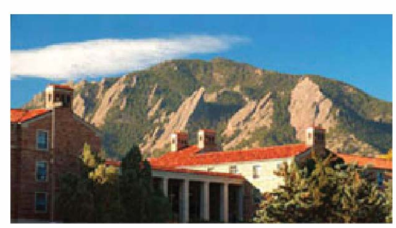
NOAA Earth System Research Laboratory
Chemical Sciences Division
Boulder, Colorado

Strategic Research Plan
2015—2020

developed April, 2015

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

CIRES



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Strategic Research Plan 2015—2020

This document presents the Strategic Research Plan for the NOAA Chemical Sciences Division for the period 2015 – 2020. The document was developed and edited by Christine A. Ennis with input from the scientific staff of CSD.

April, 2015

NOAA Vision and Mission Statements

National Oceanic and Atmospheric Administration

Vision
Healthy ecosystems, communities, and economies
that are resilient in the face of change

Mission
To understand and predict changes in the Earth's environment,
from the depths of the ocean to the surface of the sun,
and to conserve and manage our coastal and marine resources

Office of Oceanic and Atmospheric Research (OAR)

Vision
Be a trusted world leader in observing, modeling, understanding
and predicting the Earth system

Mission
To conduct research to understand and predict the Earth system;
develop technology to improve NOAA science, service, and stewardship;
and translate the results so they are useful to society

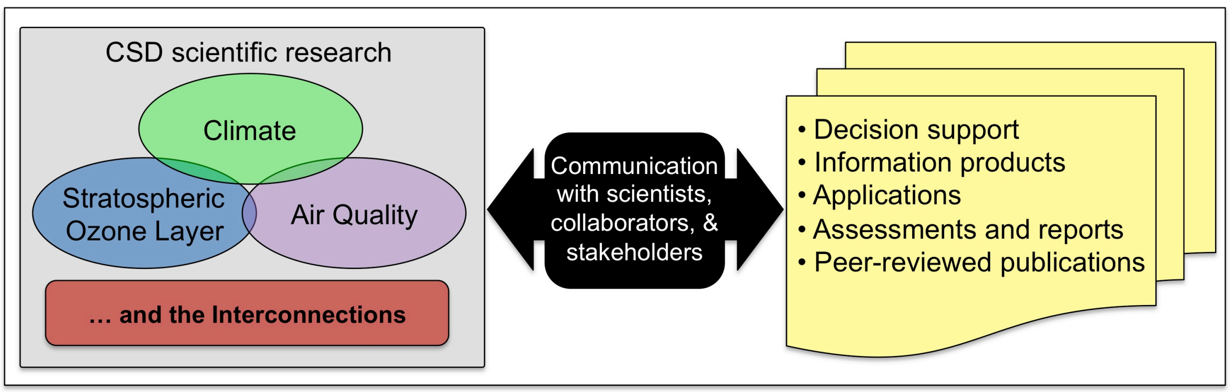
Earth System Research Laboratory (ESRL)
Chemical Sciences Division (CSD)

Vision
A nation that has the needed scientific understanding and information about
our atmosphere (environmental intelligence) to make optimal decisions in
the interests of the well being of current and future generations

Mission
To advance scientific understanding of three major environmental and societal
issues of our time: climate change, air quality, and stratospheric ozone
depletion through atmospheric research on the chemical and related physical
processes that affect Earth's atmospheric composition

ESRL Chemical Sciences Division Research Perspective

The vision statement of the ESRL Chemical Sciences Division (CSD) is “A nation that has the needed scientific understanding and information about our atmosphere (environmental intelligence) to make optimal decisions in the interests of the health and safety of current and future generations.” NOAA has a deep commitment to healthy ecosystems, communities, and economies that are resilient in the face of change, reflecting its role as the Nation’s steward of the atmosphere and oceans. We in turn interpret our atmospheric mission to be one of advancing scientific understanding of three major environmental and societal issues of our time: climate change, air quality, and stratospheric ozone. The advancements are accomplished through fundamental and applied research involving emissions and the chemical and related physical processes that affect Earth’s atmospheric composition. An important measure of success for CSD research is the ability to communicate our scientific results to stakeholders and policymakers who will use the information to underpin decisions and solutions for the challenges posed by present and projected changes in climate, air quality, and stratospheric ozone.



CSD’s approach to climate change, air quality, and stratospheric ozone research has distinct competencies:

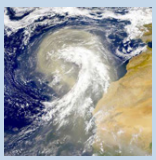
- Identifying new research directions and gaps in current understanding;
- Developing new instrumentation, sampling methods, and modeling techniques;
- Conducting laboratory studies of fundamental physical and chemical processes;
- Observing the composition and physical state of the atmosphere from a variety of platforms;
- Formulating and using models and diagnostic and interpretive methods to advance the understanding of atmospheric processes; and
- Communicating our results to other scientists and stakeholders through decision support, information products, applications, assessments and reports, and publications in the peer-reviewed literature.

In all of these competencies, we actively engage stakeholders and collaborators to help define the research objectives or communication approaches in order to enhance the effectiveness and efficiency of all our activities. Our stakeholders are most often industry, policymakers, and other governmental and non-governmental agencies and officials with national and international affiliations. Our scientific collaborators come from other agencies, universities, industry, and the private sector and have national and international affiliations.

CSD scientific research and communication competencies are supported by a current staff of approximately 127, comprised of scientists, engineers, technicians, students, information technologists, and administrative professionals. The staff includes both Federal and non-Federal employees; the latter are associated primarily with the Cooperative Institute for Research in Environmental Studies (CIRES).

The Chemical Sciences Division consists of seven Program Areas and a Directorate. Although the groups each have a research specialty or focus area related to climate, air quality, or the stratosphere and stratospheric ozone, the group activities cut across these topics depending on the needs and interests of each group and ongoing research activities. For example, our field intensive activities involving NOAA aircraft platforms routinely draw expertise and staff from more than one group.

Program Areas in the Chemical Sciences Division



Cloud and Aerosol Processes

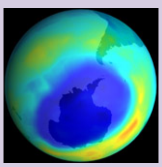
Measuring and understanding how atmospheric particles affect clouds, climate, and air quality

Program Leader: Dan Murphy

Tropospheric Chemistry

Developing and deploying state-of-the-art instruments to understand how processes in the lower atmosphere affect air quality and climate today – and in the future

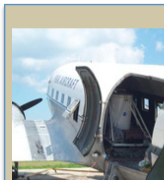
Program Leader: Tom Ryerson



Chemistry & Climate Processes

Understanding atmospheric chemistry and climate processes with integrated analysis and modeling

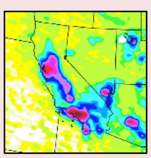
Program Leader: Karen Rosenlof



Atmospheric Remote Sensing

Developing and using laser-based instruments for deployment on land, ship, and aircraft to understand atmospheric processes that affect air quality, weather, and climate

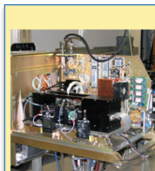
Program Leader: Alan Brewer



Regional Chemical Modeling

Using models and observations to understand atmospheric pollutant transport, processing, and effects on air quality and climate

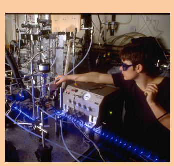
Program Leader: Michael Trainer



Atmospheric Composition and Chemical Processes

Conducting airborne field measurements critical to understanding climate, air quality, and ozone depletion

Program Leader: Ru-Shan Gao



Chemical Processes and Instrument Development

Developing instrumentation to improve our ability to study key atmospheric species in the laboratory and field

Program Leader: Jim Burkholder

The remainder of this document presents CSD's strategic research plan for the next five years, covering the period 2015-2020. These research plans are organized into four principal topics: climate, air quality, the stratospheric ozone layer, and interconnections between topics. This is followed by future prospects for Research to Applications and a description of the primary research partnerships and collaborations in which CSD is engaged.

I. Climate

CSD's climate research targets scientific areas that are most needed for understanding and predictions in climate science, and/or are a focus for potential policy formulation. This research integrates laboratory, field, and modeling work to understand atmospheric processes related to chemistry, dynamics, and radiation.

Research Topics and CSD Activities

Non-CO_2 greenhouse gases including short-lived climate pollutants

- *Methane, nitrous oxide* – quantifying their sources (both natural and anthropogenic, such as agriculture (CH_4, N_2O) and fugitive emissions from energy development activities (CH_4); understanding atmospheric processes that affect their abundances and lifetimes in the atmosphere and hence their climate influence; understanding climate feedbacks
- *Tropospheric ozone* – understanding the processes that shape the global tropospheric distribution of ozone, including quantifying emissions of ozone precursors and understanding the roles of intercontinental transport and transformation, and stratospheric intrusions
- *Hydrofluorocarbons and other climate-relevant gases* – assessing their climate impacts (radiative forcing, global warming potentials) and other environmental effects through laboratory and modeling work

Atmospheric fine particles (aerosols, including black carbon)

- *Aerosol formation and chemical composition* – studying the chemistry related to the formation of atmospheric aerosols and determining their chemical composition, including the organic content of aerosols
- *Direct radiative effects of aerosols* – understanding the effects of stratospheric and tropospheric aerosols on climate (heating and cooling); elucidating how the properties (e.g., particle number and size) and location of aerosols affect the radiative balance
- *Indirect effects of aerosols* – understanding how aerosols affect cloud formation, extent, and optical properties, as well as precipitation and snow albedo; studying how aerosols alter atmospheric chemical composition
- *Stratospheric aerosol layer* – understanding trends and variability in the stratospheric aerosol layer and the relative roles of natural and anthropogenic precursor emissions; understanding how changes in the aerosol layer affect stratospheric climate (temperature and transport)
- *Development of instrumentation* – developing and applying new measurement techniques to evaluate sources, amounts, and evolution of particles and to determine the chemical composition and radiative and other climate-related properties of aerosol particles

Climate system understanding

- *Global energy budget* – using new approaches to advance understanding and reduce uncertainties in the global energy budget, especially with respect to aerosols and aerosol-cloud interactions
- *Water vapor* – understanding the role of upper tropospheric and stratospheric (UT/S) water vapor in the climate system; understanding processes controlling the stratospheric entry value of water; understanding changes in the water vapor distribution and their implications for climate; developing instruments to increase the accuracy of atmospheric measurements of water vapor; developing data sets to allow trends and variability analysis; modeling trends and feedbacks of upper tropospheric and stratospheric water vapor
- *Analysis of climate model results* – using models to study aspects of future climate change, and to detect climate change in the observational record

I. CLIMATE RESEARCH

Climate-relevant dynamical and radiative processes in the atmosphere

- *Dynamics* – investigating drivers, variability, trends, and impacts of the atmospheric circulation in the stratosphere; studying changes in the stratospheric mean meridional circulation, transport between stratosphere and troposphere, and midlatitude//tropical mixing; understanding stratosphere-troposphere dynamical coupling; developing a climatology of stratospheric warmings
- *Dynamical effects on temperature, water vapor* – understanding the influence of the QBO, ENSO, and sudden stratospheric warmings on tropical temperatures and water vapor transport into the stratosphere
- *Boundary-layer meteorology* – characterizing emissions, dispersion effects, and ozone transport in the lower atmosphere; improving the representation of near-surface dynamics in models

Scientific Motivation

- Aerosols and non-CO_2 greenhouse gases (such as ozone and methane) contribute directly to climate forcing, are key to many climate feedbacks, and link climate change and air quality (science and policy); however understanding is incomplete.
- Water vapor in the UT/LS plays important roles in cirrus cloud formation and chemical processes, and it represents a major term in Earth's radiative balance. A better understanding and quantification of the processes controlling water vapor and its distribution in the UT/LS is needed to properly account for past changes in the Earth's climate and reliably project future changes.
- Direct and indirect forcings by aerosols represent the largest uncertainty in the forcing of the climate system. These forcings link climate change with air quality in both science and policy.
- A process-level understanding of the aerosol-cloud-chemistry system is needed to support climate prediction.
- Modelng studies of dynamical and radiative aspects of the climate are required for projecting future climate.

Contributions to the NOAA Strategic Plan Goals, Enterprise Capabilities, and Objectives

NOAA Goals and Enterprise-Wide Capabilities	NOAA Objectives
Climate Adaptation & Mitigation	Improved scientific understanding of the changing climate system and its impacts
	Mitigation and adaptation choices supported by sustained, timely, and reliable climate services
	Assessments of current and future states of the climate system that identify potential impacts and inform science, service, and stewardship decisions
Science & Technology Enterprise	A holistic understanding of the Earth System through research

Societal Benefits

- **Information for decisions regarding mitigation:** Some non-CO_2 greenhouse gases and black carbon are subjects of current policy discussions. CSD's science helps decision makers identify the most effective choices and approaches, including options for which the atmosphere would have a faster response than CO_2 mitigation, as well as any options that are easily obtainable.
- **Information for decisions regarding adaptation:** CSD's research contributes to improving climate models, which help our society anticipate, plan for, and adapt to future climate change.

Key Future Activities

The ability to make climate projections requires a fundamental understanding of earth/ocean/atmosphere processes. This includes making and interpreting laboratory and field measurements as well analysis of satellite constituent data. It also includes modeling on a variety of scales and complexities, ranging from simple mechanistic models to detailed process models as well as complex earth system models. CSD's expertise in diagnosing atmospheric chemical, radiative, and dynamical processes and communicating science to interested decision makers and stakeholders will keep the Division in a position to respond strongly to the growing climate challenge.

Our primary climate research goal is to obtain a basic understanding of key processes in the Earth's climate system in order to improve, both qualitatively and quantitatively, simulations of climate and climate change. A second important goal is to provide to national and international policymakers the best possible information for guiding policy decisions in the presence of increasing greenhouse gases.

Research areas CSD will address in the next 5 years include laboratory studies to determine climate properties of replacement compounds for species regulated by the Montreal Protocol; instrument development and deployment to improve our understanding of aerosol processes in the troposphere and stratosphere; refining upper tropospheric and stratospheric water measurements, as well as expanding our understanding of forcing and feedbacks related to stratospheric water vapor; making measurements of climate-relevant species in focused field studies to study energy sector and wildfire impacts; characterizing emissions for climate-relevant species using both top-down and bottom-up techniques; and theoretical and data analysis studies of chemical, dynamical, and radiative processes, including examination of the energy budget, climate feedbacks, and cloud processes.

Examples of specific studies planned are listed below:

Laboratory Studies

- Study the climate-relevant properties of short-lived greenhouse gases and of new substances proposed as replacements for ozone-depleting substances or other uses, especially short-lived hydrofluorocarbons.

Greenhouse gas and aerosol studies & instrumentation:

- Participate in the NASA Atmospheric Tomography Mission (ATom), using research aircraft flights around the world to better understand chemical and aerosol-related processes in the atmosphere, with a focus on methane, ozone and black carbon (2015-2019). (D. Fahey and T. Ryerson are Co-Investigators; several CSD instrument teams will participate)
- Extend prior work to develop a rigorous and quantitative comparison between observations and chemistry-climate model calculations of tropospheric ozone concentrations, from the surface to the tropopause (see also Air Quality activities).
- Extend research on the climate implications of black carbon in the cryosphere, and black carbon wet removal.
- Advance instrumentation to characterize black carbon: photoacoustic spectrometry; laser-induced incandescence.
- Deploy the new CSD-developed optical particle counter (Printed Optical Particle Spectrometer, POPS) and radiometer (Upward Looking Radiometer, ULR) instruments on Unmanned Aircraft Systems (UAS) in studies of aerosol radiative forcing (e.g., on UAS platforms such as Manta, Pilatus, R^2Drone; and on balloons). Expand use of these instruments on a balloon-based glider system with the intent of establishing a global network (Global Ozone and Aerosol profiles and Aerosol Hygroscopic Effect and Absorption Optical Depth (GOA^2HEAD))
- Complete development of new aerosol instrumentation: a simplified photoacoustic instrument for field measurements of aerosol single scattering albedo; an open-path cavity ringdown instrument to study enhanced aerosol light scattering at ambient relative humidity; and a broadband cavity-enhanced spectrometer to measure UV aerosol extinction.

- Explore the possibility of using lidars to study bioaerosol production near the ocean surface, and continue development of other new bioaerosol measurement techniques to assess their abundance, types, and potential role in the climate system (see also Interconnections plans).
- Develop a new sulfur dioxide (SO_2) instrument to explore the sulfur budget of the UT/LS on high-altitude aircraft platforms.

Water vapor

- Advance instrumentation, measurements, and analyses of water vapor to understand the potential climate feedback from UT/LS water vapor and cirrus clouds, and to evaluate satellite observations and model performance and parameterizations.
- Complete work in leading an international scientific assessment of UT/LS water vapor.

Energy sector and wildfire impacts

- Lead and participate in the Fire Influence on Regional and Global Environments Experiment (FIREX) designed to study biomass burning (wildfires) (2015-2019).
- Continue sampling of oil and gas development activities, agricultural activities, and the shift of the energy economy to biofuels and natural gas (2015-2019).
- Conduct the Wind Forecast Improvement Project (WFIP, 2015-16) to characterize how complex terrain influences wind energy forecasts.

Emissions

- Continue to advance and improve emissions inventories for climate-relevant gases and aerosol precursors using atmospheric observations and models (top-down approach).
- Characterize the emissions, formation, and atmospheric concentrations of climate-relevant gases, aerosol precursors, and aerosols from oil and gas development activities, agricultural sources, wildland fires, and urban sources, as well as bioaerosol and dust.

Theoretical and data analysis studies

Global scale

- Conduct dynamical analyses to examine processes forcing changes in circulation that affect species transport, and to explore the degree to which observations support model calculations, with implications for future climate model projections.
- Conduct radiative forcing and climate feedback analyses using output from the Climate Change Model Intercomparison project, in order to better constrain the Earth's energy budget and future climate changes.
- Assess tropical widening using reanalyses, constituent data; test widening response in climate models due to different stratospheric ozone scenarios as well as climate intervention scenarios.
- Construct a new database of sudden stratospheric warnings (SSWs) for use in model verification and data analysis.

Cloud scale

- Extend research on aerosol-cloud interactions to show how the meteorological environment around convective storm systems strongly modulates aerosol indirect effects.
- Continue to develop a process-level understanding of the aerosol-cloud-chemistry system in support of improved climate prediction, with an increasing focus on mixed-phase clouds and precipitation.
- Use ship-based profiles of atmospheric turbulence to evaluate model performance and develop improved techniques (using mass flux analysis) for estimating the upward transport of moist air into the upper troposphere.
- Use ship-based measurements of the surface wind field to study precipitation-driven outflows and their role in convection initiation.

Multi-scale

- Continue analysis of data from past airborne missions (Global Hawk Pacific Mission [GloPac], HIAPER Pole to Pole Observations [HIPPO], Midlatitude Airborne Cirrus Properties Experiment [MACPEX], Dynamics of the Madden-Julian Oscillation [DYNAMO], VOCALS Ocean-Cloud-Atmosphere-Land Study [VOCALS], Studies of Emissions, Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys [$SEAC^4RS$], and Airborne Tropical Tropopause Experiment [ATTREX]).
- Continue analysis of ship-based Doppler lidar measurements made during the VOCALS and DYNAMO (Dynamics of the Madden-Julian Oscillation) missions.

II. Air Quality

CSD conducts research to advance understanding of the sources and processes that control air quality (AQ) at local, regional, and global scales. CSD research is focused on ozone and aerosols (particulate matter, PM) and is conducted via a combination of focused regional field studies, laboratory studies, modeling studies, and theoretical analyses.

Research Topics and CSD Activities

Ozone and other trace gases that affect air quality

- *Precursor emissions* – quantifying the natural and anthropogenic sources of ozone precursors, such as transportation, power generation, energy exploration and development, agricultural activities, soils and vegetation, and wildland fires; evaluating and improving emissions inventories of ozone precursors
- *Processes involved in formation and removal of surface ozone* – identifying regional factors that influence the photochemistry of surface ozone; elucidating the nighttime processes that affect ozone and air quality; quantifying the kinetics and pathways of reactions that affect ozone formation and removal
- *Other trace gas pollutants* – identifying and understanding processes that form other pollutants that affect air quality, such as isocyanic acid (HNCO), nitryl chloride ($ClNO_2$), and nitrous acid (HONO)

Aerosols and air quality

- *Emissions of aerosols and aerosol precursors* – understanding emissions of aerosols and their trends, especially black carbon; quantifying the natural and anthropogenic sources of aerosols and aerosol precursors, such as transportation, power generation, energy exploration and development, agricultural activities, soils and vegetation, and wildland fires; improving inventories of aerosol precursor emissions
- *Processes involved in aerosol formation and growth* – understanding the formation of secondary organic aerosols and sulfate aerosols; investigating black carbon and its role in air quality; studying the kinetics and pathways of reactions that affect aerosol formation, growth, and removal

Transport and mixing of air pollutants

- *Long-range transport of pollutants* – understanding the increasingly important role of intercontinental transport processes in air quality, especially with regard to ozone, aerosols, and their precursors
- *Other dynamical processes* – elucidating regional transport processes; advancing the understanding of the role of boundary-layer processes in air quality, including transport over complex and coastal terrain

Development and advancement of instruments, methods, and AQ forecast models

- *New measurement capabilities* – designing and building state-of-the-art instruments and developing new measurement approaches to resolve knowledge gaps and advance understanding, such as instruments to measure glyoxal (CHOCHO) and organic acids
- *Advancement of AQ forecasting and U.S. emissions inventories* – applying CSD measurements and analyses to improve regional and global-scale air quality forecast models, and giving independent top-down estimates of emissions for comparison to bottom-up inventories

Scientific Motivation

- Ozone and particulate matter (PM) remain the two priority pollutants for which many areas in the U.S. are out of regulatory compliance.
- Emissions inventories have large uncertainties that limit the ability to predict air quality (ozone and PM).
- The formation of ozone, aerosols, and other air pollutants is often strongly influenced by regional factors.
- Changes in emissions, as well as distant sources, are increasingly affecting air quality at local and regional scales.

II. AIR QUALITY RESEARCH

Contributions to the NOAA Strategic Plan Goals, Enterprise Capabilities, and Objectives

NOAA Goals and Enterprise-Wide Capabilities	NOAA Objectives
Weather-Ready Nation	Healthy people and communities due to improved air and water quality services A more productive and efficient economy through environmental information relevant to key sectors of the U.S. economy
Science & Technology Enterprise	A holistic understanding of the Earth System through research

Societal Benefits

- **Scientific information to underpin societal decisions regarding air quality improvement.** CSD's research has given local, state, and national air quality managers sound scientific information for their regulatory decisions, thereby leading to more effective policies and avoiding unnecessary expenditures on policies that would have been inefficient or counterproductive. The information has revealed the regional differences in air quality processes, showing that "one size does not fit all" when designing air quality improvement strategies.
- **Information regarding the non-local and non-regional factors that influence air quality.** CSD's research has advanced the understanding of the large-scale issues (such as stratospheric intrusions and long-range transport) that affect air quality, which is typically subject to controls on a more local scale. CSD's research has provided important results that will be used by the Environmental Protection Agency (EPA) for developing regulations, as well as by municipalities and states to respond to the proposed new National Ambient Air Quality Standards for ozone.

Key Future Activities

Rising levels of ozone and other pollutants in some regions of the lower atmosphere increase pressure on policymakers to devise strategies that will preserve air quality and protect the health of the public. In a world of narrowing air quality margins and rising emissions, the need for thorough understanding of atmospheric processes is increasing. CSD's track record of uncovering previously unevaluated processes that affect air quality—from emissions to nighttime chemistry to stratospheric intrusions—puts the Division in a strong position to help the world's air quality decision makers chart a course to address future air quality challenges.

Our primary air quality research goal is to further our understanding of sources and processes that control ozone and particulate matter loading at local, regional, and global scales. This is achieved through focused measurement campaigns, laboratory work, data analyses, and modeling studies. Results provide information to guide air quality regulation decisions for national, state, and local agencies.

Research related to air quality that CSD will address in the next 5 years includes instrument and model development; focused field campaign leadership and participation; emissions studies to improve inventories and better understand processes; satellite/in situ/model comparisons to ultimately improve satellite retrievals; and studies designed to increase our understanding of ozone and aerosol drivers, trends, variability, and control strategies.

Examples of specific studies planned are listed below.

II. AIR QUALITY RESEARCH

Instrument, model, and measurement system development

- Understand and model the formation of organic aerosol in the gas phase, as well as from liquid cloud processes, for which observations suggest a missing source of oxygenated organic aerosol.
- Develop a micropulse Doppler lidar designed specifically to operate from small mobile platforms (small aircraft or off-road vehicles), and use it to study the dynamics associated with wildland fires, such as the inflow driving the fire and the vertical mixing processes that loft the smoke plume.
- Work with interagency partners to develop an operational quick-response airborne system to quantify future offshore oil spill flow rates.

Campaign participation

- Participate in intensive focused field missions:
  - Lead and participate in the 2015 Shale Oil and Natural Gas Nexus (SONGNEX) field campaign to investigate emissions and transformations of trace gases and fine particles from several oil and shale gas basins in the western U.S.
  - Study ozone and aerosols precursors arising from agricultural activities using a mobile observing platform.
  - Conduct the Fire Influence on Regional and Global Environments Experiment (FIREX) airborne study in the western U.S. to investigate biomass burning.
  - Investigate air quality on other continents, particularly East Asia, where inter-regional pollution episodes are on the rise: Expand engagement in China, and propose measurement and analysis activities to KORUS-AQ, a NASA International Cooperative Air Quality Field Study in Korea in 2016.
  - Lead and participate in the NASA Atmospheric Tomography Mission (ATom), using research aircraft flights around the world to better understand chemical and aerosol-related processes in the atmosphere, with a focus on methane, ozone, and black carbon (2015-2019).

Emissions

- Continue evaluation of emissions inventories, including those related to agriculture and oil and gas development.
- Quantify long-term changes in U.S. emissions and their impact on tropospheric ozone through model comparisons with satellite observations, measurements from field campaigns, and monitoring data.
- Continue leading national and global efforts to improve access to emissions information, convey useful science to inventory developers, and nurture community emissions activities.

Satellite

- Analyze satellite air quality data to understand seasonal cycles of ozone and its precursors, to reconcile differences between models and observations, and to better constrain surface emissions.
- Investigate the potential synergies of a surface ozone profiling network and future satellite sensors for assessing regional and local air quality.
- Constrain emissions and chemistry impacting air quality using global measurements from existing and future polar-orbiting satellites and upcoming geostationary satellite observations focused on the U.S., Europe, and East Asia.
- Quantify the national methane budget by combining existing and future satellite data with field observations and atmospheric modeling.

Ozone and aerosols

- Lead the first global scientific assessment of tropospheric ozone, the Tropospheric Ozone Assessment Report (TOAR) under the International Global Atmospheric Chemistry Project.
- Characterize the effects of oil and gas development activities on air quality in populated areas as well as remote regions.
- Partner with EPA and NASA to develop monitoring and modeling for accurately quantifying the impact of baseline ozone on the western USA and the implications for meeting proposed tightened federal air quality standards.
- Characterize biomass burning influences on air quality in populated regions.
- Characterize aerosol formation and growth in wintertime.

III. Stratospheric Ozone Layer

CSD's research on the stratospheric ozone layer advances the scientific understanding of the processes that govern composition of the stratosphere, with a focus on stratospheric ozone depletion and recovery. CSD's contributions involve laboratory measurements, atmospheric observations, modeling, and theoretical analysis. CSD also participates in and co-leads the quadrennial assessments of ozone depletion that provide decision-support information for the Montreal Protocol.

Research Topics and CSD Activities

Chemical and related radiative and dynamical processes that affect the stratospheric ozone layer

- *Recovery of the ozone layer* – investigating anthropogenic and natural processes that affect stratospheric ozone; studying ozone variability and trends; developing approaches for detecting ozone-layer recovery; making high-altitude aircraft ozone measurements
- *Emissions that affect the ozone layer* – advancing understanding of the role of nitrous oxide (N_2O) emissions in stratospheric ozone depletion; studying the implications of the phase-out of hydrochlorofluorocarbons (HCFCs) and other ozone-depleting substances; projecting the growth in emissions of hydrofluorocarbon (HFC) substitute gases
- *Dynamical and radiative processes that affect stratospheric ozone* – analyzing trends and variability in stratospheric transport, mixing, and temperature
- *Laboratory kinetics studies* – determining the kinetics and products of chemical reactions and photolytic processes important in the stratosphere
- *Stratospheric ozone climatology* – developing improved ozone climatologies, one based on multiple satellites and one based primarily on sondes, for use in model calculations of ozone-climate interactions and analysis of stratospheric ozone trends and variability

Atmospheric lifetimes of ozone-depleting substances (ODSs) and current or proposed substitute gases

- *Ozone-depleting substances* – refining the understanding and quantification of atmospheric lifetimes and ozone depletion potentials (ODPs) of ODSs and substitute chemicals through laboratory and model studies; developing approaches for evaluating very short-lived substances (VSLS) in the ODP framework

Science, leadership, and service for the Montreal Protocol quadrennial ozone assessments

- *Science* – serving as lead authors, contributing authors, and reviewers of the ozone assessments
- *Leadership* – leading and coordinating the writing and reviewing of the ozone assessments in collaboration with the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO)
- *Service* – Editing, printing, and distribution of the documents associated with the ozone assessment

Scientific Motivation

- Scientific uncertainties persist regarding ozone-layer recovery in a changing climate. The issue of ozone-layer recovery is important for human and ecosystem health, and is a prime topic for international and national decision makers.
- Industry is proposing new substances to replace those that are harmful to the ozone layer, but the new compounds are often "unknowns" with respect to their environmental effects.

III. STRATOSPHERIC OZONE LAYER

Contributions to the NOAA Strategic Plan Goals, Enterprise Capabilities, and Objectives

NOAA Goals and Enterprise-Wide Capabilities	NOAA Objectives
Climate Adaptation & Mitigation	Improved scientific understanding of the changing climate system and its impacts Mitigation and adaptation choices supported by sustained, timely, and reliable climate services Assessments of current and future states of the climate system that identify potential impacts and inform science, service, and stewardship decisions
Science & Technology Enterprise	A holistic understanding of the Earth System through research

Societal Benefits

- **Sound scientific information for decisions during the critical "accountability" phase of ozone-layer protection:** CSD research has provided reliable information to the U.S. State Department for their international negotiations, EPA for its regulatory decisions, and U.S. industries for their evaluations and decisions related to the use of ozone-depleting substances and their replacements.
- **Cost savings for industry and the consumer; protection for climate and the ozone layer:** CSD's laboratory and modeling studies have evaluated proposed new substances for their potential effects on climate change and ozone depletion *before* production by industry, thereby avoiding costly "false starts" while protecting the ozone layer and climate.

Key Future Activities

Ozone-depleting substances will continue to gradually decline in the atmosphere. The response of the ozone layer will be one of recovery from ODSs — but complicated by emissions of greenhouse gases that create an atmosphere for ozone recovery that is different from that during the era of ozone depletion. CSD ozone research will continue assessing properties of ODS replacements that affect the stratospheric ozone layer, as well as study how GHG-related changes in stratospheric circulation and temperature affect stratospheric ozone, and examine the impact that projected changes in stratospheric ozone will have on climate as a whole.

Our main stratospheric ozone research goal is to understand the interactions between climate change and ozone layer evolution through improving our understanding of processes responsible for ozone depletion. This goal is driven by our mission to provide national and international policymakers the best possible information for guiding ozone-related policy decisions.

Research related to stratospheric ozone that CSD will address in the next 5 years includes conducting laboratory studies to assess the ozone depletion potentials (ODPs) of replacement compounds for species regulated by the Montreal Protocol; studying the interaction between GHG-induced stratospheric dynamical changes and ozone distributions using models and global measurements; and assessing the dynamical, chemical, and radiative impacts of decreasing amounts of ozone-depleting gases coupled with increasing GHGs.

Examples of specific studies planned are listed below.

Laboratory studies

- Evaluate the atmospheric impacts of the next generation of compounds proposed as replacements for ozone-depleting substances, such as fluoro-amines and new hydrofluoro-olefins, as well as other very short-lived substances.

Dynamical studies

- Analyze observational data (satellite, aircraft) for ozone, water vapor, and age-of-air species, looking at trends and variability.
- Analyze model output, both from Climate Model Intercomparison Project (CMIP) runs and chemistry-climate model (CCM) runs done by CSD.
- Use an idealized model (Tropical Leaky Pipe) to help diagnose key characteristics of the stratospheric transport that can explain discrepancies between global chemistry-climate model output and trace gas measurements.
- Analyze the Studies of Emissions and Atmospheric Composition, Clouds, and Climate Coupling by Regional Surveys (SEAC4RS) data for evidence of transport of very short-lived species (VSLS) that destroy ozone into the stratosphere.
- Analyze the Airborne Tropical Tropopause Experiment (ATTREX) data to examine transport issues that affect temperature and ozone-relevant species.
- Evaluate historical changes in the mean meridional stratospheric circulation using output from reanalyses and climate models as well as continued assessment of changes in temperature and species distributions.
- Assess changes in transport of stratospheric ozone into the troposphere using both model output and sonde data.

Chemical and radiative studies

- Lead the ozone comparison chapter for the SPARC Reanalysis Intercomparison Project (S-RIP).
- Evaluate how future emission scenarios of N_2O, CH_4, and CO_2 separately influence total ozone abundances in the tropics and extratropics.
- Complete the satellite ozone merged dataset (SWOOSH).

IV. Interconnections: Climate, Air Quality and the Stratospheric Ozone Layer

The topics of climate, the stratosphere, the ozone layer, and air quality have scientific interconnections that are not fully explored and that have implications for societal decision making. CSD research contributes to the scientific understanding of these interconnections, and this area is expected to be an important aspect of CSD's future research.

Research Topics and CSD Activities

Interconnections occur throughout CSD's research on air quality, climate, and the stratosphere. This section highlights some of the prominent examples of the very interconnected CSD research endeavor.

Process studies interconnecting air quality, climate, and the stratosphere

- *Pollutants and processes that affect both air quality and climate* – studying the dual roles of aerosols (organic aerosols, black carbon) and some pollutant gases (especially tropospheric ozone) in air quality and climate; leading and conducting field missions at the nexus of air quality and climate in key U.S. regions; studying pollutants and their effects on Arctic climate and air quality
- *Stratospheric processes and air quality* – investigating the contribution of stratospheric intrusions to tropospheric ozone

Process studies interconnecting climate and the stratosphere

- *Climate change and ozone-layer recovery* – understanding climate processes that influence ozone-layer recovery; advancing understanding related to the detection and projection of ozone-layer recovery at the poles and globally
- *The connection of stratospheric composition and climate* – investigating how seasonal ozone depletion affects surface climate in Antarctica and surrounding areas; understanding how composition changes alter stratospheric circulation and dynamics and feedbacks on the troposphere; studying the linkages between the stratospheric aerosol layer and climate, and between stratospheric water vapor and climate, as well as associated climate feedback processes
- *Ozone-depleting substances (and their substitutes) and climate* – evaluating the co-benefits of the Montreal Protocol for the protection of the ozone layer and climate; quantifying the climate impacts of ozone-depleting substances (ODSs) and substitutes for ODSs; elucidating the role of nitrous oxide as an ozone-depleting substance; advancing the scientific basis of ozone-layer and climate decision making

Emissions interconnecting air quality and climate

- *Emissions* – quantifying individual (geographic, sectoral, etc.) emissions and their contribution to climate forcing and air quality change
- *Changing atmospheric composition* – evaluating the climate impacts (global warming potentials, GWPs) and air quality effects of new substances used as replacements for ozone-depleting substances; identifying the environmental and health impacts of atmospheric degradation products of replacement compounds
- *Energy policy* – understanding the air quality effects of emissions from different energy technologies; understanding atmospheric dynamical factors involved in wind energy
- *Agriculture* – identifying the climate and air quality impacts of emissions related to agricultural practices

IV. INTERCONNECTIONS

Scientific Motivation

- Aerosols affect climate through direct and indirect effects that are not fully understood; aerosols are an important aspect of air quality.
- Pollution likely plays an important role in both the air quality and the climate of the Arctic, a region of particularly pronounced climate change and potential rapid development.
- The projections of ozone-layer recovery are made more uncertain by climate change.
- Stratospheric composition (ozone, aerosols, water vapor, some ODSs and replacement compounds), as well as stratospheric circulation and dynamics, are changing in ways that affect radiative forcing and climate feedback processes, but scientific understanding is incomplete.

Contributions to the NOAA Strategic Plan Goals, Enterprise Capabilities, and Objectives

NOAA Goals and Enterprise-Wide Capabilities	NOAA Objectives
Climate Adaptation & Mitigation	Improved scientific understanding of the changing climate system and its impacts Mitigation and adaptation choices supported by sustained, timely, and reliable climate services Assessments of current and future states of the climate system that identify potential impacts and inform science, service, and stewardship decisions
Weather-Ready Nation	Healthy people and communities due to improved air and water quality services. A more productive and efficient economy through environmental information relevant to key sectors of the U.S. economy.
Science & Technology Enterprise	A holistic understanding of the Earth System through research

Societal Benefits

- **Win-win strategies for climate and air quality:** CSD's research on short-lived climate forcing agents such as black carbon, aerosols, HFCs, and ozone provides decision makers with information needed to evaluate options that could yield near-term climate benefits and provide win-win strategies for benefiting both climate and air quality.
- **Win-win strategies for climate and the ozone layer:** Decision makers can use CSD's scientific information to find approaches that will achieve both climate mitigation and ozone-layer protection.

Key Future Activities

The overarching view of CSD research is that environmental issues — and their solutions — are interconnected. CSD's research strength lies in understanding these interfaces between climate, air quality, the stratosphere, and the ozone layer, and in providing useful information to decision makers.

CSD activities related to the crossovers between climate, the stratospheric ozone layer, and air quality are varied, and encompass much of what has been described in previous sections of this document. Air quality policies affect climate; policies established to protect the ozone layer affect climate; and policies enacted to mitigate climate change impact both air quality and the ozone layer. The connections between aerosols and climate, and in particular aerosols and clouds, stratospheric ozone and air quality, and climate changes and tropospheric ozone are the key topics covered by CSD interconnections research. The major goal is to provide scientific information that helps identify options for air quality management that will also benefit climate change mitigation and for climate policy issues that influence air quality.

Interconnections work planned for the next 5 years includes instrument development, laboratory studies, field campaigns, analysis of past campaign data, emissions inventory refinement, and combined model and data studies. There will be a strong focus on understanding the impact of wildfires, the impacts of oil and gas activities and wind energy efforts, aerosol climate forcing, aerosol-cloud interactions, and climate change impacts on tropospheric ozone.

Examples of specific studies planned are listed below:

Instrument development

- Expand broadband absorption measurements into the deeper UV spectral region, targeting brown carbon, formaldehyde, sulfur dioxide, and bromine oxide; and develop very broadband measurements that simulate satellite observations of gases and aerosols.
- Make further advances in technologies to measure bioaerosols, and conduct measurements at Reunion Island in the Indian Ocean to investigate the impact of bioaerosols on air quality and climate.
- Develop new instrumentation to study the optical properties that link aerosols to climate and tie in to satellite measurements.
- Move from research-grade to more robust, autonomous lidar systems for profiling tropospheric ozone, and use an observation network approach (TOLNET, Tropospheric Ozone Lidar Network, in collaboration with NASA centers); and develop lidars for use in spatial arrays and on mobile platforms.

Laboratory studies

- Work to determine impacts on climate and the ozone layer of new substances proposed by industry for use in societal applications such as air conditioning, refrigeration, and manufacturing.

Field campaigns

- Quantify air quality and climate impacts of oil and gas exploration and development activities through field work, model development, and theoretical analyses.
- Conduct field and laboratory observations and analyses to understand the effects of wildfires on climate and air quality in the Fire Influence on Regional and Global Environments Experiment (FIREX), to be led by CSD in 2015-2019.
- Lead and participate in intensive, focused field missions to accomplish objectives in both air quality and climate, including proposed participation in the Southern Hemisphere Clouds, Radiation, and Aerosol Transport Experiment (SOCRATES) mission to evaluate the interactions of clouds and atmospheric composition in the southern oceans.
- Use data from in the NASA Atmospheric Tomography Mission (AToM) (2015-2019) to examine the roles of reactive nitrogen and aerosol in the global-scale chemistry and radiative forcing.

Past campaign data analysis

- Analyze organic and sulfate aerosol data from the Southeast Nexus (SENEX) and California Nexus (CalNEX) field missions led by CSD, to develop models of inorganic and organic aerosol formation; evaluate the radiative implications of aerosol formation mechanisms and precursor trends; and understand connections between air pollution, biogenic emissions, and radiative forcing.
- Characterize wintertime oxidation chemistry of anthropogenic emissions and the impacts on regional and global aerosol and ozone budgets, using data from the 2015 Wintertime INvestigation of Transport, Emissions, and Reactivity (WINTER) field mission.

Emissions inventory development/refinement

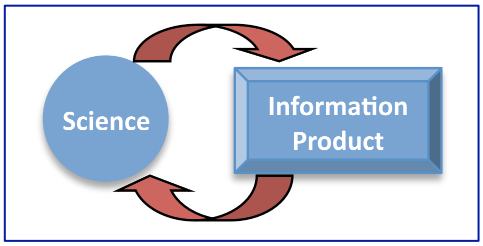
- Within the framework of GEIA (Global Emissions Initiative), improve inventories of air quality-related and climate-relevant emissions through a combination of different approaches that include bottom-up methodologies, new applications of in-situ and remote-sensing observations, and inverse modeling activities.

Model and data studies

- Quantify impacts of the full cycle of biofuel usage (i.e., growth, processing, refining, and use) on climate and air quality.
- Conduct model runs to evaluate climate sensitivity to stratospheric water vapor and ozone.
- Conduct studies of how changes in atmospheric composition (such as water vapor and ozone) affect atmospheric circulation, for example by using observations to force climate models.
- Use climate model sensitivity studies to look at causes of tropical temperature changes, as well as impacts of Southern Hemisphere polar ozone changes.
- Combine model and measurements of ultrafine aerosol to study aerosol-cloud interactions and estimate the contribution of various mechanisms to the formation of new particles and how these particles grow and influence clouds.
- Continue quantifying the sources (natural versus anthropogenic), processes (aqueous and gas phase), and effects of secondary organic aerosols in the troposphere.
- Extend work on the effects of stratospheric intrusions on surface-level ozone, especially as it relates to local efforts to meet national air quality standards.
- Analyze ship-based measurements of boundary-layer wind structure for possible incorporation into numerical models to predict offshore wind energy generation potential; also use high-resolution wind and turbulence profiles from networks of Doppler wind lidars to evaluate and improve NOAA operational numerical model prediction of wind resources over complex mountain areas.

Research to Applications:
CSD's Communication of Decision-Relevant Information to Stakeholders in Government, Industry, and the Public

Research with Impact: CSD's primary products are its scientific papers in the peer-reviewed literature, but CSD takes several steps to then convey that information beyond the scientific community — in user-friendly formats that communicate ***decision-relevant information*** to stakeholders at all levels in government, industry, non-governmental organizations, and the public. CSD's scientific information is also included in information products produced by other national and international organizations.



Payoffs

These information products and interactions
provide key scientific input to policy and management decisions
of industry and local, state, national, and international governments
regarding three societally relevant topics:
Climate • Air Quality • Stratospheric Ozone Layer

Prospectus for the Future

The Chemical Sciences Division is committed to continuing its strong contributions to decision-support information and assessments:

- Work is in progress on the first international scientific assessment of tropospheric ozone, with a CSD scientist chairing the 11-member Steering Committee. The effort is under the auspices of the International Global Atmospheric Chemistry (IGAC) Project, which operates under the umbrella of the International Geosphere-Biosphere Programme (IGBP).
- Work is also well along on a scientific assessment of water vapor, under the Stratosphere-troposphere Processes and their Role in Climate (SPARC) project of the World Climate Research Programme (WCRP). A CSD scientist serves as one of three international cochairs of that assessment.
- CSD expects to continue its leading contributions to the scientific assessment for the Montreal Protocol, under the auspices of the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP).
- CSD will also propose several of its scientists for roles in future climate assessments, such as of the one currently under discussion by the Intergovernmental Panel on Climate Change (IPCC).
- CSD will continue its longstanding role in the NASA/JPL evaluation of kinetics data, which underpins the efforts of the climate and ozone-layer assessments, as well as atmospheric chemistry research in general.

Partnerships and Collaborations
Synergies through Vital Partnerships

NOAA/CIRES: A vital and unique partnership. NOAA/OAR has nine Cooperative Institutes with various universities. In Boulder, the Cooperative Institute for Research in Environmental Sciences (CIRES) is a joint endeavor of the University of Colorado and NOAA, having been founded in 1967. Over these ~48 years, CIRES has played a vital role in the local Federal–State venture involving the University, CSD, and other NOAA entities in Boulder. Currently, about 60% of CSD's personnel are CIRES staff. The CIRES component reflects a spectrum of professional levels, ranging from senior researchers to students, and is involved with the research of all of the CSD's seven Program Areas.

A culture of collaborations—internal and external. A hallmark of CSD's research through the years has been strong and extensive collaborative activities with other national and international research institutions, e.g., universities, other Federal Agencies, other NOAA Laboratories and Programs, and the private sector. Some of the most telling indications of these close scientific interactions are the publications of CSD; *the majority of them involve coauthors from other institutions.* This is true throughout CSD's publications, whether they are theoretical, laboratory, or observation-based papers. Within NOAA/OAR, CSD most often collaborates with the three other Divisions of the Earth System Research Laboratory in Boulder (Global Monitoring Division, Physical Sciences Division, Global Systems Division), the Pacific Marine Environmental Laboratory (Seattle), the Geophysical Fluid Dynamics Laboratory (Princeton), and the Air Resources Laboratory (Silver Spring, MD). CSD also collaborates with OAR's National Severe Storms Laboratory (Norman, OK), the Great Lakes Environmental Research Laboratory (Ann Arbor, MI), and the Atlantic Oceanographic and Meteorological Laboratory (Miami, FL). In addition, CSD collaborates with other NOAA Line Offices (National Weather Service, National Environmental Satellite, Data, and Information Service, National Marine Fisheries Service, and National Ocean Service).

End-to-end engagement with stakeholders. Finally, CSD's partnerships involve its stakeholders. CSD uses an "end-to-end" approach that embraces interactions with decision makers and stakeholders in its research endeavors—not only after the research but especially *before* the research. In this approach, CSD engages stakeholders to identify their most urgent questions, and as research progresses, CSD follows through to deliver the information in user friendly, policy-relevant formats. CSD uses the questions and feedback that we receive from all interested parties to determine the ongoing alterations and adjustments in our research directions that are needed to fill in gaps in understanding and to lay new paths for future research.

Key Partnerships

- NOAA Cooperative Institutes
- Other ESRL Divisions, OAR Labs, and NOAA Programs
- Other NOAA Line Offices (NWS, NESDIS, NMFS, NOS)
- Other U.S. Agencies (e.g., NASA, DOE, NSF, NCAR)
- WMO/UNEP
- State/Local Organizations (e.g., CARB, TCEQ, Utah DEQ)
- Academia
- Private Sector / Industry
- International Organizations

NOAA ESRL Chemical Sciences Division
Boulder, Colorado
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