

Appendix C

Selected Carbon Cycle Research Observations and Measurement Programs¹

<https://doi.org/10.7930/SOCCR2.2018.AppC>

C.1 Aquatic Observations Gulf of Mexico Ecosystems and Carbon Cruise (GOMECC)

Description: The third GOMECC (GOMECC-3) performed a large-scale survey of ocean acidification trends and dynamics in the Gulf of Mexico on the National Oceanic and Atmospheric Administration's (NOAA) *Ronald H. Brown* ship. The NOAA Ocean Acidification Program has been charged with setting up an ocean acidification monitoring network to quantify the increase in near-surface water carbon dioxide (CO₂) and associated changes in inorganic carbon speciation. As part of the observing scheme, dedicated research cruises are conducted to investigate the water column properties along select transects, and pertinent surface water characteristics are evaluated along the cruise track. Coastal ocean measurements of unprecedented quality are used to improve understanding both of where ocean acidification is happening and of how ocean chemistry patterns are changing over time. GOMECC-3 is the most comprehensive ocean acidification cruise to date in this region, also including sampling in the international waters of Mexico for the first time.

Sponsoring agency: NOAA

Observation type: Cruise

Location: Gulf of Mexico

¹ This appendix is a partial listing; some important observations may not be presented. Some content is adapted from *Our Changing Planet: The U.S. Global Change Research Program for Fiscal Year 2016* and includes information from GLOBALVIEW-CO2 (www.esrl.noaa.gov/gmd/ccgg/globalview/co2/co2_intro.html).

Timeline: GOMECC-3, July 18, 2017, to August 21, 2017; GOMECC-2, July 21, 2012, to August 7, 2012; GOMECC-1, July 10, 2007, to August 4, 2007

More information: www.aoml.noaa.gov/ocd/gcc/GOMECC3; www.aoml.noaa.gov/ocd/gcc/GOMECC2; and www.aoml.noaa.gov/ocd/gcc/GOMECC1

Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP)

Description: GO-SHIP collaborations bring together scientists with interests in physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems, and other users and collectors of ocean interior data. The program also coordinates a network of globally sustained hydrographic sections as part of the global ocean and climate observing system, including physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems. GO-SHIP provides approximately decadal resolution of the changes in inventories of heat, freshwater, carbon, oxygen, nutrients and transient tracers, covering the ocean basins from coast to coast at full depth (top to bottom). Its global measurements are of the highest accuracy required to detect these changes.

Sponsoring agencies: National Science Foundation (NSF) and NOAA

Observation type: Sustained ocean cruise observations

Location: Global ocean

Timeline: 2006 to present

More information: www.pmel.noaa.gov/co2/story/Hydrographic+Cruises and www.go-ship.org

High-Resolution Ocean and Atmosphere $p\text{CO}_2$ Time-Series Measurements

Description: High-frequency autonomous CO_2 moorings monitor and improve understanding of the coastal ocean carbon balance, continent-scale carbon budgets and impacts of ocean acidification in coastal regions.

Sponsoring agency: NOAA

Observation type: Sustained ocean cruise observations

Location: Coastal and open ocean

Timeline: 2005 to present

More information: www.pmel.noaa.gov/co2/story/Coastal+Moorings and www.pmel.noaa.gov/co2/story/Open+Ocean+Moorings

Surface Ocean CO_2 Atlas Project (SOCAT)

Description: SOCAT is a synthesis activity for quality-controlled, surface ocean $f\text{CO}_2$ (i.e., fugacity of CO_2) observations by the international marine carbon research community, including more than 100 contributors. SOCAT data is publicly available, discoverable, and citable. SOCAT enables the quantification of the ocean carbon sink and ocean acidification and the evaluation of ocean biogeochemical models. Celebrating its 10th anniversary in 2017, SOCAT represents a milestone in biogeochemical and climate research and in informing policy.

Sponsoring agency: NOAA

Observation type: Surface ocean CO_2 synthesis

Location: International

Timeline: 2007 to present

More information: www.socat.info/ and www.pmel.noaa.gov/co2/story/SOCAT

Surface Water $p\text{CO}_2$ Measurements from Ships

Description: NOAA's automated measurement campaign of surface water CO_2 from 17 ships of opportunity (SOOP- CO_2) quantifies the fluxes of CO_2 on seasonal and regional scales.

Sponsoring agency: NOAA

Observation type: Sustained ocean cruise observations

Location: Global ocean

Timeline: 2005 to present

More information: www.aoml.noaa.gov/ocd/ocdweb/occ_soop.html and www.pmel.noaa.gov/co2/story/Volunteer+Observing+Ships+%28VOS%29

C.2 Terrestrial Observations

AmeriFlux Network

Description: The AmeriFlux Network, a community of sites and scientists measuring ecosystem carbon, water, and energy fluxes across the Americas, is committed to producing and sharing high-quality eddy covariance data. AmeriFlux investigators and modelers work together to generate understanding of terrestrial ecosystems in a changing world.

Sponsoring agencies: U.S. Department of Energy (DOE) and many partners

Observation type: Surface network

Location: Western Hemisphere

Timeline: 1996 to present

More information: ameriflux.lbl.gov

Detrital Input and Removal Experiment (DIRT) Network

Description: The international DIRT network was established to assess how rates and sources of plant litter inputs control the long-term stability, accumulation, and chemical nature of soil organic matter in forested ecosystems over decadal time scales. Sites span climatic and soil gradients, with sampling occurring about every 10 years.

Sponsoring agencies: NSF and others

Observation type: Distributed field campaign

Location: United States and global

Timeline: 1956 to present

More information: dirtnet.wordpress.com

Free-Air CO_2 Enrichment (FACE) Experiments

Description: FACE research technology creates a platform for multidisciplinary, ecosystem-scale research on the effects of elevated atmospheric CO_2 concentrations over extended periods of time. FACE technology is capable of providing a means by which

the environment around growing plants may be modified to realistically simulate future concentrations of atmospheric CO₂. FACE field data represent plant and ecosystem responses to concentrations of atmospheric CO₂ in a natural setting possible during the next century.

Sponsoring agencies: DOE, Smithsonian Environmental Research Center (SERC)

Observation type: Distributed field campaign

Location: United States and global

Timeline: 1994 to present

More information: science.energy.gov/~media/ber/berac/pdf/Face_report.pdf and facedata.ornl.gov

Forest Inventory and Analysis (FIA)

Description: The FIA program provides statistically reliable quantitative estimates of forest area and ownership; species, volume, total tree growth, mortality, and removals; wood production and utilization rates; and forest carbon including soils. More than 150,000 forested sample plots are on non-federal lands. FIA measurements of forest carbon are the basis for U.S. reporting to the United Nations Framework Convention on Climate Change for the annual monitoring of carbon in the National Greenhouse Gas Inventory.

Sponsoring agency: U.S. Department of Agriculture (USDA) Forest Service

Observation type: Distributed field campaign supplemented by remote sensing

Location: United States

Timeline: 1930 to present

More information: www.fia.fs.fed.us

Greenhouse gas Reduction through Agricultural Carbon Enhancement network (GRACEnet)

Description: GRACEnet is a research program initiated to better quantify greenhouse gas (GHG) emissions from cropped and grazed soils under current management practices and to identify and further develop improved management practices that will enhance carbon sequestration in soils, decrease GHG emissions, promote sustainability, and provide a sound scientific basis for carbon credits and GHG

trading programs. This program generates information needed by agroecosystem modelers, producers, program managers, and policymakers. Coordinated multilocation field studies follow standardized protocols to compare 1) net emissions of GHGs including CO₂, nitrous oxide (N₂O), and methane (CH₄); 2) carbon sequestration; 3) crop and forage yields; and 4) broad environmental benefits under different management systems. These systems typify existing production practices, maximize carbon sequestration, minimize net GHG emissions, and meet sustainable production and broad environmental benefit goals (e.g., carbon sequestration; net GHG emissions; and water, air, and soil quality). The data are accessible through a Geospatial Portal for Scientific Research (GPSR) application that is an ongoing effort of the USDA Agricultural Research Service (ARS) to increase the availability of research data to the broader scientific community. The data contained within this application represent complex relationships of data among hundreds of scientific measurements.

Sponsoring agency: USDA ARS

Observation type: Field campaign

Location: United States

Timeline: 2003 to present

More information: www.ars.usda.gov/anrds/gracenet/gracenet-home and www.data.nal.usda.gov/dataset/gracenet-greenhouse-gas-reduction-through-agricultural-carbon-enhancement-network_150

Gridded Soil Survey Geographic (gSSURGO) Database

Description: The gSSURGO database is the most detailed level of soil geographic data developed by the National Cooperative Soil Survey (NCSS) in accordance with NCSS mapping standards and at a variety of map scales. The three soil geographic databases are the Soil Survey Geographic (SSURGO) database, the State Soil Geographic (STATSGO) database, and the National Soil Geographic (NATSGO) database. These tabular data representing soil attributes are derived from properties and characteristics stored in the National Soil Information System (NASIS), such as soil organic carbon,

soil texture, bulk density, available water storage, salinity, water table depth, depth to bedrock, flooding, potential wetland soil landscapes, associated metadata, and land management.

Sponsoring agency: USDA Natural Resources Conversation Service (NRCS)

Observation type: Distributed field, remote-sensing, and air campaign

Location: United States

Timeline: ~1930 to present

More information: www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053628

International Soil Carbon Network (ISCN)

Description: The ISCN is a self-chartered, scientific community resource devoted to the advancement of soil carbon research. The network coordinates independent soil research and monitoring efforts in the United States and internationally. ISCN members contribute to an open-access, community-driven soil carbon database.

Sponsoring agencies: USDA Forest Service, NRCS, and National Institute of Food and Agriculture; U.S. Geological Survey (USGS); and Lawrence Berkeley National Laboratory

Observation type: Distributed field campaign

Location: United States and global

Timeline: 2012 to present

More information: iscn.fluxdata.org/data/access-data

Landsat

Description: The Landsat series of satellites provides the longest temporal record (over 45 years) of moderate resolution data of the Earth's surface on a global basis. Landsat is a critical element of national and global carbon observation capability, providing foundational data covering many sectors of carbon observations and monitoring, such as forests, agriculture, soil, water, and land use. Landsat data, unique in quality, detail, coverage, and value, are routinely used in carbon cycle studies including mapping, modeling, and assessment.

Sponsoring agencies: National Aeronautics and Space Administration (NASA) and USGS

Observation type: Repeat measurements of surface reflectance by satellites

Location: Global

Timeline: 1972 to present

More information: landsat.usgs.gov

Long-Term Ecological Research (LTER) Network

Description: As the largest and longest-lived U.S. ecological network, LTER provides scientific expertise, research platforms, and long-term datasets to document and analyze environmental change, supporting a network of over 26 LTER sites encompassing diverse ecosystems including deserts, estuaries, lakes, the ocean, coral reefs, prairies, forests, alpine and Arctic tundra, urban areas, and production agriculture. The network was created to conduct research on ecological issues that can last decades and span huge geographical areas, assembling a multidisciplinary group of more than 2,000 scientists and graduate students.

Sponsoring agencies: NSF, USDA Forest Service, USDA ARS, U.S. Department of Interior (U.S. DOI) National Park Service, U.S. DOI Fish and Wildlife Service, and U.S. Environmental Protection Agency

Observation type: Distributed field campaign, airborne, and surface network

Location: Continental United States, Alaska, Antarctica, and islands in the Caribbean and the Pacific

Timeline: 1980 to present

More information: lternet.edu

Next-Generation Ecosystem Experiment (NGEE)–Arctic

Description: Initial research of NGEE-Arctic will focus on the highly dynamic landscapes of the North Slope (Barrow, Alaska), where thaw lakes, drained thaw lake basins, and ice-rich polygonal ground offer distinct land units for investigation and modeling. This project involves mechanistic studies in the field and the laboratory; modeling of critical and interrelated water, nitrogen, carbon, and energy dynamics; and characterization of important interac-

tions, from molecular to landscape scales, that drive feedbacks to the climate system.

Sponsoring agency: DOE

Observation type: Field campaign

Location: Alaska

Timeline: 2012 to 2022

More information: ngee-arctic.ornl.gov

Next-Generation Ecosystem Experiment (NGEE)–Tropics

Description: NGEE-Tropics is a combined observational and modeling project to increase scientific understanding of how tropical forest ecosystems will respond to climatic and atmospheric changes, reduce uncertainty in Earth System Model projections, and discover whether tropical forests will act as net carbon sinks throughout this century. NGEE uses coupled observations and field campaigns in tropical forest regions and has developed a process-rich tropical forest ecosystem model at a resolution better than 10 km.

Sponsoring agencies: DOE, Smithsonian Tropical Research Institute, USDA Forest Service, and NASA

Observation type: Field and aircraft campaign

Location: Puerto Rico; Manaus, Brazil; and Panama

Timeline: 2016 to 2026

More information: ngee-tropics.lbl.gov

National Ecological Observatory Network (NEON)

Description: NEON is designed to collect and provide open data that characterize and quantify complex, rapidly changing ecological processes in terrestrial and aquatic environments across the United States. The comprehensive data, spatial extent, and remote-sensing technology provided by NEON enable a large and diverse user community to tackle new questions at scales not accessible to previous generations of ecologists.

Sponsoring agency: NSF

Observation type: Distributed field campaign, airborne, and surface network

Location: United States

Timeline: 2011 to 2048

More information: www.neonscience.org

PEATcosm 1 and PEATcosm 2

Description: PEATcosm is a mesocosm experiment in which 24 bins, each 1 m³, are filled with relatively intact, undisturbed peat. PEATcosm 1, established in 2011, evaluates the influence of a lower water table and the shrub and *Ericaceae* communities on carbon cycling. PEATcosm 2, currently under establishment, is assessing the effect of water tables and the tree community encroachment on carbon cycles.

Sponsoring agencies: USDA Forest Service and NSF

Observation type: *In situ* measurements of carbon processes

Location: Houghton, Michigan

Timeline: 2011 to 2022

More information: www.nrs.fs.fed.us/clean_air_water/local-resources/downloads/peatcosm_information.pdf

Rapid Carbon Assessment (RaCA)

Description: RaCA is designed to develop statistically reliable quantitative estimates of the amounts and distribution of carbon stocks for U.S. soils under various land covers and to the extent possible under differing agricultural management. The project also seeks to provide 1) data to support model simulations of soil carbon change related to land-use change, agricultural management, conservation practices, and climate change and 2) a scientifically and statistically defensible U.S. inventory of soil carbon stocks.

Sponsoring agency: USDA

Observation type: Distributed field campaign

Location: United States

Timeline: 2010 to present

More information: www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054164

Spruce and Peatland Responses Under Changing Environments (SPRUCE)

Description: The SPRUCE experiment, conducted in a black spruce peat bog in the U.S. Forest Service Marcell Experimental Forest in northern Minnesota, tests mechanisms controlling the vulnerability of organisms, biogeochemical processes, and ecosystems to climate change. SPRUCE is focused on the combined responses to multiple levels of warming at ambient or elevated CO₂ levels, toward improving fundamental understanding and model representation of ecosystem processes under climate change.

Sponsoring agencies: DOE and USDA Forest Service

Observation type: Field campaign

Location: Minnesota

Timeline: 2015 to 2025

More information: mnspruce.ornl.gov

Tropical Responses to Altered Climate Experiment (TRACE)

Description: The TRACE experiment, conducted in wet tropical forests in the Luquillo Experimental Forest in northeast Puerto Rico, evaluates the effects of temperature increase on soil structure, biogeochemical cycling, plant physiology, and other key ecosystem processes, with a particular focus on understanding the relationship between temperature and carbon cycling. TRACE uses infrared heat to warm soils and understory plants and small resistance heaters to warm individual leaves in the forest canopy with the ultimate goal of improving the fundamental understanding and model representation of tropical forest processes in a warmer world.

Sponsoring agencies: USDA Forest Service and DOE

Observation type: Field campaign

Location: Puerto Rico

Timeline: 2015 to 2020 (est.)

More information: www.forestwarming.org and www.fs.usda.gov/iitf

C.3 Atmospheric Observations

Arctic-Boreal Vulnerability Experiment (ABOVE)

Description: ABOVE is a large-scale investigation of the impact of environmental change on ecosystem function, ecosystem services, and its implications for social-ecological systems in Alaska and northwestern Canada. ABOVE research links field-based, process-level studies with geospatial data products derived from airborne and satellite sensors, providing a foundation for improving analysis and modeling capabilities for northern ecosystems.

Sponsoring agencies: NASA in partnership with DOE, DOI, USDA Forest Service, and the State of Alaska, as well as several Canadian federal and provincial agencies.

Observation type: Satellite and aircraft

Location: Alaska and western Canada

Timeline: September 2015 to September 2023

More information: above.nasa.gov

Atmospheric Radiation Measurement (ARM) Airborne Carbon Measurements (ACME)

Description: The Atmospheric Radiation Measurement (ARM) user facility is a multi-laboratory DOE scientific user facility with numerous national and international collaborators. ARM is a key contributor to national and international climate research efforts. Its data are currently collected from three atmospheric observatories representing the broad range of climate conditions around the world. ARM also operates three mobile facilities and additional aerial facilities and conducts specialized campaigns. Data are available from all past research campaigns and the former Tropical Western Pacific observatory.

Sponsoring agencies: DOE and NASA

Location: Southern Great Plains, North Slope of Alaska, and eastern North Atlantic, along with ARM mobile and aerial facilities. (Past research campaigns included a variety of locations.)

Timeline: 1989 to present

More information: www.arm.gov/about and www.archive.arm.gov/discovery/#v/home/s/

Atmospheric Carbon and Transport (ACT)–America

Description: ACT-America involves five 6-week airborne campaigns to quantify anomalies in atmospheric carbon. The campaign enabled and demonstrated a new generation of atmospheric inversion systems for quantifying CO₂ and CH₄ sources and sinks.

Sponsoring agencies: NASA (EVS-2) and NOAA

Observation type: Aircraft

Location: Eastern United States

Timeline: July 2016 to May 2018 (est.)

More information: act-america.larc.nasa.gov

Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) Experiment

Description: AirMOSS collected and used airborne radar to collect soil moisture data from nine climatic habitats in North America to estimate how much carbon the continent is taking in or releasing to the atmosphere.

Sponsoring agencies: NASA (EVS-1)

Observation type: Aircraft

Location: Continental United States and Alaska

Timeline: March 2012 to August 2016

More Information: airbornescience.jpl.nasa.gov/campaign/airmoss

Atmospheric Tomography Mission (ATom)

Description: ATom is a global-scale aircraft sampling of the atmosphere that studies the impact of air pollution on GHGs and chemically reactive gases in the atmosphere to improve the representation of these reactive gases and short-lived climate forcers in global models of atmospheric chemistry and climate. Profiles of these gases will also provide critical information for validation of satellite data, particularly in remote areas where *in situ* data are lacking. Flights occur in each of four seasons over a 4-year period.

Sponsoring agencies: NASA (EVS-2)

Observation type: Aircraft

Location: Global

Timeline: April 2015 to April 2019

More information: science.nasa.gov/missions/atom

Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE)

Description: CARVE was a 5-year mission to measure CO₂ and CH₄ fluxes from Alaska, using sensors aboard a NASA aircraft. These measurements were combined with continuous ground-based measurements to provide temporal and regional context as well as calibration for airborne measurements. Contributions of tower and aircraft observations were provided by NOAA as well as a CARVE tower near Fairbanks that took continuous measurements of CO₂ and CH₄. Flying over 4 years with varying weather patterns allowed better understanding of the sensitivity of CO₂ and CH₄ fluxes to temperature and precipitation.

Sponsoring agencies: NASA (EVS-1) and NOAA

Observation type: Aircraft and surface network

Location: Alaska

Timeline: November 2010 to November 2015

More information: science.nasa.gov/missions/carve

Global Greenhouse Gas Reference Network (GGGRN)

Description: NOAA GGGRN's *Cooperative Air Sampling Network* involves weekly flask sampling at 76 sites worldwide, including 23 in North America, and four ocean cruise tracks. Air samples are collected in glass flasks and shipped to a central laboratory for analysis of CO₂, CH₄, carbon monoxide (CO), molecular hydrogen (H₂), N₂O, sulfur hexafluoride (SF₆), and stable isotopes of CO₂ and CH₄, as well as of many volatile organic compounds such as ethane (C₂H₆), ethylene (C₂H₄), and propane (C₃H₈).

Sponsoring agency: NOAA

Observation type: Flask measurement network

Timeline: 1967 (at Niwot Ridge, Colorado) to present (sites continuously added)

More information: www.esrl.noaa.gov/gmd/ccgg/flask.php

Description: *NOAA Global Monitoring Division's Observatories* make continuous measurements of CO₂, CH₄, CO, isotopic compositions, and other carbon cycle–relevant quantities at Barrow, Alaska; Summit, Greenland; Mauna Loa, Hawai‘i; American Samoa; and the South Pole.

Sponsoring agency: NOAA

Observation type: Continuous measurements

More information: www.esrl.noaa.gov/gmd/obop

Description: *GGGRN's Aircraft program* conducts regular profiling at 15 sites with about a 14-day measurement frequency. Flasks are analyzed for CO₂, CO, N₂O, CH₄, H₂, and SF₆, as well as isotopes of CO₂ and CH₄ and multiple halo- and hydrocarbons.

Sponsoring agency: NOAA

Observation type: Aircraft

Timeline: 1992 to present

More information: www.esrl.noaa.gov/gmd/ccgg/aircraft

Description: *GGGRN's Tall Tower program* makes continuous measurements of CO₂, CH₄, and CO at seven towers of varying heights up to about 400 m above ground level.

Sponsoring agency: NOAA

Observation type: Tall tower

Timeline: 1990s to present

More information: www.esrl.noaa.gov/gmd/ccgg/towers

Megacities Carbon Project

Description: The Megacities Carbon Project aims to demonstrate a scientifically robust capability to measure multiyear emission trends of CO₂, CH₄, and CO attributed to individual megacities and selected major sectors. Studies over Los Angeles and Paris, as well as planning for a study over São Paulo, are underway.

Sponsoring agencies: NASA, National Institute of Standards and Technology, and Keck Institute for Space Studies

Observation type: Surface measurement network

Location: Los Angeles and Paris

Timeline: August 2015 (completion of current network installation) to present

More information: megacities.jpl.nasa.gov/portal

Moderate Resolution Imaging Spectroradiometer (MODIS)

Description: MODIS is a key instrument aboard the satellites Terra (originally known as EOS AM-1) and Aqua (originally known as EOS PM-1). Terra MODIS and Aqua MODIS are viewing the entire Earth's surface every 1 to 2 days, acquiring data to improve understanding of global dynamics and processes occurring on the land, in the ocean, and in the lower atmosphere, such as gross primary productivity, land cover, evapotranspiration, thermal anomalies, chlorophyll concentration, sea ice, and water inundation.

Observation type: Satellite

Location: Global

Timeline: Terra, 1999 to present; Aqua, 2002 to present

More information: modis.gsfc.nasa.gov/about

Orbiting Carbon Observatory 2 (OCO-2)

Description: OCO-2 measures CO₂ from space with the precision, resolution, and coverage needed to provide a global picture of human and natural sources and sinks. These measurements are being combined with data from ground stations, aircraft, and other satellites to help answer key questions about the global carbon cycle and how it interacts with climate change.

Sponsoring agency: NASA

Observation type: Satellite, aircraft, and surface network

Location: Global

Timeline: July 2014 to July 2016

More information: oco.jpl.nasa.gov

O₂/N₂ Ratio and CO₂ Airborne Southern Ocean (ORCAS)

Description: ORCAS is an airborne field campaign to advance understanding of the physical and biological controls on air-sea exchange of oxygen (O₂) and CO₂ in the Southern Ocean,

through intensive airborne surveys of atmospheric O₂, CO₂, related gases, and ocean surface properties over biogeochemical regions adjacent to the southern tip of South America and the Antarctic Peninsula.

Sponsoring agencies: NSF and NASA

Observation type: Aircraft

Location: Puntas Arenas, Chile

Timeline: January–February 2016

More information: www.eol.ucar.edu/field_projects/orcas

Soil Moisture Active Passive (SMAP)

Description: SMAP is a satellite mission whose goal is to provide a capability for global mapping of soil moisture and the freeze/thaw state with unprecedented accuracy, resolution, and coverage. Science objectives are to 1) understand processes that link the terrestrial water, energy, and carbon cycles; 2) estimate global water and energy fluxes at the land surface; 3) quantify net carbon flux in boreal landscapes; 4) enhance weather and climate forecast skill; and 5) develop improved flood prediction and drought-monitoring capabilities. On July 7, 2015, SMAP's radar stopped transmitting, marking the end of soil moisture radar operations; however, the passive SMAP soil moisture radiometer continues to return data.

Sponsoring agency: NASA

Observation type: Satellite

Location: Global

Timeline: January 2015 to May 2018

More information: smap.jpl.nasa.gov

SMAP Validation Experiment 2016 (SMAPVEX)

Description: The SMAPVEX-16 campaign flew an L-band radar and microwave radiometer over U.S. and Canadian agricultural areas to further evaluate SMAP satellite data products. Additional flights were associated with SMAPVEX 2015.

Sponsoring agencies: NASA, USDA, Agriculture Canada, and Canadian Space Agency

Observation Type: Aircraft

Location: Iowa and Manitoba

Timeline: June–August 2016

More information: smap.jpl.nasa.gov/science/validation/fieldcampaigns/SMAPVEX16 and smap.jpl.nasa.gov/science/validation/fieldcampaigns/SMAPVEX15

Shale Oil and Natural Gas NEXUS (SONGNEX)

Description: The SONGEX campaign aims to 1) quantify emissions of trace gases, fine particles, and CH₄ from several types of oil and shale gas basins in the western United States at different stages of development and 2) study the chemical transformation of these emissions.

Sponsoring agencies: NOAA, NASA, and NSF

Observation type: Aircraft

Location: North Dakota, Wyoming, Utah, Colorado, Texas, and New Mexico

Timeline: March–May 2015

More information: www.esrl.noaa.gov/csd/projects/songnex

Twin Otter Projects Defining Oil/gas Well emissions (TOPDOWN)

Description: TOPDOWN aims to understand the atmospheric impact of rapidly expanding oil and gas operations in the Bakken shale play in North Dakota through downwind cross-section flights of the active field, quantifying key atmospheric trace gases (e.g., CO₂, CO, CH₄, ethane (C₂H₆), and ozone) and black carbon using airborne *in situ* sensors and complementary airborne remote-sensing instrumentation. Subsequent flights examined the Denver-Julesburg basin in northeast Colorado and the San Juan basin in New Mexico.

Sponsoring agencies: NOAA, NASA, NSF, and DOE

Observation type: Aircraft

Location: North Dakota, Colorado, and New Mexico

Timeline: May–June 2014 and April 2015

More information: www.esrl.noaa.gov/csd/groups/csd7/measurements/2014topdown

Wintertime Investigation of Transport, Emissions, and Reactivity (WINTER)

Description: WINTER evaluates the atmospheric chemical transformations and transport associated with anthropogenic emissions during winter in the mid-Atlantic region of the United States, including the Marcellus Pennsylvania shale play. Measurements will be made in large urban and industrial plumes; coal-fired power plant emissions; and distributed emissions from oil and gas extraction, agricultural or biofuel burning, and vegetation.

Sponsoring agencies: NSF and NOAA

Observation type: Aircraft

Location: Northeastern United States

Timeline: February–March 2015

More information: www.atmos.washington.edu/~thornton/field-campaigns/wintertime-investigation-transport-emissions-and-reactivity

C.4 Additional Atmospheric Observations (Listed by Institution)²

Atmospheric Chemistry Research Group School of Chemistry, University of Bristol, United Kingdom

Continuous measurements of CO₂ at three sites in the United Kingdom (2012 to 2015).

Center for Atmospheric and Oceanic Studies, Tohoku University, Japan

Continuous measurements of CO₂ at Syowa Station, Antarctica (1984 to present).

Centre for Environmental and Climate Research, Lund University, Sweden

Continuous measurements of CO₂ at Hyltemossa and Norunda, Sweden (2015 to present).

Centre for Isotope Research, University of Groningen, Netherlands

Continuous measurements of CO₂ at Station Lutjewad, Netherlands (2006 to present).

² www.esrl.noaa.gov/gmd/ccgg/globalview/co2/co2_intro.html

Climate and Environmental Physics, Physics Institute, University of Bern, Switzerland

Continuous measurements of CO₂ at Beromünster, Switzerland (2012 to present), and Jungfrauoch, Switzerland (2004 to present).

Division of Geological and Planetary Science, California Institute of Technology, United States

Continuous measurements of CO₂ at Pasadena, California (2007 to 2013), and Palos Verdes Peninsula, California (2010 to 2013).

Earth Networks, United States

Continuous measurements of CO₂ at 28 U.S. sites out of a planned 50, with data planned to be commercially available.

Energy Research Centre of the Netherlands

Continuous measurements of CO₂ at Cesar, Cabauw, Netherlands (1992 to present).

Environment and Climate Change Canada

Continuous sampling of CO₂, CO, CH₄, and other species conducted at 22 tower sites across Canada (www.canada.ca/en/environment-climate-change.html; beginning 1988–2014 to present).

European Space Agency

SCanning Imaging Absorption spectroMeter for Atmospheric CHartography (SCIAMACHY), an imaging spectrometer, performing global measurements of trace gases in the troposphere and stratosphere (www.sciamachy.org; March 2002 to April 2012).

Finnish Meteorological Institute

Continuous measurements of CO₂ at Pallas-Sammaltunturi, Finland (2000 to present).

Harvard University, NOAA, and National Center for Atmospheric Research, United States

Continuous and flask sampling by the HIAPER Pole-to-Pole Observations (HIPPO) project on five campaign flights (2009 to 2011).

Harvard University, United States

CO₂ Budget and Regional Airborne Study (COBRA) aircraft measurements of regional to continental fluxes of CO and CO₂ over North America (2003 to 2004).

Hohenpeissenberg Meteorological Observatory, Germany

Continuous measurements of CO₂ at Gartow, Hohenpeissenberg, and Lindenberg, Germany (2015 to present).

Hungarian Meteorological Service

Continuous measurements of CO₂ at Hegyhatsal, Hungary (1994 to present).

Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona, Spain

Continuous measurements of CO₂ at seven sites in Spain (2013 to present) and flask measurements at one site in Spain (2008 to 2015).

Institut für Umweltphysik, University of Heidelberg, Germany

Continuous measurements of CO₂ at Heidelberg, Germany (1996 to 2015).

Instituto de Pesquisas Energéticas e Nucleares, Brazil

Flask measurements at Arembepe, Brazil (2006 to 2010), and Farol de Mãe Luiza Lighthouse, Brazil (2010 to 2015). Aircraft flask samples at four sites in Brazil (2010 to 2012).

Izana Atmospheric Research Center, Meteorological State Agency of Spain

Continuous measurements of CO₂ at Izana, Tenerife, Canary Islands (1984 to present).

Japan Meteorological Agency

Aircraft flask measurements (2011 to 2015) and surface continuous measurements of CO₂ at three stations in Japan (1987 to present).

Laboratoire des Sciences du Climat et de l'Environnement, France

Continuous measurements of CO₂ at Amsterdam Island (2012 to present); Mace Head, Ireland (2010 to present); and Puy-de-Dôme, France (2011 to present).

Langley Research Center, NASA, United States

Continuous measurements of CO₂ via Atmospheric Vertical Observations of CO₂ in the Earth's Troposphere (AVOCET) from various campaigns, including TRACE-P, SEAC4RS, INTEX-B, INTEX-NA, DISCOVER-AQ, DC3, and ARCTAS (2001 to present).

National Center for Atmospheric Research, United States

Quasi-continuous measurements of CO₂ at five mountaintop locations in the United States: Hidden Peak, Utah; Niwot Ridge, Colorado; Roof Butte, Arizona; Fraser Experimental Forest, Colorado; and Storm Peak Laboratory, Steamboat Springs, Colorado (beginning 2005–2007 to present).

National Institute for Environmental Studies, Japan

Flask and *in situ* continuous measurements of CO₂ aboard commercial aircraft as part of the Comprehensive Observation Network for Trace gases by an Airliner (CONTRAIL) project (1993 to present).

National Institute for Environmental Studies, Japan

Observations of infrared light reflected and emitted from the Earth's surface and the atmosphere by Japan's Greenhouse gases Observing SATellite (GOSAT). Column abundances of CO₂ and CH₄ are calculated from the observational data. GOSAT flies at an altitude of approximately 666 km and completes one revolution in about 100 minutes. The satellite returns to the same point in space in three days. Its onboard observation instrument is the Thermal And Near-infrared Sensor for carbon Observation (TANSO), which consists of two sub-units: the Fourier Transform Spectrometer (FTS) and the Cloud and Aerosol Imager (CAI).

National Institute of Water and Atmospheric Research, New Zealand

Continuous measurements of CO₂ at Baring Head Station, New Zealand (1972 to present).

National Science Foundation, United States

Stratosphere-Troposphere Analyses of Regional Transport (START08) aircraft measurement campaign departing from Colorado (April–June 2008). Co-sponsors include the National Center for Atmospheric Research, University of Colorado, Harvard University, University of Miami, Princeton University, NOAA Earth System Research Laboratory, Texas A&M University, and The Pennsylvania State University.

NOAA Chemical Sciences Division, United States

Campaign-mode continuous measurements of CO₂ by a number of projects including the Aerosol, Radiation, and Cloud Processes affecting Arctic Climate (ARCPAC, 2008), California Nexus (CalNex, 2010), Southeast Nexus (SENex, 2013), Shale Oil and Natural Gas Nexus (SONGNex, 2015), and the Texas Air Quality Study (TexAQS, 2006).

Norwegian Institute for Air Research

Continuous measurements of CO₂ at Birkenes Observatory, Norway (2015 to present); Ny-Ålesund and Svalbard, Norway; and Sweden (2015 to present).

Oceans & Atmosphere Flagship – GASLAB, Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia

Flask sampling for multiple trace gas species at 15 sites worldwide, including three in North America: Alert, Canada; Mauna Loa, Hawai'i; and Estevan Point, British Columbia (early 1990s to present).

Oregon State University, United States

Continuous measurements of CO₂ at seven sites in Oregon (most beginning in 2007 to present).

The Pennsylvania State University and NOAA Global Monitoring Division, United States

Continuous monitoring of CO₂, CH₄, and CO by the Indianapolis Flux Experiment (INFLUX) at seven tower sites around Indianapolis, Indiana (2011 to 2012).

The Pennsylvania State University, United States

Measurements of CO₂, CH₄, and CO at 18 various U.S. tower and surface sites conducted intermittently for periods of up to 3 years (2007 to present).

Ricerca sul Sistema Energetico, Italy

Continuous measurements of CO₂ at Plateau Rosa Station, Italy (2008 to present).

Schauinsland Station, Umweltbundesamt (UBA, German Environment Agency)

Continuous measurements of CO₂ at Schauinsland, Baden-Wuerttemberg, Germany (2014 to present).

Scripps Institution of Oceanography (SIO), United States

Flask sampling by SIO at 16 locations worldwide including seven in North America: Alert, Nunavut, Canada; Baja California Sur, Mexico; Barrow, Alaska; Cold Bay, Alaska; Cape Kumukahi, Hawai‘i; La Jolla, California; and Mauna Loa, Hawai‘i (beginning 1957–1996, most continuing to present).

South African Weather Service

Continuous measurements of CO₂ at Cape Point, South Africa (1993 to present).

Swiss Federal Laboratories for Materials Science and Technology

Continuous measurements of CO₂ at Jungfraujoch, Switzerland (2009 to present).

University of East Anglia, United Kingdom

Continuous measurements of CO₂ at Weybourne, United Kingdom (2007 to present).

University of Helsinki, Finland

Continuous measurements of CO₂ at Hyytiala, Finland (2012 to present).

University of Minnesota, United States

Continuous measurements of CO₂ at Rosemount Research and Outreach Center, Minnesota (2007 to present).

University of Science and Technology, Poland

Continuous measurements of CO₂ at Kasprowy Wierch, High Tatra, Poland (1996 to present).

Utah Atmospheric Trace Gas & Air Quality Lab, University of Utah, United States

Continuous measurements of CO₂ at six sites in Utah (available from 2001 to present).