursting. However, for the BAO Tower LIDAR validation, the area of interest was from surface to approximately 15km. Therefore, free-flying balloons with cut-off valves and a tether system were designed to more effectively measure ozone in the area of interest. Ten free-flying ozonesondes were launched and recovered after cut-down at

15km, and 22 tethered profiles up to 330 meters above the surface were collected as part of this validation experiment.

Fast-LVOS

GMD participated in the Fast-LVOS spring/summer ozone study in the Las Vegas valley in 2017. A total of 27 ozonesondes were launched from May-June in North Las Vegas and timed to coincide with aircraft transits. The study was conducted to determine whether stratospheric intrusions were a primary cause of high ozone events during the summer. Ozonesondes, along with LIDAR and aircraft measurements, were deployed to determine the source and mechanics of descending stratospheric air and whether they contributed to the diurnal buildup of surface ozone in the Las Vegas Valley.

ATTREX

NASA's Airborne Tropical TRopopause EXperiment (ATTREX) was performed to study moisture and chemical composition in the tropical tropopause layer where pollutants and other gases enter the stratosphere and potentially influence our climate. A key focus of the mission was upper atmospheric water vapor, which can significantly impact Earth's energy budget, ozone layer, and climate. Our balloon-borne vertical profile measurements of ozone and water vapor over Guam provided validation data for instruments aboard NASA's high-altitude WB-57 aircraft.

POSIDON

NASA's Pacific Oxidants, Sulfur, Ice, Dehydration, and cONvection (POSIDON) Experiment was a focused airborne science mission to study dehydration, cirrus clouds, and the chemistry of OH and sulfur in the tropical upper troposphere and lower stratosphere over the western Pacific. Our balloon-borne soundings of ozone and water vapor from Guam were used to validate in situ measurements of these trace gases by instruments aboard the NASA high-altitude Global Hawk unmanned aircraft.

DATA HOMOGENIZATION PROJECT

During the nearly 35-year period of ozonesonde observations, there have been several instrument design changes from manufacturers, as well as adjustments to sonde preparation and data-processing techniques. Overcoming potential discontinuities and/or sudden biases after changes is addressed through laboratory testing of sondes, sensor solutions, and pump flow rate efficiency measurements in the GMD laboratory, as well as with field-site dual ozonesonde comparisons. In addition, we participate in the regular intercomparison campaigns -
Juelich Ozone Sonde Intercomparison Experiment (JOSIE) held approximately every 4-8 years in Juelich, Germany, as discussed in the JOSIE-SHADOZ 2017 section.

These campaigns, along with NOAA laboratory tests, provided the background for the ozonesonde data homogenization of the long-term sites BLD, SPO, MLO, and SMO. In addition, the ozonesonde profile data now includes the estimated ozone uncertainty following WMO and JOSIE guidelines. The new, calculated uncertainty for ozonesonde profiles in the troposphere is ±2 ppbv ± 5-10% in the troposphere and ± 4-5% for the stratosphere. TOC accuracy and precision, based on comparison with the GMD Dobson is < 5%.

Since 2010, there have been no changes in the ozonesonde model (En-Sci model 2Z), standard operating procedures, sensing solutions (1% KI, 2.5% KBr and 1/10th see 1.0%KI-0.1b in Table 6.4), and radiosonde (Inter-Met) used in the NOAA GMD ozonesonde network.

6.4 WATER VAPOR

WATER VAPOR OVERVIEW

Monthly water vapor vertical profiles are measured by balloon-borne NOAA frost point hygrometers (FPH) that we launch from Boulder, CO (BLD); Hilo, HI (near MLO), and Lauder, NZ (LDR). The goal is to routinely monitor vertical profiles of water vapor in the upper troposphere and lower stratosphere (to approximately 28 km). Since 2004, nearly all flights of the NOAA FPH have been accompanied by an ozonesonde. Water vapor soundings over Boulder since 1980 provide a unique, long-term, high-resolution, and high-accuracy data record that documents interannual variations in atmospheric dynamics and is capable of revealing changes in the large-scale overturning (Brewer-Dobson) circulation due to climate change. In 2019, the BLD water vapor sounding program added its 39th consecutive year of balloon-borne upper tropospheric and lower stratospheric (UTLS) water vapor profiles.

The Boulder site (40°N) continued weekly balloon launches with Vaisala radiosondes (since 2011) as part of the GCOS Reference Upper-Air Network (GRUAN), of which it became a certified site in September 2014. Along with these weekly Vaisala radiosonde launches, we continue to provide monthly FPH profiles to GRUAN from both BLD and LDR. Vaisala ceased production of its RS92 radiosonde in 2016, requiring the BLD site to transition to the new Vaisala RS41 radiosonde in 2017. Multiple GRUAN sites around the world performed dual flights with RS92 and RS41 radiosondes to ensure minimal impacts (e.g., biases) on the radiosonde data records.

We continue (since 2004) to collaborate with National Institute of Water and Atmospheric Research (NIWA) colleagues at Lauder, New Zealand (45°S) by providing them with all instruments and supplies needed to launch a monthly NOAA FPH and ozonesondes. The ongoing 15-year FPH record at LDR does not indicate any significant long-term trends in UTLS water vapor since 2004.

Our third FPH site, at Hilo, Hawaii (20°N), continues with monthly profiles since 2010, complementing the longer mid-latitude measurement records in the Northern (BLD) and Southern (LDR) hemispheres. This wide latitudinal coverage in FPH sites is advantageous for global monitoring because the behavior of UTLS water vapor varies substantially from pole to pole.

INSTRUMENT

The NOAA FPH has remained mostly unchanged over the past five years. In 2016, a firmware update was initiated to limit the amount of heat applied to the mirror near the top of the flight. This helps to avoid unwanted frost burn-off that occurred on some past flights. In 2018, the infrared LED that had been used in the optics of the FPH (Figure 6.2) became obsolete and, after extensive lab testing, was replaced. Except for this, the mechanical, optical, and electrical systems of the instrument did not change significantly over the past five years, allowing for very stable measurements over this time period.

The current instrument incorporates a continuous copper cold finger and gold-plated mirror piece that protrudes from the cryogen-filled dewar into the airflow path of the hygrometer (Figure 6.2). 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 proportional-integral-derivative (P-I-D) values based on the measured frost point temperature enhances the ability of the FPH to stably control the frost layer over the extremely wide range (>105) of water vapor

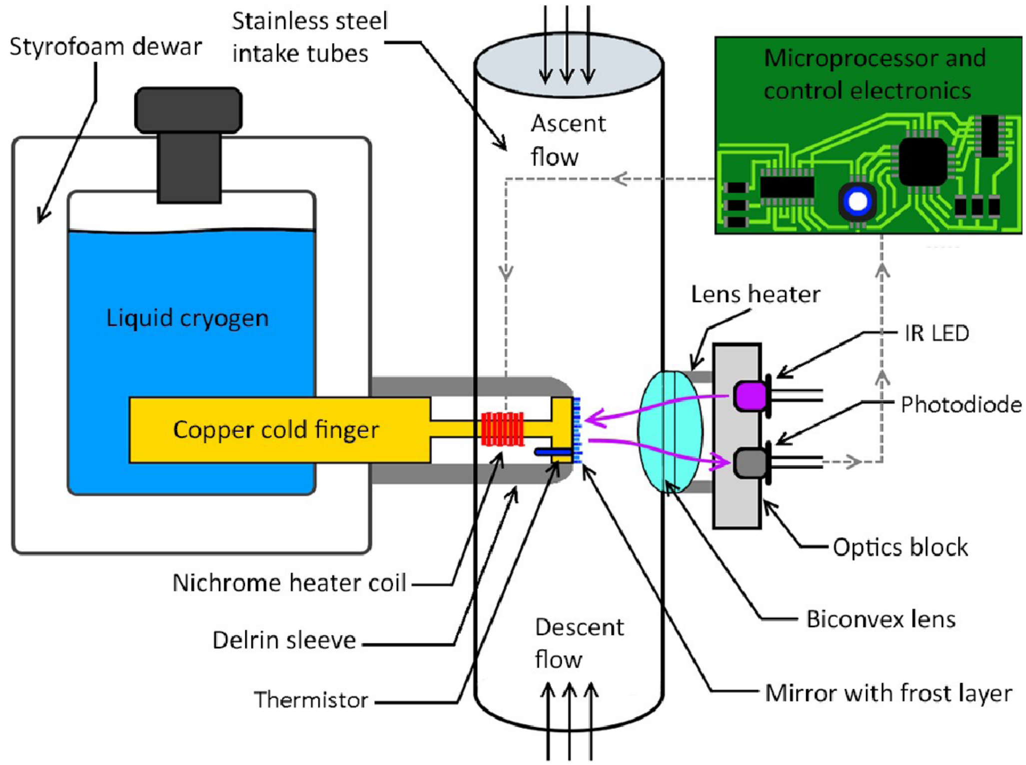

Figure 7.2: Schematic of the NOAA FPH instrument.

number density in the atmosphere. Robust Styrofoam packaging provides thermal insulation to keep the FPH stable over an ambient temperature range of -80° to +30°C and minimizes payload damage when it lands.

THERMISTOR CALIBRATION UPGRADE

In 2014, a new technique was implemented to autonomously calibrate the mirror thermistors used in the NOAA FPH. Instead of manually maintaining the calibration bath at fixed temperatures of 0°, -45°C, and -79°C, the bath is now initially cooled down to -93°C with liquid nitrogen and then allowed to slowly warm while the resistance of each thermistor is continuously logged. The new lower range of calibration temperatures removes the need for calibration fit corrections that were applied to curve extrapolations below -79°C. A new fifth-order polynomial fit accurately ties thermistor resistances to mirror temperatures at six calibration temperatures: -91°, -80°, -59°, -39°, -15° and +19°C. A NIST-traceable platinum resistance thermometer is still utilized to continuously record the bath temperature during the calibration along with the measured resistance values of 40 thermistors. This process takes roughly 48 hours during which the bath warms from -93°C to above 19°C. The new six-point fit reduces calibration errors over the full temperature range to better than ±0.01°C compared to ±0.06°C for the historical three-point fit (Figure 6.3).

STRATOSPHERIC WATER VAPOR SOUNDING CAMPAIGNS AND INTERCOMPARISONS

Stratospheric water vapor and ozone vertical profiles were measured from balloons in conjunction with in situ measurements from high-altitude NASA aircraft near Guam as part of the ATTREX (2014) and POSIDON (2016) campaigns. Please see the brief descriptions of these campaigns above (in the ozonesonde section) and the acronym definitions in Table 6.3. Both campaigns were designed to better understand how the tropical tropopause layer influences the composition of the stratosphere, especially its water vapor content.

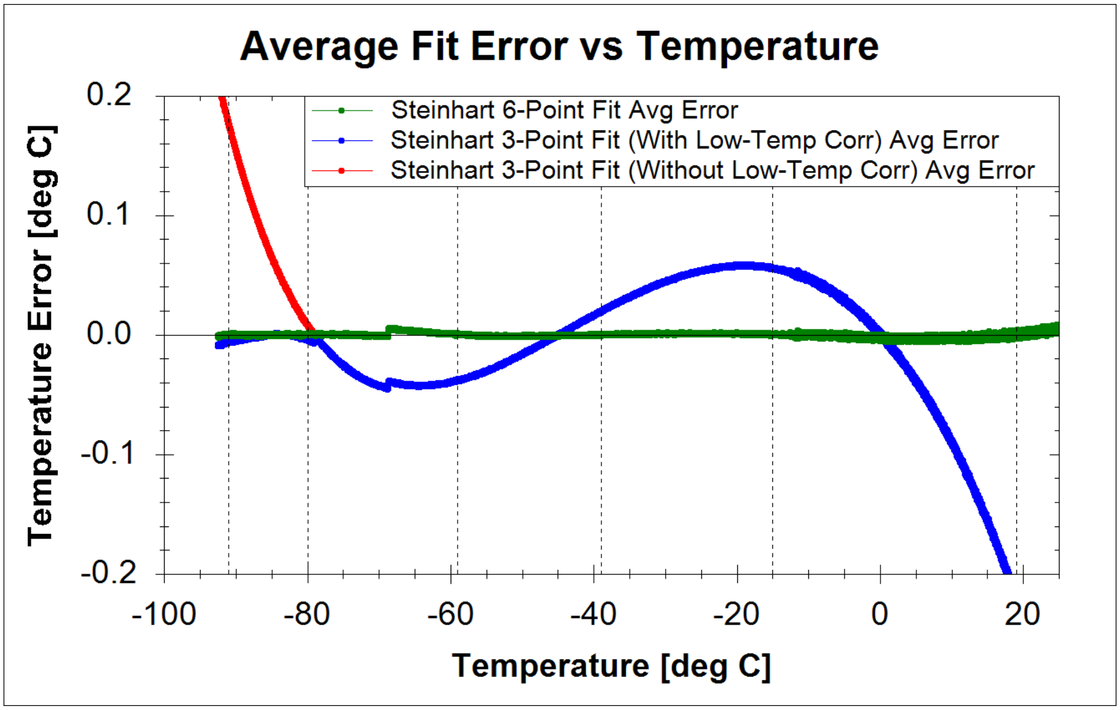

Figure 7.3: Differences between independent fits to thermistor calibration data and the cold bath temperature measured by a NIST-traceable platinum resistance thermometer. The new 6-point fit greatly reduces thermistor calibration errors. From Hall et al. (2016).

Satellite validation using our FPH (and ozonesonde) profiles from all three FPH sites remains a top priority. The UTLS water vapor profiles from most balloon flights are compared with water vapor measurements by the Microwave Limb Sounder (MLS) aboard the Aura satellite. A recent analysis has shown that since about 2010, the MLS water vapor retrievals have drifted to high biases relative to our FPH measurements (Figure 6.4). In July 2017, the third generation Stratospheric Aerosol and Gas Experiment (SAGE III) was installed on the International Space Station (ISS). The SAGE III/ISS measures stratospheric water vapor and ozone, among other trace gas species and aerosols. A coordinated effort to launch an ozonesonde and FPH monthly, when the ISS passes over Boulder, started in August 2017 and is planned to continue past 2020.

OZWV SOFTWARE

The OZWV group has developed many software packages to facilitate and modernize weather balloon data collection, output, processing, intercomparison, and homogenization. SkySonde Client/Server has been used for over ten years by NOAA, NASA, NIST, and many other agencies to collect, plot, and output radio telemetry from thousands of weather balloon flights. The package was recently updated to support the use of Software-Defined Radio (SDR) receivers, which are small, affordable, simple to set up, and provide much greater data reception quality for noisy signals when compared to older radio receivers.

Another widely-used program developed within OZWV is Balloon Prediction. This software forecasts weather balloon trajectories and landing locations using wind data from the NOAA GFS model and NWS radiosonde profiles. Trajectory and landing predictions are important for selecting the best launch days for safety (e.g., avoiding airports, city centers, etc.), signal strength (e.g., avoiding mountains or anything that blocks line of sight), and ease of payload recovery (e.g., landing along gridded roads and away from private gated areas). Recent work has allowed the inclusion of new model data servers, increased the altitude range of trajectories, refined the total column ozone calculation, and improved mapping. These

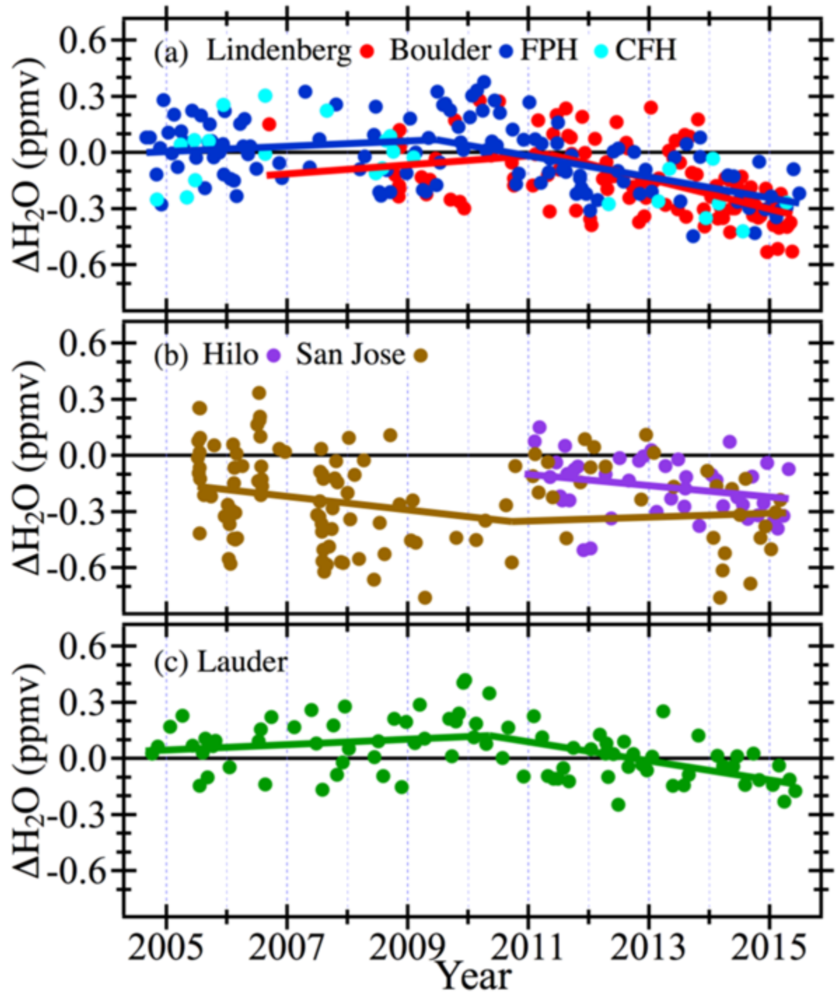

Figure 6-: Differences between water vapor mixing ratios measured at 68 hPa over five different sites by balloon-borne frost point hygrometers and the satellite-based MLS instrument (v3.3 retrievals). The comparison shows a slow drift in FP–MLS differences at four of the five sites that started in about 2010 From Hurst et al. (2016).

software tools are publicly available for download on our website at: https://gml.noaa.gov/aftp/data/ozwv/Ozonesonde/3_Software/

Many other software tools are frequently used internally and by outside groups with whom we collaborate. SkySonde Processor is used for balloon-borne data quality control, processing, plotting, comparison to satellites and other instruments, and producing output files in many formats (including netCDF, AMES, and ICARTT). New features have been added for plotting and comparing ozone and water vapor profiles to the satellite-based MLS instrument, and future development will add the SAGE III/ISS ozone and water vapor profiles. Additionally, we have created software for lab-based plotting and pre-flight testing of ozonesondes (Ozonesonde Viewer), for automation of the FPH thermistor calibration, and for combining MERRA-2 reanalysis products with balloon data, jet stream locations, and other model information for the OCTAV-UTLS JETPAC project. Another program allows us to process tens of thousands of archived balloon-based vertical profiles into modern homogenized data formats.

6.5 SURFACE OZONE OVERVIEW

Surface ozone (O3) is an air pollutant and health hazard when urban pollution emissions and photochemical reactions produce ozone levels that exceed the National Ambient Air Quality standards (NAAQS). In addition, the presence of ozone throughout the troposphere plays a major role in

Table 7.5: Surface Ozone Network

Site	Location	Dates Active	Station Notes
ARH	Arrival Heights, Antarctica	1998-Current	NIWA Collaboration
BAO	Erie, Colorado USA	2008-2016	Discontinued
RPB	Ragged Point, Barbados	1989-2017	
BMW	Tudor Hill, Bermuda	1988-Current	
BRW	Barrow, Alaska USA	1973-Current	
EUK	Eureka, Canada	2016-Current	University of Toronto Collaboration
LAU	Lauder, New Zealand	2003-Current	NIWA Collaboration
MBO	Mt. Bachelor, Oregon	2018-Current	University of Washington Collaboration
MLO	Mauna Loa, Hawaii	1973-Current	
NWR	Niwot Ridge C1, Colorado USA	1991-Current	INSTAAR Collaboration
PCO	Pico, Azores, Portugal	2011-2015	Discontinued
SMO	Cape Matatula, American Samoa	1976-2016	Instrument needs repair
SPO	South Pole, Antarctica	1975-Current	
SUM	Summit, Greenland	2000-Current	
BOS	Table Mountain, Colorado	2016-Current	
THD	Trinidad Head, California	2002-Current	
TIK	Tiksi, Russia	2009-2017	Discontinued
TUN	Tundra Lab, Colorado USA	2003-Current	INSTAAR Collaboration
WKT	Moody, Texas USA	2006-2014	Discontinued
WVR	Weaverville, California USA	2011-Current	NCUAQMD Collaboration
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atmospheric chemistry processes, regulating the oxidation capacity of the troposphere and background levels of trace chemicals. Ozone is a short-term climate forcer and greenhouse gas. Generally, ozone has a positive effect on temperature and temperature has a positive effect on ozone. Observed ozone mixing ratios are influenced by anthropogenic and naturally emitted precursors, stratosphere-troposphere exchange, local meteorology, and long-range transport.

NOAA GMD monitors near-ground ozone levels at sixteen locations around the world. Twelve of these sites measure ozone conditions that are generally representative of background conditions. The other sites are used to monitor the changes to the baseline ozone due to local influences such as emissions from the oil and gas industry, wildfires, and biomass burning. These sites provide information on possible long-term changes in tropospheric ozone near the surface.

GROUND-LEVEL OZONE

GMD has measured surface-level ozone since 1973 at Barrow, Alaska, and Mauna Loa, Hawaii. The most recent monitoring began at Mt. Bachelor, Oregon, through a collaboration with the University of Washington. Table 6.5 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 WASHINGTON COLLABORATION: MT. BACHELOR, OREGON

Through collaboration with the University of Washington, NOAA GMD installed an ozone monitor at Mt. Bachelor in Oregon. Co-located measurements include carbon monoxide, carbon dioxide, mercury, aerosol properties, carbon cycle flasks, and meteorology with additional campaign measurements made at the location. The ozone measurements at this location are used to understand upper troposphere-lower stratospheric air mass influence, long-range transport of pollutants from Eurasia, and wildfire influence on ozone conditions.

NOAA PHYSICAL SCIENCES COLLABORATION: EUREKA, CANADA

As a part of the International Arctic Systems for Observing the Atmosphere (IASOA) project and in collaboration with NOAA Physical Sciences Division and the University of Toronto, a surface ozone monitor was installed at Eureka, Canada. This measurement is an important addition for understanding long-term trends in Arctic ozone as well as investigating seasonal ozone depletion events and bromine chemistry. In 2020, NOAA's Physical Sciences Laboratory ended their contract with the station and passed the management and collection of observations from the site back to its Canadian partners. Due to the importance of the tropospheric surface ozone data, the University of Toronto has decided to continue collecting the surface ozone data, while continuing collaboration with NOAA GMD.

LOCAL MEASUREMENTS: BOULDER, COLORADO

Following the discontinuation of the Boulder Atmospheric Observatory in Erie, Colorado, in 2016, measurements of local ozone conditions in the Northern Front Range were moved to Boulder, Colorado, at the Table Mountain facility.

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 (2020 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. Data are archived in netCDF and text files on the NOAA GMD FTP site and are also archived at the World Data Center for Reactive Gases.

6.6 AIRCRAFT OZONE

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. As of 2019, three locations (Table 6.6) have ongoing routine measurements, and the program provides instrumentation and data analysis for a variety of special projects and campaigns. Due to limited funding in recent years, the aircraft program has discontinued measurements at seven locations, and data processing has not been completed for the remaining active flights since January 2017. The flights provide data that highlight pollution events, boundary layer stability, ozone trends, biomass burning episodes, and atmospheric mixing dynamics.

Table 6.6: Aircraft Network

Site	Location	Dates Active	Flight Frequency
ACG	Alaska Coast Guard	2011-Current	Seasonal
CAR	Briggsdale, Colorado	3/2004 – Current	2/Month
CMA	Cape May, New Jersey	8/2005 – 4/2016	Discontinued
ESP	Estevan Point, British Columbia	3/2009 – 12/2013	Discontinued
HIL	Homer, Illinois	9/2009 – 8/2014	Discontinued
NHA	Worcester, Massachusetts	5/2005 -- Current	1/Month
SCA	Charleston, South Carolina	10/2005 – 4/2013	Discontinued
SGP	South Great Plains, Oklahoma	6/2006 – 3/2016	Discontinued
THD	Trinidad Head, California	4/2005 – 8/2015	Discontinued
WBI	West Branch, Iowa	1/2005 – 4/2014	Discontinued

Section 7 - GLOBAL RADIATION (GRAD) RESEARCH GROUP RESEARCH OVERVIEW

The Global Radiation (GRAD) Research Group provides observational and theoretical research on the Earth's surface radiation budget. 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 SOLRAD). 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 United States (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, land surface characteristics, and cloud forcing and feedbacks with surface radiation, are important and inclusive components. Our group collaborates with other research groups in areas of air quality research, climate research, weather forecasts, satellite retrievals, and renewable energy.

7.1. BASELINE OBSERVATORIES AND REGIONAL RADIATION

SITE LOCATION AND DATA PRODUCTS

Table 7.1 lists the current NOAA GRAD Baseline and Regional Observatory radiation sites, locations, 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 before 1998) averages for the irradiance data are available upon request for all non-BSRN stations.

Table 7.1: The current G-RAD NOAA Baseline and Regional Observatories, location, and topography.

Station	Latitude	Longitude	Elevation	Topography	Inception	Closed
Barrow (BRW)	71	-156.6	8	Tundra	Jan-76	--
Trinidad Head (THD)	41	-124.15	104	Forest	2-Apr	17-Jun
Boulder Atmos Obs (BAO)	40	-105.08	1584	Plains	Sep-89	17-Jul
Bermuda (BERM)	32	-65	60	Island	Apr-91	--
Mauna Loa (MLO)	20	-155.58	3400	Mountain	Jan-76	--
Kwajalein (KWAJ)	9	168	10	Island	Apr-92	19-Nov
American Samoa (SMO)	-14.25	-171	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.

Measurements Made at Each Station								
Broadband Irradiance (unless otherwise noted)								
	BRW	THD	BAO	BER	MLO	KWJ	SMO	SPO
Direct solar	X	X2	X3	X	X	X1	X	X
Diffuse solar	X	X2	X3	X	X	X1	X	X
Total downward solar	X	X2	X3	X	X	X4	X	X
Reflected solar	X		X3					X
Downward IR	X	X2	X3	X	X	X1	X	X
Upward IR	X		X3					X
Other Measurements								
Spectral optical depth	X	X2	X3	X	X	X1		X
Soil Temperatures	X							
Apparent transmission					X			

Discontinued: 1 -? Feb-?2017, 2 -? Jun-?2017, 3 -? July-?2017, 4 -? Nov-?2019

*Ten measurements are made from depths of 5 cm to 120 cm.

SITE, INSTRUMENT, OR DATA MODIFICATIONS (2014-2018)

The stations in Alert, Eureka, and Summit are no longer managed by the NOAA GRAD group. Some data collection, calibration, and technical help continue to occur, but we are no longer in charge of the regular operations at these sites. Due to difficult weather conditions at the Summit station, they often have solar tracker reliability issues. Between 2016 and 2017, GRAD deployed one CM11 pyranometer and one SPN1 pyranometer to supplement missing tracker data. In 2017, GRAD calibrated the Summit radiometers and refurbished the solar tracker to make it more reliable in the future.

The GRAD group has had to decommission several measurement sites over the past five years. In 2016, it was decided to shut down all research at the Boulder Atmospheric Observatory (BAO). All solar instrumentation was removed from BAO in July 2017, including the upwelling instruments from the 300m tower. The NOAA Trinidad Head Observatory was shut down in 2017. All solar radiometers and the solar tracker were removed in June of 2017 when the station was decommissioned. The BSRN station in Kwajalein (KWAJ) received a complete refurbishment in 2015, including a new solar tracker, new meteorology instruments (MET), and a solar instrument exchange. Early in 2017, the solar tracker began to have tracking issues and soon after quit working altogether. The global pyranometer and MET measurements continued to work without the solar tracker operating. It was later decided to decommission the KWAJ BSRN site and discontinue all measurements there.

Maintenance and upgrades were performed at various sites to continue high-quality data collection. In 2016, the Barrow observatory received an upgraded data logger, including new signal cables and DC fan power supply. In August 2017, a one-year experiment was initiated on the roof of the Barrow observatory. The De-Icing Comparison Experiment (D-ICE) was designed to test various pyranometer and pyrgeometer ventilation techniques to determine the best way to keep radiometer domes clear of snow and ice in cold environments. Two new tables were installed on the observatory roof to hold all test instruments. Due to the limited roof space, the GRAD global pyranometer was moved to the new table and the old table was deconstructed. The location of the global measurement did not move significantly. During the setup for D-ICE, we were able to install a new sonic snow depth sensor on the albedo rack, which replaced the previously broken sensor. In 2018, the albedo rack communications were upgraded to a Wi-Fi link for data transfer. The BSRN station in Bermuda was refurbished in 2017. A new data logger was installed, along with new signal cables and an upgraded DC fan power supply. New MET instrumentation was installed and the solar radiometer exchange was performed. General maintenance was performed to combat the corrosive environment experienced at island stations. Our other island site in American Samoa received DC fans for their ventilated radiometers in 2018. The downwelling global, diffuse, and downwelling infrared pyranometers are all ventilated with the new DC fans.

7.2 SOLARRADIATION NETWORK (SOLRAD)

HISTORY OF SOLRAD AND STATION INFORMATION

The Solar Radiation Network (SOLRAD) (previously referred to as ISIS) 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 original, but now defunct, U.S. SOLRAD network. The old U. S. SOLRAD network began in the 1970s with approximately 30 U.S. stations located primarily at NWS offices. After several buildups and failures, the U. S. SOLRAD was abandoned in 1993. Ten of those stations were preserved as ISIS (now referred to as SOLRAD). 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 for those stations are listed in Table 7-3. 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. The name of this network was changed back to SOLRAD in 2017.

Table 7.3: Locations and operating periods of the ten original ISIS (now SOLRAD) stations.

Station name	Latitude	Longitude	Elevation (m)	Start date	End date	Nearest city	Station ID
Albuquerque	35	-107	1617	3-Mar-95	N/A	Albuquerque, NM	ABQ
Bismarck	47	-101	503	9-Jul-96	N/A	Bismarck, ND	BIS
Hanford	36	-120	73	25-Apr-96	N/A	Hanford, CA	HNX
Madison	43	-89	271	12-Jun-96	N/A	Madison,WI	MSN
Oak Ridge	36	-84	334	20-Oct-95	8-Jun-07	Oak Ridge, TN	ORT
Seattle	48	-122	20	23-Mar-95	N/A	Seattle, WA	SEA
Salt Lake City	41	-112	1288	29-Aug-96	N/A	Salt Lake City, UT	SLC
Sterling	39	-77	85	25-Aug-95	N/A	Herndon, VA	STE
Tallahassee	30	-84	18	15-Jan-95	30-Oct-02	Tallahassee, FL	TLH
Desert Rock	37	-116	1007	30-Jun-95	28-Jun-98	Mercury, NV	DRA

SOLRAD STATION INFRASTRUCTURE

SOLRAD stations measure only downwelling solar radiation. A typical station is shown in Figure 6-1. SOLRAD instrumentation and their characteristics are listed in Table 7.4. The direct-normal and diffuse

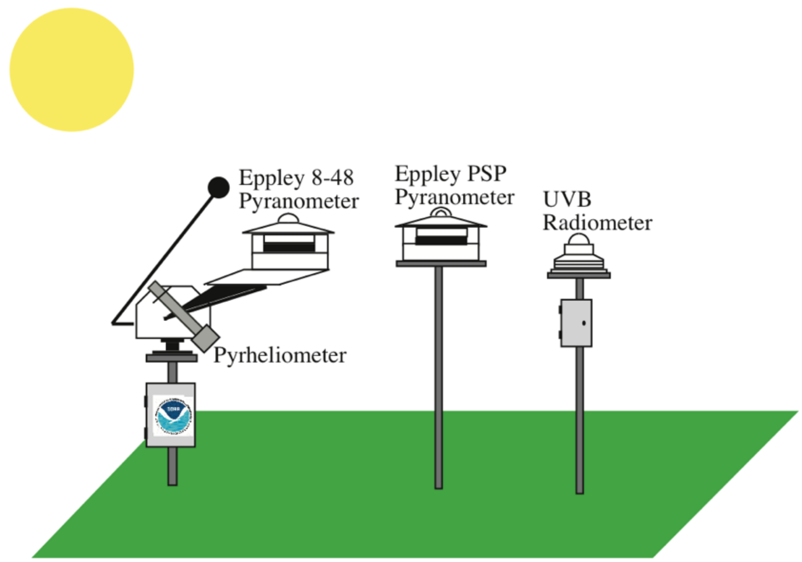

Figure 7.1: Complement of instruments at each SOL- RAD network station. Only downwelling radiation is measured at these sites.

Table 7.4: Instruments and measurements employed at the SOLRAD sites.

Instrument/Model	Manufacturer	Wavelength Range	Dome/Diffuser	Detector	Parameter measured
Precision Filter Pyranometer (PSP)	Eppley Laboratory	280-2800 nm	Two WG295 Schott Filter Domes	Thermopile	Global solar irradiance (GHI)
Pyranometer, 8-48	Eppley Laboratory	280-2800 nm	One WG295 Schott Filter dome	Thermopile	Diffuse horizontal solar irradiance (DHI)
Normal Incidence Pyrheliometer (NIP)	Eppley Laboratory	280-2800 nm	WG295 Window	Thermopile	Direct Normal solar irradiance (DNI)
UVB Radiometer, UVB-1	Yankee Environmental Systems	280-320 nm	Schott WG280 quartz dome and UG11 filter	GaAsP Photodiode	Erythemal UV irradiance
UVB Radiometer, model 501A	Solar Light	280-320 nm	Fused silica (quartz)	GaAsP Photodiode	Erythemal UV irradiance
Pyrgeometer, model PIR (Madison Only)	Eppley Laboratory	4000-50,000 nm	Silcon dome with interference filter coating	Thermopile	Upwelling and downwelling infrared irradiance

components of downwelling solar are measured by instruments mounted on a solar tracker, which are combined for the best estimate of downwelling solar radiation. A single-black- detector pyranometer is deployed as a backup in case the solar tracker fails. In June 2009, the UVB radiometer at Madison, Wisconsin was replaced with a pyrgeometer at the request of the local host.

In the past, we attempted to visit SOLRAD stations on an annual basis; however, without funding that was practically unachievable. Site visits were made on trips of opportunity, e.g., nearby conferences and side trips from SURFRAD sites. However, since 2017, when it was decided to use CPO funding for SOLRAD, site visits have been more frequent.

DATA PRODUCTS & QUALITY ASSURANCE

When ARL-Oak Ridge operated SOLRAD from 1995 through January 2002, 15-min averages of 1-sec samples were collected. When ARL SRRB took over on 1 February 2002, they increased the temporal resolution to three min. They also began to distribute daily data files from the anonymous FTP site at: ftp:/aftp.cmdl.noaa.gov/data/radiation/solrad/. Daily SOLRAD files for individual stations are organized temporally in UTC. They are available in station and year subdirectories and made available on the following workday. In addition, graphic displays of daily time series of measured quantities can be accessed on the interactive website: https://gml.noaa.gov/grad/solrad/solradpick.html.

The SOLRAD FTP site has a folder labeled "1995– 2001" that contains data before ARL 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 or NCEI), i.e., hourly averages organized in monthly files and local standard time: ftp://aftp.cmdl.noaa.gov/data/radiation/isis/1995-2001/ISISNCDC. Batteries, fans, and other equipment that deteriorates are replaced, and instruments are exchanged 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, SOLRAD 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 SOLRAD data before they are released.

QCRad products were updated to version 3 for the SOLRAD sites, and advanced products from the RadFlux Analysis were produced, e.g., clear-sky radiation variables and cloud cover. Note that the calculations are slightly different or modified for these products compared with SURFRAD sites, given that downwelling IR radiation is unavailable. These products are available at ftp://aftp.cmdl.noaa.gov/data/radiation/solrad/qcrad_v3 and ftp://aftp.cmdl.noaa.gov/data/radiation/solrad/ RadFlux, respectively.

6 2 SURFRAD NETWORK

MISSION AND RATIONALE

The U.S. Surface Radiation Budget Network (SURFRAD) was established in 1993 with support from NOAA's Office of Global Programs. Its data record began in January 1995. SURFRAD is the first and only operational national-scale radiation budget network of its kind. With its continuous measurements of the surface radiation budget, SURFRAD supports global change research, NOAA and NASA satellite programs, renewable energy activities, and numerical modeling for weather and climate. 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 (3,500–10,000 nm). That sum represents the available energy at the surface for atmospheric heating and evaporation—the primary energy sources for weather and climate. Thus, accurate model synthesis and satellite-based estimates of surface net radiation are essential for credible climate studies and assessments.

During the 2014 – 2018 reporting period, ancillary measurements have been added to increase the versatility of SURFRAD data for research. These include cloud cover, cloud-base height, aerosol optical depth, spectral surface albedo, atmospheric state variables, direct and diffuse solar irradiance, UVB radiation, and photosynthetically active radiation. Several of these are new products are discussed below. In addition, twice-per-day interpolated atmospheric soundings at SURFRAD site locations are produced, and available and advanced products from RadFlux Analysis, e.g., clear-sky radiation variables, transmissivity, and cloud cover, have been made available. Network-wide annual averages for 23 years of continuous surface net radiation measurements from SURFRAD are shown in Figure 7.2. From 1996 to 2012, there was an extraordinary increase of surface net radiation over the United States and then a return to average values from 2013 onward. Analysis of the individual surface radiation budget (SRB) components shows that those trends were primarily due to systematic changes in cloud cover.

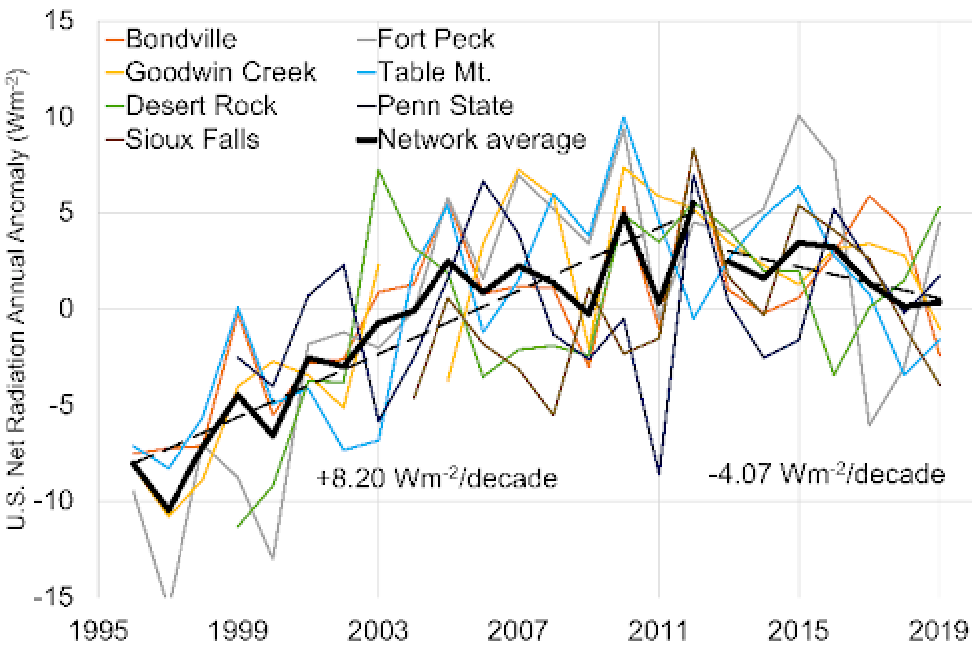

Table 7.2: SURFRAD network-wide annual averages for 23 years of continuous surface net radiation measurements .

SURFRAD STATIONS

The SURFRAD network is shown in Figure 7.3. Four stations began in 1995. 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 foreach station are listed in Table 7.5. The spatial distribution of SURFRAD stations represents a good cross-section of U.S. climates. Pictures of SURFRAD stations and their surroundings are available at https://gml.noaa.gov/grad/surfrad/.

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 on a solar tracker. The solar tracker is on a separate post, typically south of the main platform. A 10-m tower located 25 m or more north of the main platform supports downward viewing radiometers that measure reflectedsolar and upwelling IR irradiance and most meteorological instruments. The only exception is that the barometer is located under the mainplatform. Because of local constraints, the tower

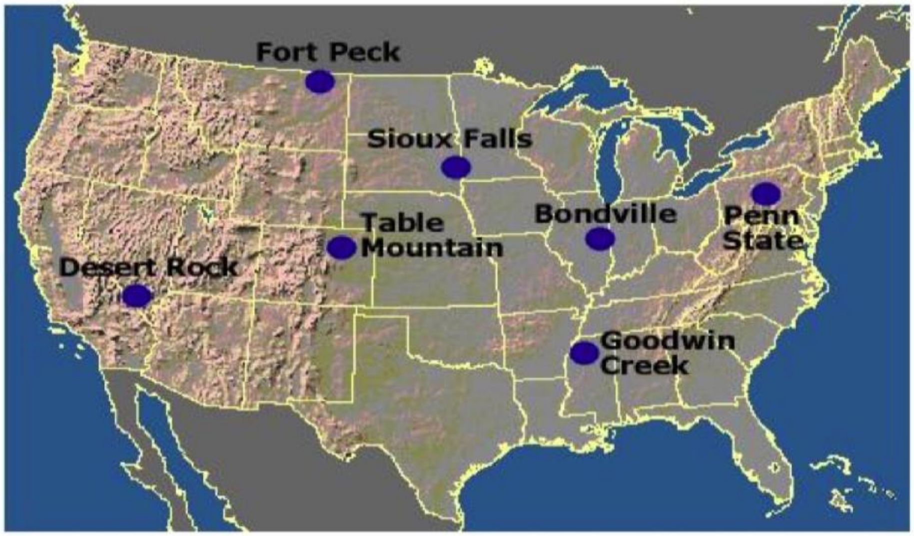

Figure 7.3: The seven SURFRAD site locations, distributed to represent distinct climatological regimes across the continental U.S

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	-88	213	1 Jan. 1995	Bondville, IL	BON	Prairie grass
Fort Peck	48	-105	634	28 Jan. 1995	Poplar, MT	FPK	Prairie grass
Goodwin Creek	34	-90	98	1 Jan. 1995	Batesville, MS	GWN	Pasture
Table Mountain	40	-105	1689	19 Jun. 1995	Boulder, CO	TBL	Sand, rock, desert shrubs, sparse grasses
Desert Rock	37	-116	1007	16 Mar. 1998	Mercury, NV	DRA	Scattered desert shrubs
Penn State	41	-78	376	29 Jun. 1998	Pine Grove Mills, PA	PSU	Grass and crops
Sioux Falls	44	-97	473	15 Jun. 2003	Sioux Falls, SD	SXF	Prairie grass

at Desert Rock is located south of the main platform, and the solar tracker is the furthest north, but they are far enough away from each other that interference is not an issue.

The rectangular grating, hereafter referred to as the main platform, is elevated about 2 m above ground level. Initially, Eppley solar trackers were deployed, but they were replaced in 1999 by SCI-TEC (now Kipp & Zonen) units. The solar tracker hosts a pyrgeometer that measures downwelling thermal infrared, a shaded Eppley 8-48 pyranometer for diffuse solar, and a pyrheliometer that is kept trained on the solar disk. A cross arm at the8-m level of the tower, also aligned north to south, supports the down-looking radiometers. A listing of all SURFRAD instruments and their characteristics is in Table 7-7. In addition, you can find instrument descriptions at https://gml.noaa.gov/grad/instruments.html.

Changes were made 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 stations included a diffuse solar measurement. Initially, a single-detector pyranometer was shaded to measure diffuse solar, but during the 2001

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 Schott filter dome	Thermopile	Diffuse solar irradiance
Pyrheliometer, model CHP1	Kipp & Zonen	280--2800 nm	Quartz window	Thermopile	Direct-normal solar irradiance (DNI)
Pyrgeometer, model PIR	Eppley Laboratory	4000--50,000 nm	Silicon dome with interference filter coating	Thermopile	Upwelling downwelling thermal infrared irradiance
UVB Radiometer, model UVB-1	Yankee Enviromental Systems		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 (PAR)
MFRSR	Yankee Environmental Systems	415, 500, 1623, 670,870, 940 nm and broadband solar	Spectralon diffuser	Silicon photodiode, interference filters	Global and diffuse spectral irradiance
Total Sky Imager	Yankee Environmental	N/A	Reflective mirror	Camera	Total sky image, fractional cloud cover
Wind anemometer, model 05103	R. M. Young	N/A	N/A	Propeller and vane	Wind speed and direction
Temperature, RH probe	Vaisala	N/A	N/A	Platinum resistance thermometer/ INTERCAP, capacitive chip (for RH)	Temperature, relative humidity
Barometer, model PTB110	Vaisala	N/A	N/A	Silicon capacitor	Air pressure
Ceilometer	Vaisala	N/A	N/A	Pulsed diode laser LIDAR	Cloud base and boundary layer height
MFR	Yankee Environmental Systems	415, 500, 1623, 670,870, 940 nm and broadband solar	Spectralon diffuser	Silicon photodiode, interference filters	Upwelling spectral irradiance

instrument exchanges, these were replaced with Eppley model 8-48 pyranometers that do not have a thermal offset error common to single-detector pyranometers.

Thermal offsets in all diffuse solar data prior to introduction of the model 8-48 were corrected. During the instrument exchanges in 2000, the up-looking pyrgeometer was moved from the main platform to the solar tracker so that its dome could be shaded according to accepted standards. Shading the pyrgeometer dome prevents errors in the downwelling IR measurements caused by uneven heating of the dome 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 https://gml.noaa.gov/grad/surfrad/getcals.html.

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

New CHP-1 Kipp and Zonen pyrheliometers were installed to replace the Eppley Normal Incidence Pyrheliometer (NIP). The new pyrheliometers have Figure 7.4: The six NEUBrew site locations in the continental United States. a 50 percent improvement in precision, as determined during an intercomparison study, Michalsky et al., 2011.

From 2013 to 2015, the MFRSR at the seven SURFRAD sites was replaced with a newer version MFRSR. This newer version replaced the silicon channel with a thermopile channel, and replaced the 615- nm channel with a 1625-nm channel for added information on larger aerosol particles. In addition, the instruments were modified to improve the internal temperature stabilization. The revised MFRSR and new MFR are

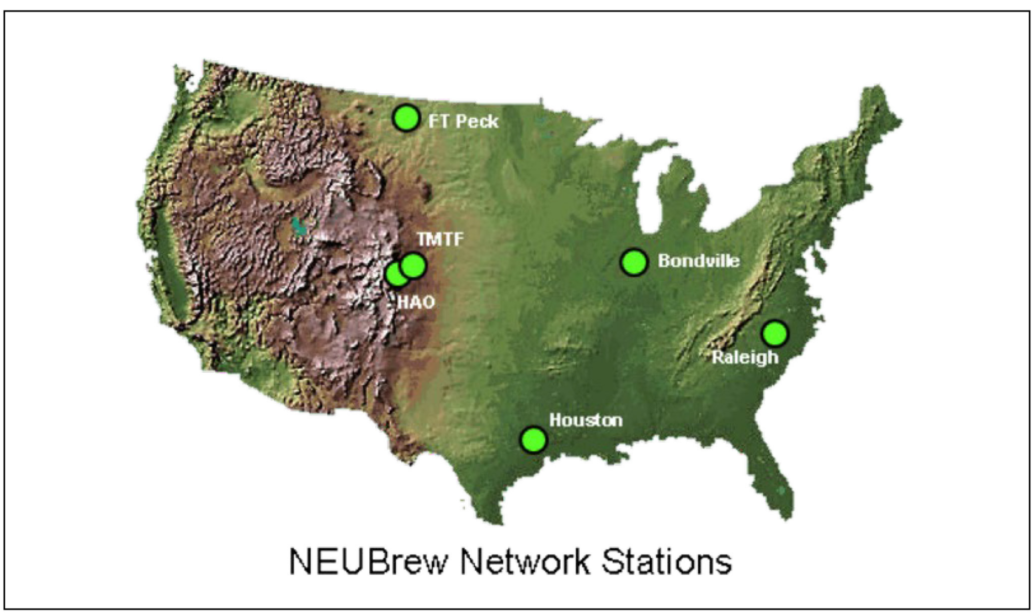

Figure 7.4: The six NEUBrew site locations in the continental United States.

listed in Table 7.7. During 2015 and 2016, a down-pointing MFR head was added to the tower cross arm at all stations for upwelling spectral measurements in support of GOES-R product development and Cal/Val activities (Figure 7.4). For installation dates of the revised MFRSR and MFR, see Table 7.7.

In 2018, seven Vaisala CL-51 ceilometers that can detect clouds up to 13,000 feet were purchased and installed at three SURFRAD sites in support of NCEP NWP improvements (Figure 7.5). The Vaisala high-range ceilometers were installed at Table Mountain, CO, Fort Peck, MT, and Goodwin Creek, MS. Installation dates are given in Table 7.8. These ceilometers detect clouds in three layers and provide cloud-base height (CBH). There is also a nominal planetary boundary layer height product (PBLH). A proposal to improve this product for atmospheric research studies has been submitted. The remaining four ceilometers will be installed in 2019.

Table 7.7: Installation dates of Multi-Filter Rotating Shadowband Radiometers (MFRSR) and Multi-Filter Shadowband Radiometers (MFR) at 7 SURFRAD sites.

Instrument	Location	MFRSR Start Date	MFR Start Date
MFRSR/MFR	Bondville, IL	6/16/2016	6/17/2016
MFRSR/MFR	Desert Rock, NV	11/14/2015	11/14/2015
MFRSR/MFR	Goodwin Creek, MS	7/1/2017	7/1/2017
MFRSR/MFR	Fort Peck, MT	10/10/2016	10/10/2016
MFRSR/MFR	Penn State, PA	7/15/2016	7/15/2016
MFRSR/MFR	Sioux Falls, SD	9/12/2013	9/20/2016
MFRSR/MFR	Table Mountain, CO	8/23/2016	8/23/2016

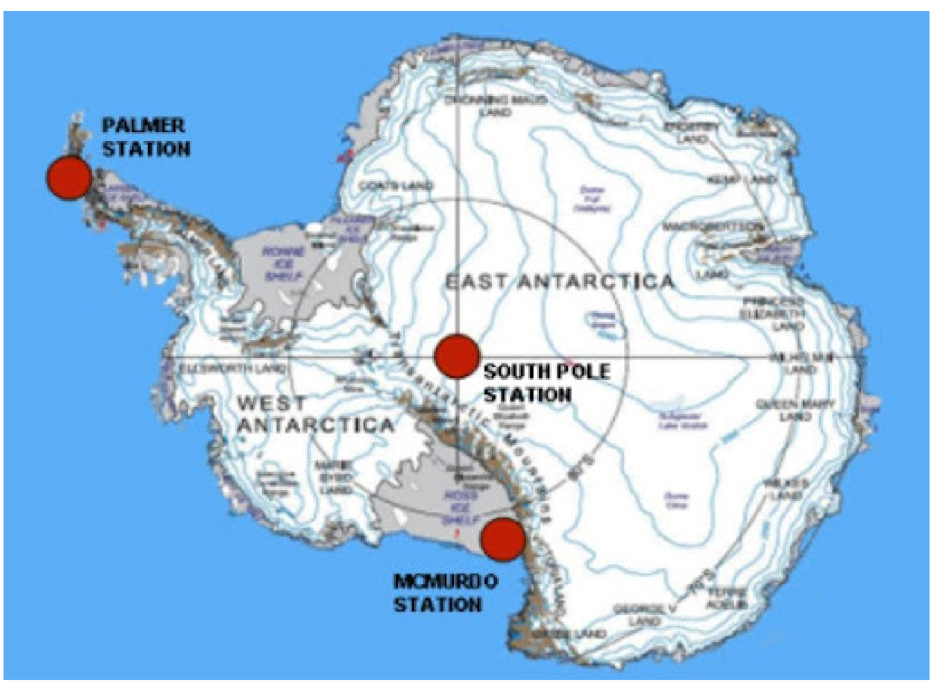

Figure 7.5: The Antarctic UV monitoring stations are located at the three U.S. Antarctic research sites and represent different radiation environments across the continent

Table 7.8: Installation dates of Vaisala CL-51 ceilometers

Model	Location	Start Date
Vaisala CL51	Table Mountain, CO	20180630
Vaisala CL51	Fort Peck, MT	20180928
Vaisala CL51	Goodwin Creek, MS	20181108

SURFRAD PRODUCTS

The GRAD group makes daily quality-controlled SURFRAD data files in UTC available the following workday on the GMD anonymous FTP site at ftp://aftp.cmdl.noaa.gov/data/radiation/surfrad/. Monthly averages of the measurements and computed variables are available at ftp://aftp. cmdl.noaa.gov/data/radiation/surfrad/averages/. SURFRAD data are also reorganized into monthly tables of hour averages in local standard time and sent to the National Centers for Environmental Information (NCEI). NCEI then reformats that data and forwards 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). SURFRAD data and local radiosonde soundings are routinely sent to the BSRN data archive in Bremerhaven, Germany. In April 2004 through the BSRN, all SURFRAD stations became members of the Global Climate Observing System (GCOS). Since 2019, SURFRAD one- minute data have been archived at NCEI in NetCDF format.

SURFRAD broadband radiation and meteorological data were originally recorded as three-min averages of one-sec samples. On 1 January 2009, data collection switched to one-min averages of one-sec samples. Total Sky Imager data were always recorded at one-min frequency. Text files of cloud fraction data derived from the TSI images are available at ftp://aftp.cmdl.noaa.gov/data/radiation/surfrad in the subdirectory labeled "TSI", and the one-min raw and processed TSI images are 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, 1623 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 iterations. 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. Until 2016, data from MFRSRs operated by the USDA at Bondville and Fort Peck were used, but were constrained by their three-min data. In 2015 and 2016, our own MFRSRs were installed and now we record 1-min data at those two sites. The MFRSR is the only radiometer that is not replaced annually because it is calibrated in situ, enabling instrument consistency. Aerosol optical depth (AOD) is computed at the frequency of the raw data and made available in files for each station at ftp://aftp.cmdl.noaa.gov/data/radiation/surfrad/aod/.

The sensitivity of several MFRSR channels degraded over time, and by 2012 and 2013, AOD data quality had declined. In the worst case, AOD was not computed for the Penn State station from 2009 to 2014. However, MFRSR data has been available from Penn State since 2015. In 2013, the Sioux Falls MFRSR was the first to be replaced with a newly designed model. The new models include a near IR channel centered on 1623 nm that replaces the 615 nm channel, improving the retrieval of aerosol size distribution. Since 2016, all SURFRAD sites have new model MFRSRs with the 1623 nm channel.

In 2015 and 2016, down-viewing MFRSR heads were installed on SURFRAD towers. Those measurements were synchronized with the up- looking MFRSR to enable the computation of spectral albedo from 415 nm to 1625 nm and Normalized Difference Vegetation Index (NDVI). These products are still in development for calibration methodology and QA/QC of the final product. Preliminary products can be found at ftp://aftp.cmdl.noaa.gov/user//lantz/Albedo_ preliminary/.

Vertical profiles of temperature and moisture are desirable for the 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 co-located with an operational radiosonde, but in January 2011, the launch site was about 120 km southeast to the Las Vegas airport.

All of the processed SURFRAD radiation, meteorological, AOD, interpolated soundings, and monthly mean products are viewable graphically on interactive web pages at https://gml.noaa.gov/grad/surfrad/. The objective "QCRad_V3" data quality control method is applied to SURFRAD data daily, and those files are available on at ftp://aftp.cmdl.noaa.gov/data/radiation/surfrad/qcrad_v3/. QCRad_V3 files are converted to NetCDF format and submitted to NCEI on a quasi-monthly basis. The QCRad_V3 files are used as input to the RadFlux algorithm that computes equivalent clear-sky irradiance and many other useful products for all radiation parameters at the temporal resolution of the input data. RadFlux files also host the original data and calculated fractional cloud cover at the temporal resolution of the data. Daily RadFlux files for all SURFRAD stations can be found at ftp://aftp.cmdl.noaa.gov/data/radiation/surfrad/RadFlux/.

SURFRAD QUALITY ASSURANCE

To prevent problems, maintenance of long-term measurements requires preemptive measures, i.e., quality assurance. For example, SURFRAD instruments are ventilated or heated 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 by the solar beam and prevent sampling of the direct solar beam at sunrise and sunset by the inverted pyranometer on the tower. On a regular schedule, we replace batteries, fans, and other equipment that gradually deteriorates. We exchange instruments annually 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 to 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, SURFRAD solar radiometers were calibrated at the National Renewable Energy Laboratory in Golden, Colorado, but from 2005 on, they have been calibrated by the World Meteorological Organization Region 4 Regional Solar Calibration Center in Boulder, Colorado. Both calibration centers apply essentially the same methods and WRR-traceable standards. Mitigation is used at all stations to minimize interference by birds, especially on the mirrored surfaces of the TSI and pyrgeometers. A buried lightning protection system was installed at Goodwin Creek, MS and Sioux Falls, SD to protect against ground surges from nearby strikes. Finally, to ensure a reputable product, an analyst checks all SURFRAD data before being released.

7.3 UV MONITORING

OVERVIEW

The need for accurate, long-term, ground-based solar UV measurements arose in response to the discovery in the 1980s of the Antarctic ozone hole. 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. These stations have expanded to include atmospheric factors that modulate UV radiation at the surface (e.g., clouds and aerosols) and impacts on ecosystems and human health. The NOAA UV monitoring program now includes a six-station continental U.S. network (NEUBrew), a three-station Antarctic network, and two high-resolution NIWA UV spectroradiometers located at Boulder, Colorado, and Mauna Loa, Hawaii.

NEUBrew NETWORK

The NEUBrew network comprises six stations operating within the continental United States (Figure 7.4). NOAA and EPA equipped each station with a Mark IV Brewer spectrophotometer (Brewer) that is co-located 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 for direct sun measurements. The Brewer is a single monochromator-scanning instrument. 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 7.9). We established all six NEUBrew sites between July and November 2007. Only the Boulder and Mountain Research Station sites remain from the original 21-site EPA network. The Boulder, Bondville, and Ft Peck sites are co-located with NOAA SURFRAD sites. The Houston and Raleigh sites are co-located with USDA monitoring sites. You can find complete network and instrument information at https://gml.noaa.gov/grad/neubrew/. The NEUBrew network operates Brewer Mark IV spectrophotometers, a multi-functional measurement instrument making spectral UV, total column ozone, ozone profile, NO2 column, and SO2 column measurements. In the summer of 2014, all network instruments were returned to Boulder for refurbishment. The order-sorting NiSO4 filter was replaced with a more modern and more stable crystal, referred to as an UVC-7 filter. Only eight of the ten Brewers underwent the replacement. We decided that the two most stable instruments, Brewers 141 and 146, should keep their original NiSO4 filters for comparison purposes. In October 2014, all ten Brewers were recalibrated for total column ozone measurements. They were then moved back to their monitoring stations and calibrated for spectral UV irradiance measurements. More recently, all NEUBrew Brewer control computers were upgraded to a more stable operating system, from CentOS to Mint, both Linux-based operating systems.

Need caption for Table 7-9

Station	Latitude	Longitude	Elevation (m)	Install Date
Bondville, IL	40	3/28/1900	7/31/1900	26-Sep-06
Boulder, CO	40	4/14/1900	8/15/1904	5-Jul-06
Houston, TX	30	4/4/1900	3/4/1900	5-Jun-13
Ft Peck, MT	48	4/14/1900	9/25/1901	6-Nov-06
Mountain Research Station, CO	40	4/14/1900	1/1/1908	10-Oct-06
Raleigh, NC	36	3/18/1900	9/28/1900	12-Oct-06

The Antarctic UV Monitoring Network

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) maintained the network to provide ground- based measurements of spectral UV irradiance. After 23 years of NSF operation, GMD assumed management of the network in May 2010. Station information is listed in Table 6-10. You can access network information and data at https://gml.noaa.gov/grad/antuv/. We equipped each site with a BSI-built SUV-100 spectroradiometer, solar pyranometer, Eppley TUVR broadband UV radiometer, and a BSI GUV-541 or GUV-511 radiometer.

The system control computers at all three Antarctic UV monitoring stations were or are in the process of being upgraded to Windows 10. They were formerly using Windows 7. The support for Windows 7 will

Need caption for Table 7-10

Station	Latitude	Longitude	Elevation (m)	Install Date
Palmer	64° 46’ S	64° 03’ W	21	May-88
McMurdo	77° 50’ S	166° 40’ E	183	Mar-88
South Pole	90° 0’ S	0.0° E	2,835	Feb-88

expire in January 2020.

NOAA owns and operates two NIWA-manufactured UV spectroradiometers. They are designated as UV5 and UV3 and located at Boulder, Colorado and Mauna Loa, Hawaii, respectively. The coordinates of both instruments and their installation datesare listed in Table 7-11. In the spring of 2017, the UV fiber optic bundle that connects the entrance cosine collector with the dispersing monochromator was damaged on UV5. In September 2019, NIWA loaned us a spare fiber bundle. The damaged cable was then replaced with the loaner along with the proper closing and opening calibrations. The control computers for UV5 and UV3 are also being updated with Windows 10 from Windows 7 in accord with the mandate from NOAA’s IT department.

Need caption for Table 7-11

Station	Latitude	Longitude	Elevation (m)	Install Date
Boulder,CO	39.991° N	105.261° W	1650	Jun-98
Mauna Loa, HI	19.536° N	155.576° W	3397	May-95
South Pole	90° 0’ S	0.0° E	2,835	Feb-88

7.4 SPECIAL PROJECTS

CALIBRATION CAMPAIGNS

The GRAD Solar Radiation Calibration Facility (SRCF) is designated as the World Meteorological Organization (WMO) Region 4 Regional Radiation Center (RRC). GRAD maintains and operates a group of reference cavity radiometers that are used to perform regular calibrations on the broadband radiometers used at GRAD observatories and field sites. GRAD reference cavity radiometers participate in regional and international intercomparisons annually to maintain direct traceability to the WMO World Radiometric

Reference (WRR). Every five years, the WMO hosts the International Pyrheliometer Comparison (IPC) in Davos, Switzerland, to provide an opportunity for RRCs and other observation networks to obtain a new WRR scale factor for their reference cavity radiometers (Figure 7.6). In 2015, NOAA GRAD participated in the 12th WMO IPC (IPC-XII) and received a new WRR scale factor for each cavity radiometer in the reference group. During years that the IPC is not held, GRAD participates in the National Pyrheliometer Comparison (NPC) that takes place at the National Renewable Energy Lab (NREL) in Golden, Colorado. GRAD attended the NPC in 2014, 2016, 2017, and 2018. GRAD plans to attend all future comparisons to maintain traceability to the WRR for our standard reference group of cavity radiometers

Need caption for Figure 7.6

While in Davos for IPC-XII, GRAD also participated in two other intercomparisons that were being held concurrently: the 4th Filter-Radiometer Comparison (FRC-IV) and the 2nd International Pyrgeometer Comparison (IPgC-II) (Figure 7.6). FRC-IV was a comparison of instrumentation capable of measuring aerosol optical depth (AOD). The goal of FRC-IV was to compare instruments operated by different global or national networks and attempt to quantify possible deviations between networks so future AOD measurements can be improved and standardized. GRAD operated three instruments during this comparison to be added into the analysis. IPgC-II was a comparison of pyrgeometers from different measurement networks around the world. All pyrgeometers were calibrated against the current World Infrared Standard Group (WISG) and provided traceable scale factors to the current WMO standard. GRAD supplied three pyrgeometers for this comparison to be included in analysis.

In 2017, the GRAD group participated in the second International UV Filter Radiometer Comparison (UVC-II) hosted in Davos, Switzerland. Similar to the above comparisons, the goal of UVC-II was to provide instrument calibrations that are traceable to the world standard group operated by the World Calibration Center for UV (UCCUV) in Davos. GRAD sent one Yankee UVB-1 instrument to be included and calibrated during this comparison.

7.5 CALIBRATION CENTERS CENTRAL UV CALIBRATION FACILITY

INTRODUCTION AND MISSION

In 1994, the Surface Radiation Research Branch of NOAA's Air Resources Laboratory established the Central UV Calibration Facility (CUCF). On 1 October 2005, the CUCF became part of the Global Radiation group of NOAA's newly formed Earth System Research Laboratories, 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 NIST's Optical Technology Division 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 performs calibrations and

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characterizations and developed standards of spectral irradiance for many international agencies and universities around the world. Information and services for the CUCF can be found at https://gml.noaa.gov/grad/calfacil/cucfhome.html.

Researchers from the United States and around the world have used CUCF services and facilities. A partial listing of many past and current users of the facility includes: 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. A list of calibration activities is in Table 7-12

HIGHLIGHTS AND MODIFICATIONS TO SYSTEMS

One of the operational requirements implied by the MOU was to be able to directly measure instruments from any origin and manufacturer. There are a few very modified instruments that, at present, can only be measured at CUCF. With the consolidation of the Surface Radiation Research and Solar and Infrared Radiation groups into the Global Radiation group, the purview for the CUCF has expanded from the UV region to the Near IR region. Though the founding MOU for the CUCF focused on the UV spectral region,

Need caption for Table 7-12

Instrument Type	# of Type	Measurements Requested	Reason for Measurments (If Known)	Instrument Managing Agency
Yankee Environmental Systems UVB-1	6	Angular & Spectral Responsivities Absolute Irradiance	Annual Check of field standards	NOAA_GRAD-CUCF
Yankee Environmental Systems UVB-1	2	Angular & Spectral Responsivities Absolute Irradiance	Post repair Calibration	NOAA_GRAD-SURFRAD
PNNL remanufactured VisMFRSR	3	Spectral Responsivity	Spectral Response systems crosscheck	ARM_SGP facility
Yankee Environmental Systems MFR-7 TSR model	1	Angular & Spectral Responsivities	Closing calibration	Cloud & Aerosol Laboratory National Central University Taiwan
Yankee Environmental Systems UVMFRSR	2	Angular & Spectral Responsivities Absolute Irradiance	Pre-deployment cycle calibration	USDA_UV-B Monitoring Program Colorado State University
2015				
Yankee Environmental Systems UVB-1	1	Angular & Spectral Responsivities Absolute Irradiance	Deployment Cycle Calibration	USDA_UV-B Monitoring Program Colorado State University
Yankee Environmental Systems MFR-7 Mk. 2	2	Angular & Spectral Responsivities	Deployment Cycle Calibration	Cloud & Aerosol Laboratory National Central University Taiwan
Yankee Environmental Systems MFR-7 TSR model	1	Angular & Spectral Responsivities	Deployment Cycle Calibration	Cloud & Aerosol Laboratory National Central University Taiwan
Yankee Environmental Systems MFR-7 TSR-1625 variant	4	Angular & Spectral Responsivities Absolute Irradiance	Pre & Post deployment calibrations for WMO Filter Radiometer Comparison (FRC-IV)	ARM_SGP facility
Yankee Environmental Systems MFR-7 TSR-1625 variant	6	Angular & Spectral Responsivities Absolute Irradiance	New Instrument Calibration	NOAA_GRAD-SURFRAD
Yankee Environmental Systems MFR-7 Mk. 2	1	Angular & Spectral Responsivities Absolute Irradiance	Deployment Cycle Calibration	USDA_UV-B Monitoring Program Colorado State University
Yankee Environmental Systems UVMFRSR	3	Angular & Spectral Responsivities Absolute Irradiance	Deployment Cycle Calibration	USDA_UV-B Monitoring Program Colorado State University

Need caption for Table 7-12

Yankee Environmental Systems MFR-7 Mk.2 (NASA mod.)	1	Angular & Spectral Responsivities Absolute Irradiance	Pre-deployment Calibration to Korea (KORUS_AQ campaign?)	Center for Atmospheric Sciences Hampton University Virginia (NASA assoc.)
Yankee Environmental Systems UVMFRSR (NASA modified)	1	Angular & Spectral Responsivities Absolute Irradiance	Pre-deployment Calibration to Korea (KORUS_AQ campaign?)	Center for Atmospheric Sciences Hampton University Virginia (NASA assoc.)
2016				
Yankee Environmental Systems UVB-1	6	Angular & Spectral Responsivities Absolute Irradiance	Annual Check of field standards	NOAA_GRAD-CUCF
Yankee Environmental Systems MFR-7 TSR-1625 variant	10	Angular & Spectral Responsivities Absolute Irradiance	New Instrument Calibration	NOAA_GRAD-SURFRAD
Yankee Environmental Systems UVMFRSR	1	Angular & Spectral Responsivities Absolute Irradiance	Deployment Cycle Calibration	USDA_UV-B Monitoring Program Colorado State University
2017				
Yankee Environmental Systems UVB-1	2	Angular & Spectral Responsivities Absolute Irradiance	Pre & Post deployment calibrations for WMO Filter Radiometer Comparison (UVC-II)	NOAA_GRAD-CUCF
Yankee Environmental Systems UVB-2	4	Angular & Spectral Responsivities Absolute Irradiance	Annual Check of field standards	NOAA_GRAD-CUCF
Yankee Environmental Systems MFR-7 TSR-1625 variant	4	Angular & Spectral Responsivities Absolute Irradiance	Deployment Cycle Calibration	NOAA_GRAD-SURFRAD
Yankee Environmental Systems MFR-7 TSR model	1	Angular & Spectral Responsivities Absolute Irradiance	Deployment Cycle Calibration	Environmental Physics Laboratory University of Girona Spain
Yankee Environmental Systems MFR-7 Mk.2 (NASA mod.)	1	Angular & Spectral Responsivities Absolute Irradiance	Post deployment Calibration from Korea (KORUS_AQ campaign?)	Center for Atmospheric Sciences Hampton University Virginia (NASA assoc.)
Yankee Environmental Systems UVMFRSR (NASA modified)	1	Angular & Spectral Responsivities Absolute Irradiance	Post deployment Calibration from Korea (KORUS_AQ campaign?)	Center for Atmospheric Sciences Hampton University Virginia (NASA assoc.)
Repaired MFR-7 Mk.1	3	Angular & Spectral Responsivities Absolute Irradiance	Post repair calibration	USDA_UV-B Monitoring Program Colorado State University

Need caption for Table 7-12

2018

Remanufactured MFR-7 Mk1	3	Spectral response (all failed)	Post rebuild calibration	USDA_UV-B Monitoring Program Colorado State University

the same concerns and methodologies apply to the Vis and NIR spectrums as well. A new generation of Visible Multi Filter Spectro Radiometers (VisMFRSR mk. 2) were being built around the time the visible spectral response system was becoming operational in 2010. Even though this was a laboratory setting, these heads were notably more stable in signal level and temperature than earlier generations of instruments. Temperature stability was improved due a change in how the Photodiodes and filters were mounted. The diodes and filters are inserted into a machined aluminum block. This block provides useful thermal mass and ensures that the filters and detectors stay aligned to the entrance aperture. In the original design, the filters and detectors were packaged together and simply soldered to a circuit card. The circuit card in the new version employed an amplifier chip designed for use as a transimpedance amplifier. Surface-mounted components allowed the circuitry to be mounted on a single PCB that was enclosed at the base of the photodetector mounting block and an aluminum cover plate. The first instance of the new version seen by the CUCF had already been modified by NASA Goddard, changing channel wavelengths and a placing a dome over the diffuser. (Note: NASA has three such MFRSRs, 2 UV and 1 Vis.) The wavelength drives of the Vis and UV monochromators are calibrated using Mercury spectral line lamp. Each monochromator has been calibrated so that they have at least two lines in common. This allows an instrument to be scanned on both systems and the centroids checked for agreement. The variance limit is set at 0.25nm or less. Verified instances of deviation greater than 0.25nm (2.5Å) indicate that a wavelength drive needs recalibration.

In 2007, the CUCF assisted the DOE's ARM program in building a spectral response system for their calibration facility at the Southern Great Plains (SGP) facility. Periodically, SGP sends a few VisMFRSR instruments to the CUCF for a cross-check. In 2014, they sent three heads to be measured; this time, a discrepancy between the CUCF's SPR systems was found, traced to the Vis system and the wavelength registration. During the reregistration of the CUCF Vis system, SGP requested their artifact standard back for an end- of-quarter calibration check. It was sent back to be remeasured on the CUCF's freshly calibrated Vis system and found a 3.5nm deviation between the most recent SGP and CUCF measurements. SGP's system designer chose an HgCd line lamp for their scale standard. This lamp has two strong lines, a Cd triplet at 361.1625 nm and an Hg triplet at 365.0158 nm. The Hg line tends to be much more intense, and the software will preferentially use that if it is in the wavelength range specified. SGP personnel were able to re-establish the wavelength registration with help from the CUCF.
In 2015, SURFRAD acquired a series of the new MFRSR instruments. These had two modifications: a thermopile replacing the Si photodiode in the center channel and a 1625 nm channel, with InGaAs photodiode replacing the 615 nm channel. The 1625 nm filters were measured on the Cary 5e before they were mounted on the InGaAs photodiodes. The 1625 nm channel is beyond the current range of Vis SPR system and so not measured as a complete package. Multiple data sets were then used to create both CUCF and YESDAS format calibration files for these heads. The ability to perform spectral calibration on the 1625 nm is possible but will require significant work and equipment modifications.

NASA Goddard/Hampton University sent in heads U0582 and V0579 for calibration prior to deployment to Seoul, Korea in 2017. The angular response showed a very sharp change in the plots for both E-W and N-S compared to measurements made in 2011. On close examination, plots for U0582 also showed a small but noticeable change from the 2010 measurement. With the instrument mounted in the Angular response bench, the cause of the change was soon found. In field trials, the dome showed vapor inside indicating a leak. The dome was remounted but much more adhesive was used, filling some of the space between the dome and the Horizon ring. The adhesive used in both cases was a NASA approved urethane modified with Cabosil silica, a very white reflective filler. With the material restricted to the groove for the dome not much light was reflected. With the adhesive filling the gap between the Dome and Horizon ring, a lot of light was scattered around the dome. (Carbon black might have been a better choice for a filler material.) Still, with the variance measured a correction for the actual response to the desired Lambertian response was possible.

CALIBRATED LAMPS

In September of 2019, three lamps were identified as stable enough to be considered for use as Secondary Vertical 1000W FEL Standard Lamps. At present, the three lamps have had posts soldered on the lamps. These lamps still need to be boxed, potted, and labeled. A calibration transfer from the primary NIST Standard lamp would be required. Once completed these lamps could be used as transfer standards for Horizontal lamps used in the Portable Field Calibrator.

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Section 8 - Gas Calibration and Quality Control Activities

Trace gas standards and calibration activities support long-term measurements of traces gases by GMD and others. GMD has a long history of preparing primary standards and propagating calibration scales within both GMD and the WMO/GAW community. In support of WMO/GAW, GMD has served as the WMO/GAW Central Calibration Laboratory (CCL) for CO2 since 1995 and for CH4, CO, N2O, and SF6 thereafter. As a CCL, GMD maintains WMO primary calibration scales and provides calibrated gas mixtures to WMO laboratories for CH4, CO, N2O, and SF6. GMD also maintains in-house scales, at various levels of maturity, for approximately 55 other trace gases.

Calibration of instrumentation for many trace gas measurements is based on analysis of air from high-pressure gas cylinders with known composition. A hierarchy of gas standards is 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 CO2, primary standards consist of modified natural air in aluminum cylinders, with CO2 abundance determined by a manometric method.

In 2010, WMO signed the Mutual Recognition Arrangement (MRA) with the Comité International des Poids et Mesures (CIPM). Under the CIPM MRA, GMD was encouraged to maintain a "Quality Management System" (QMS) and conform to international standards for calibration and measurement (ISO 17025, ISO 17034). A GMD QMS was developed and underwent peer review in 2015 and was approved for a 5-yr period. We are active in the CIPM Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology (CCQM) Gas Analysis Working Group and participate in international comparisons as appropriate.

8.1 CALIBRATION SCALE UPDATES

Between 2014 and 2018, several calibration scales were updated, including CO, SF6, CH4, and CFC-11. For current information on calibration scales, see https://gml.noaa.gov/ccl/scales.html.

For CFC-11, five new primary standards were prepared gravimetrically to replace aging standards that were starting to show signs of contamination (i.e., growth of ECD-sensitive compounds at ppt levels). New standards were prepared in 29.5-L aluminum and 34-L stainless steel cylinders. Previous CFC-11 standards were prepared in 5.9-L aluminum cylinders. The revised scale is within 1 ppt of the previous scale at ambient mixing ratios and helps resolve discrepancies between ECD-based and GC-MS-based analysis in older records when CFC-11 mixing ratios were higher (e.g., in 2000, the global mean mixing ratio of CFC-11 was 259 ppt, which is 30 ppt higher than in 2018).

For SF6, we extended the upper limit of the scale range to 20 ppt. The previous scale, X2006, was not defined above 10 ppt, and the rapid increase of SF6 in the atmosphere was quickly outpacing the scale. With the new scale, we also employ a non-linear calibration response on the ECD, which has resulted in improved reproducibility (now 0.02 ppt at 95% C.L.).

In 2014, the upper limit of the CH4 scale was extended to 5000 ppb to support measurements in urban and other high-emission environments. The previous scale, X2004, was defined by 16 standards over the nominal range 300-2600 ppb. Adding one additional primary standard at approximately 2200 ppb and five additional primary standards in the upper range, approximately 3100-5900 ppb, the new scale (X2004A) is now defined by 21 primary standards. Based on recalibration of 19 historical secondary standards, X2004A is different from X2004 by a mean and standard deviation of 0.3±0.3 ppb in the approximate range 1500 to 2000 ppb. For tertiary standards, it was -0.4±1.9 ppb over the range 300 to 2600 ppb. Actual differences depended on when standards were originally calibrated. Because of the time dependence of the difference, we asked scale users to retrieve new assignments for their standards directly from the CCL website (https://gml.noaa.gov/ccl/refgas.html). A full analysis was presented at the 2015 GGMT meeting.

The CO scale was updated in 2015. The new scale (X2014A) is based on 14 primary standards prepared gravimetrically in 2011 in 29.5-L aluminum cylinders. The primary standards cover the nominal range 30 - 1000 ppb. Because these standards are drifting upward with time (CO increasing), drift is tracked using an internal tracer method in which three parent mixtures of CO (0.1-1%) and CH4 (3%) are used to prepare a suite of "dilution standards." To make a dilution standard, an aliquot of parent mixture is diluted with CO/CH4-free air to create a ppb-level mixture in a 5.9-L aluminum cylinder. The CO mole fraction of the dilution standard is determined by measuring the CH4 and calculating CO from the CO:CH4 ratio of the parent. A suite of 16 "dilution standards" covering the nominal range 25-1000 ppb CO are prepared once or twice per year and compared to the 2011 suite of primary standards soon after preparation. The immediate comparison of the dilution standards to the primary standards ensures growth of CO in the dilution standards is insignificant. The dilution standards are discarded after comparison to the 2011 primaries and the cylinders are reused. This method will be used to assess drift rates in the coming years and may result in minor scale revisions as the drift rates are better quantified. In 2015, a second suite of 12 CO gravimetric standards (nominal range 30-1000 ppb) was produced to verify the internal tracer technique. Results of this validation work were presented at the 2015 GGMT meeting. These cylinders now form a backup set of primary standards and are routinely analyzed against the dilution standards and secondary standards.

During this reporting period, we began work on a revision of the X2007 CO2 scale. The revision will fix two known deficiencies (loss of CO2 to Viton o-rings during the measurement process, and a known calculation error related to the 2nd Virial coefficient of CO2). Preliminary results were presented at the 2017 GGMT meeting in Dubendorf, Switzerland. Preparation of five CO2 gas standards (covering the nominal range 357-491 ppm) by gravimetric methods was a new and important part of this work.

8.2 STANDARDS IN SUPPORT OF NEW OR CONTINUING MEASUREMENTS

New standards for HFO-1234yf, HFO-1234ze, CF3SF5, 1,2-dichloroethane, HCFC-21, HCFC-133a, CF4, NF3, non-methane hydrocarbons such as ethane, propane, BTEX (benzene, toluene, ethyl benzene, xylene), perfluoroamines and SO2F2 were prepared to support new measurements. In addition, we prepared new gravimetric standards for CH2Cl2, HCFC-141b, HCFC-142, CO, and CO2 to verify current scales.

8.3 INSTRUMENT CHANGES

Historically, NOAA GMD transferred the WMO CO2 mole fraction scale by non-dispersive infrared absorption (NDIR) spectroscopy and the methane mole fraction scale by gas chromatography with flame ionization detection (GC-FID). We have recently transitioned to a combined calibration system that uses laser spectroscopic methods for both CO2 and CH4.

Since April 2016, the CO2 scale has been propagated using cavity ring-down spectroscopy (CRDS), off-axis integrated cavity output spectroscopy (off-axis ICOS), and quantum cascade-tunable infrared laser differential absorption spectroscopy (QC-TILDAS). The new calibration system makes use of the ability of these analyzers to measure some CO2 isotopologues to fully account for isotopic differences among members of the primary standard set and between the primary standards and subsequent levels of standards in the calibration hierarchy. The new CO2 calibration system offers a significant advantage over the NDIR because it is calibrated over the full range of the scale and the response to the major isotopologue (16O12C16O) is linear within uncertainty. The NDIR system, which typically did not respond linearly to changes in CO2, employed groups of 3-4 bracketing primary standards to calibrate secondary standards. Reproducibility of the CO2 calibrations from 225-520 ppm (approximately 0.02 ppm, 95% C.L.) using the new system is about a factor of three better than the NDIR. Comparison of the NDIR and laser spectroscopic systems revealed small, mole fraction-dependent differences (< 0.1 ppm) due, in part, to errors in value assignment of some primary and secondary standards coupled with the use of subset of standards on the NDIR. These differences will be corrected upon revision of the CO2 scale.

In November 2016, CH4 scale propagation was transitioned from the GC-FID system to the CRDS instrument used on the CO2 laser spectroscopic system. This increased efficiency by allowing the simultaneous calibration of CH4 and CO2. The CRDS instrument is calibrated monthly using 14 secondary standards covering the range 300-5900 ppb. Reproducibility using the CRDS is around 0.2 ppb (95% C.L), which is about a factor of five better than the GC-FID system. A 9-month overlap period showed excellent agreement between the two systems (average CRDS – GC-FID = 0.0 +/- 0.3 ppb, based on 267 tank calibrations between 300 and 3000 ppb).

8.4 COMPARISONS

In addition to our role as a WMO CCL, GMD also serves as a WMO World Calibration Center (WCC) for CO2, along with the Swiss Federal Laboratories for Materials Science and Technology (Empa). As a WCC, GMD organized and carried out the 6th WMO Round Robin comparison experiment in 2014-2015. Ten cylinders (two in each of five circuits) were circulated among 40 laboratories for analysis for CO2, CH4, N2O, CO, SF6, H2, and among some laboratories for stable isotopes of CO2 and ratios of oxygen/nitrogen. Results are available on the GMD website: https://gml.noaa.gov/ccgg/wmorr/wmorr_results.php.

Table 8.1: Formal and informal comparisons of gas standards.

Comparison	Year Conducted	Gases	Participants
CCQM-K82	2013	CH4	NMIs
CCQM-K120	2016-2017	CO2	NMIs
CCQM-P116	2016	water vapor in N2	NMIs
SICE	2015	SF6	WMO labs
WMO RR 6	2014-2015	CO2, CH4, N2O, CO, H2, SF6	WMO labs, others
informal	2016	SF6	KRISS
informal	ongoing	CO2, CH4, N2O, CO, H2, SF6	MPI, INSTAAR, FMI
informal	2017 (ongoing)	CO2, CH4, N2O	NIST
informal	ongoing	halocarbons + others	AGAGE

As a CCL, we are a designated institute of WMO and have participated in a number of comparisons, both formal and informal, with National Metrology Institutes (NMIs) and others (Table 8.1). Notable comparisons carried out under the auspices of the CCQM include CCQM-K82 (CH4) and CCQM-K120 (CO2).

The WMO X2004 CH_4 scale compared favorably to the consensus value at approximately 1800 ppb CH_4 during K82 (the NOAA sample was 2.2 ppb lower than the consensus value). At approximately 2200 ppb, the WMO X2004 scale was 4.9 ppb lower than the consensus value. For CO_2, we submitted results for the K120 comparison on a provisional version of a revised CO_2 scale (X2017p). At nominal mole fractions of 380 ppm and 480 ppm, the NOAA X2017p CO_2 scale compared very well with consensus values (with 0.1 ppm). The WMO X2007 scale would also be consistent with the consensus values at these mole fractions, considering uncertainties.

8.5 WHOLE-AIR STANDARDS PREPARED AT NIWOT RIDGE

The ability to prepare cylinders containing unpolluted natural air (i.e., whole air) from a remote facility near Boulder, Colorado, has proven enormously valuable to GMD. Since the late 1970s, we have been collecting air in cylinders at or near Niwot Ridge in the Rocky Mountains west of Boulder. Cylinders of whole air are used extensively in gas analysis, as secondary and tertiary standards, as well as for testing instruments and sampling methods. Standards are also made available to outside laboratories as part of our role as a WMO/GAW Central Calibration Laboratory.

Methods and protocol for filling standards did not change over the 2014-2018 period. However, the internal software used to track cylinders and calibration progress on GMD's measurement systems, known as "Refgas Manager," was improved for easier input and information retrieval, and automated analysis reports have been added to the system.

High mixing ratio sources for targeting heavier than ambient 13C of CO_2, ambient isotopic CO_2, or C_2H_6, has been added to the set of spike gases used to modify mixing ratios of ambient air. We now have the capability to target total CO_2 (with either lighter, ambient, or heavier isotopic 12C/13C of CO_2), CH_4 (with ambient or lighter than ambient isotopic composition), CO, N_2O, SF_6, and C_2H_6 in the same cylinder. A separate high-pressure trap with MoleculiteTM has been tested and can now be added to the system as needed to disproportionately lower CO compared to the other analytes for southern hemisphere measurement programs.

The RIX model SA6 compressor used to fill cylinders with whole air at the Niwot Ridge facility is no longer manufactured. Repair and replacement parts have been available and ongoing. A replacement compressor was purchased as backup before the model was discontinued. The whole-air standards program has expanded over the years, and now around 400 standards are created each year. Scott Marrin Inc., our main supplier for new cylinders, cylinder re-certification, valving, pre-filling, and ultra-pure air supply was acquired by Praxair Inc in 2017. This initially resulted in supply problems. We now purchase from two U.S. suppliers to mitigate the risk of relying on a single vendor.

SECTION 9 - ACRONYMS/GLOSSARY

9.1 INSTRUMENTS, NETWORKS, ORGANIZATION, 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
AM	ARM Mobile Facility
AMibA	Array for Microwave Background Anisotropy
AntUV	Antarctic UV Monitoring
AOD	aerosol optical depth
AOT	aerosol optical thickness
ARCPA	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)
BSR	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-EC	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
GEO	Summit 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
ISI	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	elative 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 Ozonesond 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
SR	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
UP	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

CFC	chlorofluorocarbon
CFC-11	trichlorofluoromethane
CFC-12	dichlorodifluoromethane
CFC-113	trichlorotrifluoroethane
CH4	methane
δD in CH4	hydrogen isotopic composition of methane
CO	carbon monoxide
CO2	carbon dioxide
COS	carbonyl sulfide
DMS	dimethyl sulfide
H	hydrogen
Halon-1211	bromochlorodifluoromethane
Halon-1301	bromotrifluoromethane
Halon-2402	1,2-dibromotetrafluoroethane
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HCFC-22	chlorodifluoromethane
HCFC-141b	1,1-dichloro-1-fluoroethane
HCFC-142b	freon 142b
HFC	hydrofluorocarbon
HFC-134a	1,1,1,2-tetrafluoroethane
HFC-152a	1,1-difluoroethane
Hg	mercury
KI	potassium iodide

KBr	potassium bromide
OH	hydroxyl (radical)
MSA	methane sulfonate
NO2	nitrogen dioxide
NOx	nitrogen oxides
PAN	peroxyacetyl nitrate
PFC	perfluorocarbon
SO2	sulfur dioxide
TFA	trifluoroacetate
VOC	volatile organic carbon