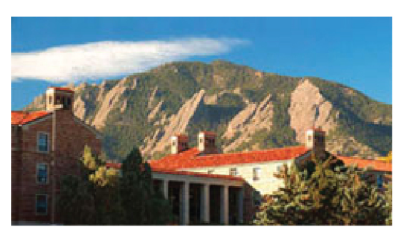
# NOAA Earth System Research Laboratory
# Chemical Sciences Division
# Boulder, Colorado

## Research Accomplishments and Plans
## Chemical Sciences Division Review
## 2008—2014

March 30—April 1, 2015

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

CIRES



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This document presents the Research Accomplishments and Plans from the Chemical Sciences Division for the period 2008 – 2014. The document was developed and edited by Christine A. Ennis with input from the scientific staff of CSD.

March 2015

**A Message from the Director**

I am pleased and honored to be the Director of the Chemical Sciences Division of the Earth System Research Laboratory, following Dr. A. R. Ravishankara (2006-2013) and Daniel Albritton (1986-2005). From them I inherited a laboratory with an outstanding team of scientific, technical support, and administrative professionals. At the same time I am humbled and challenged to be leading this outstanding team into the future.

We have a great mission within NOAA to be stewards of the atmosphere and oceans by conducting diverse research that we communicate to our NOAA colleagues, the world's scientists, stakeholders, decision makers and the public. Our research strategy is to use our portfolio of sampling instruments, field and laboratory measurements, modeling tools and analyses, and publications and assessments to fill gaps in understanding and knowledge associated with the most pressing environmental issues of our time; namely climate change, air quality, and stratospheric ozone depletion. Our history of numerous, varied, and substantial accomplishments covering the last several decades shows that our research strategy is a successful one.

Our research topics today are highly diverse. Air quality has led us to study aerosol formation, emissions from anthropogenic activities such as agriculture and oil and gas extraction, nighttime chemical transformations, decadal trends in atmospheric composition, biogenic emissions, hemispheric transport of ozone and its precursors, and transport of ozone from the stratosphere and other continents. Climate change has led us to study climate model performance, methane emissions from oil and gas activities and animal feedlots, black carbon aerosol in the atmosphere and cryosphere, formation of cloud systems, aerosol global radiative forcing, stratospheric water vapor, plankton layers in the ocean, and the global warming potentials and future emissions of synthetic gases. Stratospheric ozone depletion has led us to study chlorine photochemical reactions in the laboratory, the role of nitrous oxide in ozone depletion, the abundances of hydrofluorocarbons in the atmosphere, ozone and circulation trends in the stratosphere, and the recovery of stratospheric ozone.

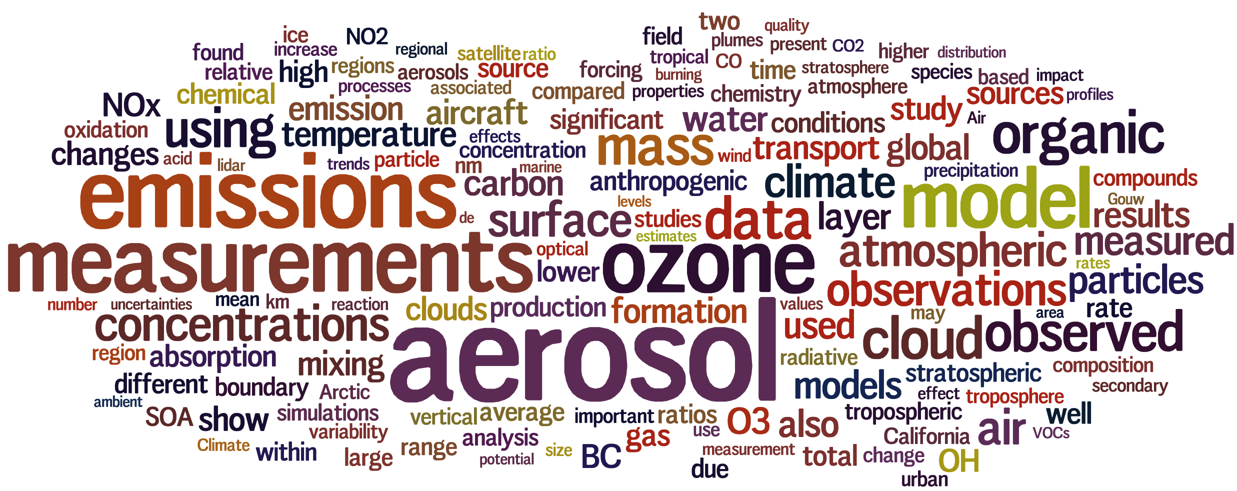
Our broad-based research aligns well with NOAA's strategic goals related to Climate Adaptation and Mitigation, a Weather Ready Nation, and our Science and Technology Enterprise. NOAA has tremendous responsibility for the health of our atmosphere, oceans and ecosystems, which includes the health and safety of our population. Thus, NOAA has accepted a great responsibility for our Nation; it is one that we in CSD are pleased and proud to share in and work diligently to discharge.

This document attempts to capture our accomplishments over the last 7 years. Here we describe our research topics and motivation and offer a partial list of highlights and specific accomplishments. This period has been extraordinarily productive with numerous field, laboratory, and modeling activities and substantial communication of our research to policymakers, stakeholders, and the public. This document is only one of several produced in support of this 2015 review process. These documents are best combined with the presentations and posters that are part of the formal review in order to create the most comprehensive overview of our scientists, their accomplishments, and our scientific strategy and style.

A sustained high level of creativity, quality, and performance distinguishes our accomplishments. These same features describe our professional team comprised of Federal workforce employees, members of the Cooperative Institute for Research in Environmental Sciences (CIRES) of the University of Colorado-Boulder, and members of the Science and Technology Corporation. Our staff is our most important resource; its health and vitality will continue to be my highest priority.

The Chemical Sciences Division has accomplished much in this review period and has a great mission with an exciting and challenging future ahead. I hope you share this vision after reading our Research Accomplishments and Plans document.

David W. Fahey
Director, Chemical Sciences Division




A word cloud derived from the titles of the approximately 800 peer-reviewed papers published with first authors or coauthors from the ESRL Chemical Sciences Division in the period 2008 – 2014. To date, other scientists have cited these publications more than 16,000 times. (Courtesy of Karen Rosenlof) (http://www.wordle.net/)

# Contents

# 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

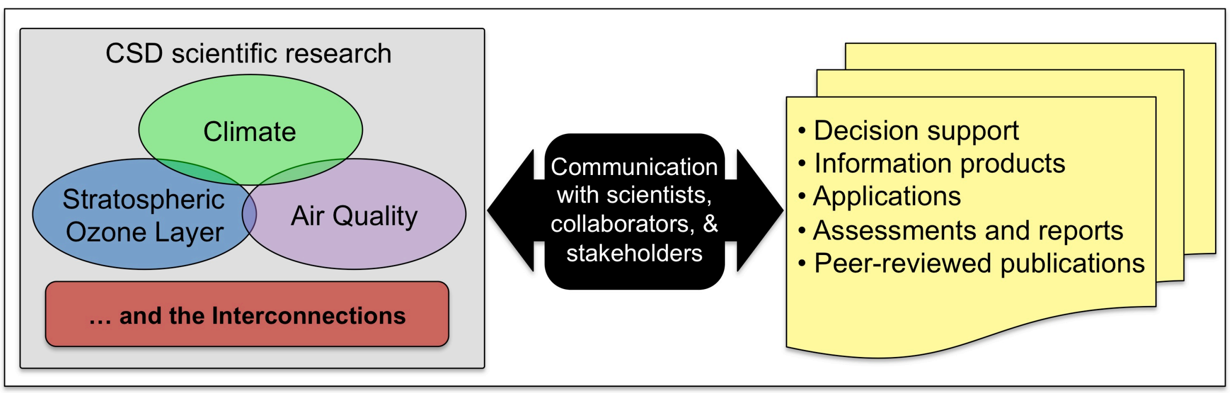
**Earth System Research Laboratory (ESRL)**
**Chemical Sciences Division (CSD)**

**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:

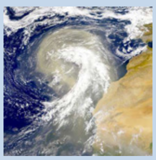
- Identifying new research directions and gaps in current understanding;
- Developing new instrumentation, sampling methods, and modeling techniques;
- Conducting laboratory studies of fundamental physical and chemical processes;
- Observing the composition and physical state of the atmosphere from a 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

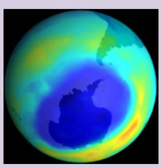
**Measuring and understanding how atmospheric particles affect clouds, climate, and air quality**

**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**

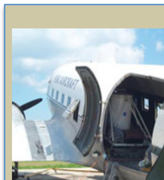
**Program Leader: Tom Ryerson**



### Chemistry & Climate Processes

**Understanding atmospheric chemistry and climate processes with integrated analysis and modeling**

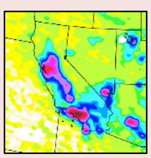
**Program Leader: Karen Rosenlof**



### 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**

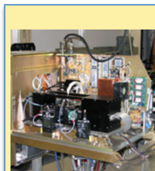
**Program Leader: Alan Brewer**



### Regional Chemical Modeling

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

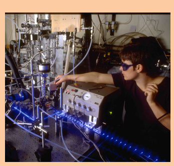
**Program Leader: Michael Trainer**



### 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 research accomplishments and plans, looking back over the past seven years (2008–2014) since the last formal review. For simplicity, four principal topics are described separately: climate, air quality, the stratospheric ozone layer, and interconnections between topics, with the material for each divided into the following sections:

- Research topics and activities
- Scientific motivation
- Contributions to NOAA strategic plans goals, enterprise capability, and objectives
- Societal benefits
- Some recent highlights of CSD research
- Selected CSD accomplishments
- Key future activities

The last sections describe CSD Research to Applications and CSD Partnerships and Collaborations.

# 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<br>Mitigation and adaptation choices supported by sustained, timely, and reliable climate services<br>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.

## Some Recent Highlights of CSD Research on Climate

- A modeling study led by CSD demonstrated that climate change that takes place due to increases in carbon dioxide concentrations is largely irreversible for 1,000 years after emissions completely stop. The reason is that, although removal of atmospheric carbon dioxide occurs thereby decreasing radiative forcing, there is slower loss of heat to the ocean, so that atmospheric temperatures do not drop significantly for at least 1,000 years. A second related study, also using the Bern 2.5CC Earth Model of Intermediate Complexity (EMIC), examined the persistence of global warming due to a range of non-$CO_2$ greenhouse gases. That study showed that warming due to non-$CO_2$ greenhouse gases, although not irreversible, lasts longer than the changes in greenhouse gas concentrations themselves. This is a consequence of the competition between decay of the radiative forcing and ocean heat uptake. Hence the warming effect of various greenhouse gases depends not just on the lifetimes of the gases, but is also strongly dependent upon climate system timescales.

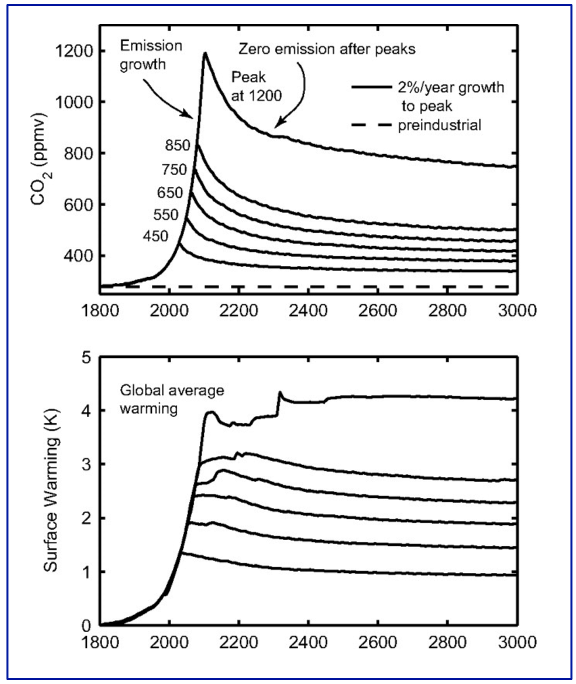



**Figure I-1.** A 2009 study used the Bern 2.5CC EMIC to assess the irreversibility of $CO_2$-induced climate change. (*Top*) $CO_2$ concentrations; the peaks are reached through a ramp up of $CO_2$ emissions at a rate of 2%/year to peak $CO_2$ values of 450, 550, 650, 750, 850, and 1200 ppmv. (*Bottom*) Globally averaged surface warming (degrees Celsius) for these cases (note that this model has an equilibrium climate sensitivity of 3.2 °C for $CO_2$ doubling).

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- Changes in stratospheric water vapor content play a significant role in climate. CSD is at the forefront of water vapor instrument development and is among the leaders of international efforts to resolve discrepancies in measuring water vapor at ultra-low values relevant to the stratosphere (in MACPEX in 2011, and Aqua-VIT in 2013). Efforts culminated in CSD developing an in-flight calibration system that has been used with the CSD water Chemical Ionization Mass Spectrometer (CIMS) instrument (on the NASA WB-57) and the CSD water/total water Tunable Diode Laser (TDL) instrument (on the NASA Global Hawk Unmanned Aircraft System).

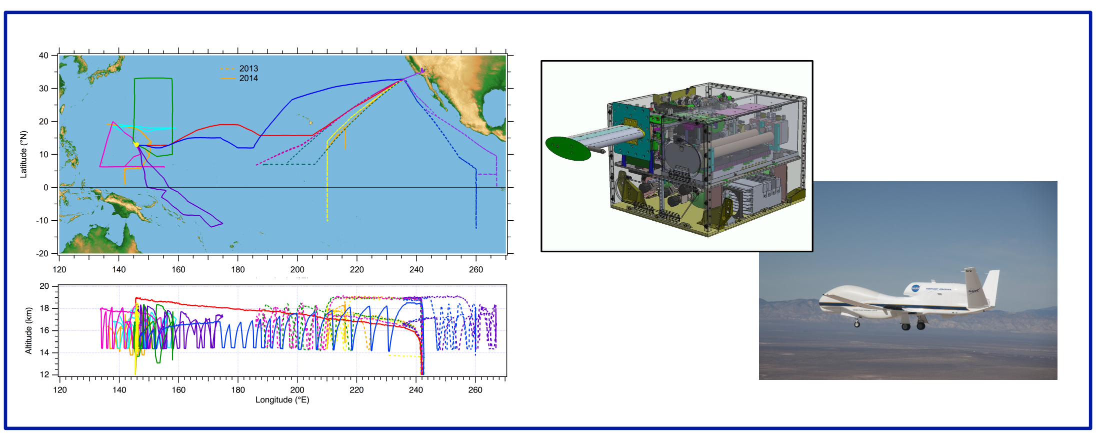



**Figure I-2.** The CSD tunable-diode-laser water vapor instrument was flown on the NASA Global Hawk Unmanned Aerial System (UAS) during the Airborne Tropical Tropopause Experiment (ATTREX). ATTREX sampled the tropical tropopause layer over the Pacific in 2013-2014.

- CSD scientists used a new approach to identify sources of methane (a potent greenhouse gas) in the Los Angeles air basin, solving a longstanding mystery about why atmospheric measurements indicate about 35% higher methane than values predicted by some inventories of the sources. Hydrocarbon measurements were used to develop “fingerprints” of the different sources (such as landfills, oil and gas pipeline leaks, dairy farms, and oil extraction and development activities). The researchers found that the extra methane is likely coming from sources related to fossil fuels. Those sources include leaks from natural gas pipelines and other oil and gas activities, as well as seepage from natural geologic sites such as the famous La Brea Tar Pits.

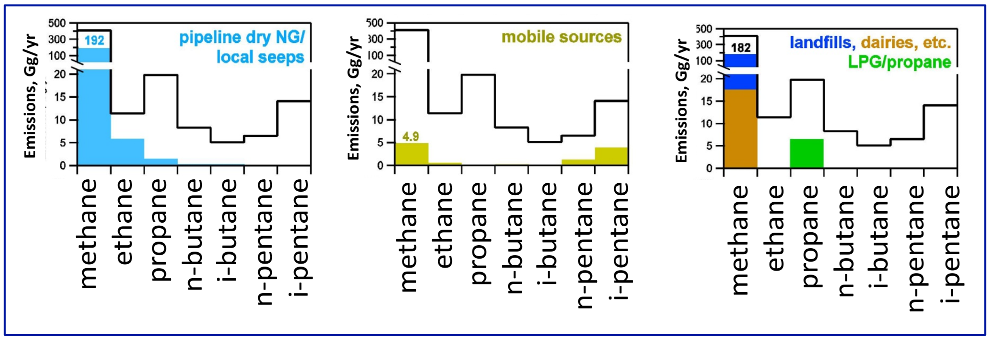
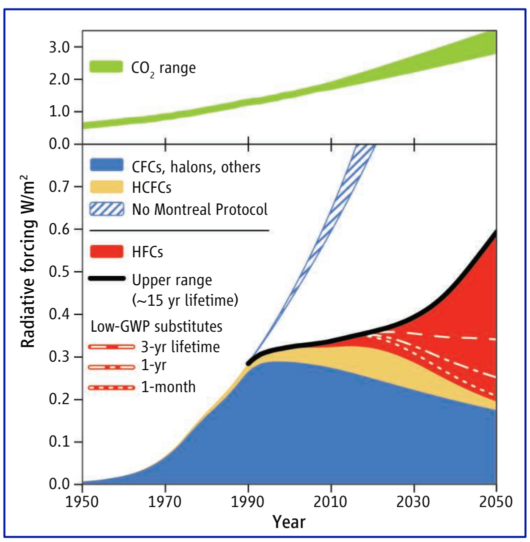



**Figure I-3.** CSD’s measurements revealed the hydrocarbon “fingerprints” of different sources of methane in Los Angeles.




- Hydrofluorocarbons (HFCs) are substitute gases for ozone-depleting substances that have been phased out of global use under regulations of the Montreal Protocol, which was developed to protect the stratospheric ozone layer. HFCs do not deplete ozone, but many of them are potent greenhouse gases. Their use is projected to increase sharply in the coming decades from growth in refrigeration, air conditioning equipment, and foams in the developing world. CSD scientists and colleagues evaluated the climate contribution of HFC growth, and concluded that the HFC climate contribution could be a large fraction of the total greenhouse gas forcing by 2050.

**Figure I-4.** Past and projected radiative forcing from ozone-depleting substances (CFCs, halons, HCFCs) and HFCs. Different scenarios for HFC use are shown by the white dashed lines. For comparison, the top panel shows forcing from carbon dioxide.

- CSD research showed for the first time that interactions between certain types of neighboring clouds can result in synchronized rain patterns within a large cloud system. The study demonstrated the important role of suspended particles (aerosol), through their control on precipitation, in determining not only the *local* properties of the cloud (such as its ability to rain, or how much energy it reflects to space) but also the *large-scale organization* of the cloud system.

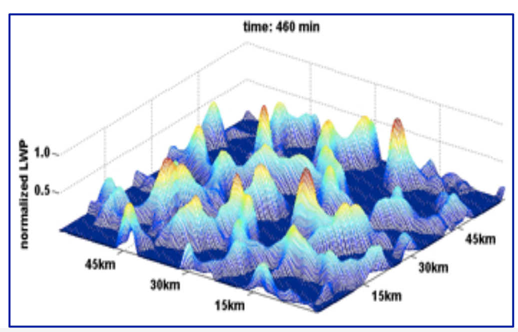



**Figure I-5.** Snapshot of a coupled, oscillating cloud system. CSD research showed that the open cellular cloud structure, as represented by the liquid water path (LWP), evolves in a synchronized, periodic fashion. The precipitation generated by these clouds also has a periodic behavior.

## Selected CSD Accomplishments in Climate Research (January 2008 – February 2015)

Non-$CO_2$ greenhouse gases

- Examined the trends and influences on free tropospheric ozone over the U.S., finding springtime increases of 29% from 1984-2011 in the western U.S. and demonstrating the role of long-range transport processes in determining local ozone levels *(see also the Air Quality highlight)*
- Quantitatively assessed the accuracy of chemistry-climate model simulations of the trends and seasonal variation of tropospheric ozone, using measurements collected from around the world and several models *(see also Air Quality accomplishments)*
- Conducted laboratory work to evaluate the lifetime and radiative impact of several perfluorocarbons and $NF_3$, which are potent long-lived greenhouse gases
- Developed a synthesized and consistent satellite record of water vapor data, for use in interannual variability and trends analyses
- Quantified the fugitive methane emissions from natural gas drilling operations in the Uintah Basin, Utah, and in three major gas fields in the eastern U.S., using a mass balance approach relying on CSD measurements of methane, mixing layer depth, and horizontal winds; found a wide variation in the amount of methane emitted per unit of natural gas produced

Aerosols

- Discovered that the soot particles in snow are larger than had been expected, and can have smaller warming effects on the snow surface (~30% smaller decreases in albedo) than previously thought
- Showed that distant biomass burning sources are a more important contributor than previously thought to the black carbon and organic aerosols in the Arctic (i.e., "Arctic haze")
- Measured black carbon (BC) aerosol loadings during the 2009-2011 HIAPER Pole to Pole Observations (*HIPPO*) campaign above the remote Pacific from 85°N to 67°S, gathering over 700 vertical profiles that give a climatology of BC in the remote regions, and revealing gradients of BC concentration that reflect global-scale transport and removal of pollution
- Showed that oils from partially burned vegetation coat the soot from wildland fires, causing the soot to absorb more light (compared with soot from other sources) by 50 to 70%, which has implications for the effects of the soot on climate
- Completed measurements and analyses with Chinese colleagues showing that the refractory black carbon component of aerosol has the potential to strongly influence local meteorology and climate parameters in the highly polluted Pearl River Delta region of China
- Used the HIPPO black carbon data to show that the AeroCom model suite overestimates loads (and therefore also overestimates black carbon lifetime) over the Pacific, more severely in the upper troposphere/lower stratosphere (factor of ~10) than at lower altitudes (factor of ~3), with bias roughly independent of season or geographic location
- Helped to initiate, lead, and author a major scientific publication on the role of black carbon in the climate system, showing that black carbon is the second most important anthropogenic climate forcing agent
- Examined the various sources of measurement uncertainty in aerosol direct radiative forcing (DRF), finding that the largest contributor to total uncertainty is the single scattering albedo component; also developed a framework from which the uncertainty in DRF can be determined for a specific time and location
- Conducted studies to better understand the influence of aerosols on cloud formation, showing that most cirrus clouds are formed when ice freezes on particles of mineral dust and on metallic particles from industrial activities or combustion, all of which are affected by human activities; and that sea salt aerosol production from precipitation-induced winds is an important mechanism controlling marine stratus
- Analyzed airborne observations of aerosol composition gathered by the NOAA Particle Analysis by Laser Mass Spectrometry (PALMS) instrument throughout the tropical tropopause layer, showing that acidic, sulfate-rich particles below 12 km came from a marine source, whereas neutral, organic-rich aerosol above 12 km came from a continental source

- Also used PALMS measurements to characterize the chemical composition of stratospheric aerosols and distinguish their sources (stratosphere versus troposphere), phase, and potential for heterogeneous chemistry and ice nucleation
- Used measurements and models to show that observed increases in the stratospheric aerosol layer over the 2000s can be attributed to volcanic emissions from small to moderate volcanic eruptions during that period, rather than increases in anthropogenic source gases *(also mentioned in the Interconnections highlights)*
- Completed a modeling study of the Asian Tropopause Aerosol Layer (ATAL), concluding that its presence it most likely due to anthropogenic emissions, but its source cannot solely be attributed to emissions from Asia; Chinese and Indian emissions contribute ～30% of the sulfate aerosol extinction in the ATAL during volcanically quiescent periods.
- Developed a new scheme, using CSD laboratory data, to parameterize aerosol nucleation that is now used in climate models and has led to better agreement of models with observations of aerosols
- Carried out analyses to better define the effects of aerosols on climate, showing that: closing the global energy budget requires a net aerosol effect of about −1.2 W $m^{-2}$ (cooling); aerosol indirect effects must be considered at the scale of dynamic cloud systems rather than as individual effects on single clouds; and aerosol pollution alters the morphology of marine stratus clouds from open to closed cells, with large implications for the radiative effect of the clouds
- Identified processes that buffer cloud and precipitation responses to aerosol perturbations
- Used laboratory and modeling to develop a chemical mechanism for the aqueous formation of secondary organic aerosol, and made advances in parameterizing the mechanism for use in global models
- Found that in an ammonia-rich urban environment, changes to aerosol behavior with aging can impact significantly the visibility and climate forcing of aerosol

Climate system understanding and analyses

- Used a new approach (examining location-by-location temperature changes rather than using global averages) to detect the emergence of climate change signals in the observational record
- Analyzed emissions data from power plants, finding that power plants that use natural gas, in combination with a new technology to extract more energy from the fuel, release far less carbon dioxide per kilowatt-hour of energy produced than coal-fired power plants
- Showed that climate intervention ideas to inject particles into the stratosphere to cool the climate could, by reducing direct sunlight, have the unintended consequence of decreasing the peak electricity provided by large solar collectors by as much as one-fifth
- Used climate models and a well-known ecosystem classification system to look at shifts between climate zones over a two-century period (1900 to 2098), demonstrating that as the Earth warms, its climate zones shift at an accelerating pace
- Analyzed the climate implications of single-basket versus multiple-basket trading approaches
- Showed that Earth's energy budget can be evaluated using first principles and observations, without relying on climate models
- Applied lidar techniques to characterize thin plankton layers (a major $CO_2$ sink) in the ocean
- Showed that spatial variations in temperature trends across the continental U.S. are connected to the hydrologic cycle, which suggests a role for aerosol and land-use changes, especially in the southeastern U.S. (leading to CSD's 2013 SENEX field campaign)
- Used satellite data and modeling to show that the regional redistribution of aerosols over the past decade has had little effect on the net clear-sky radiative forcing (i.e., there has been almost exact cancellation of the radiative effects of aerosol increases and decreases in different parts of the world)
- Published greenhouse gas concentrations for the Representative Concentration Pathways (RCPs) and their extensions beyond 2100 (Extended Concentration Pathways, ECPs), which were used in climate model scenarios for the international assessments on climate and the ozone layer

Climate-relevant dynamical and radiative processes

- Discovered that black carbon is a valuable tracer of extra-tropical mixing into the tropics and of the dominant circulation in the lower stratosphere
- Concluded that the El Niño-Southern Oscillation (ENSO) climate impacts over North America are largely associated with a tropospheric pathway, whereas ENSO's climate impacts over the North Atlantic and Eurasia are greatly affected by the stratospheric pathway; therefore including the stratosphere should improve seasonal prediction forecasts
- Used temperature and constituent measurements to deduce historical changes in the Brewer-Dobson circulation (BDC)
- Used a tropical pipe model to test how changes in BDC mass flux and associated mixing affect long-lived species evolution, showing that changes in mixing not currently accounted for in climate models could bring models into agreement with measured estimates of age-of-air trends
- Critically examined the range of estimates for tropical widening over the past 30 years, finding that extremely high estimates of tropical widening are the consequence of using subjective metrics, and that objective metrics are recommended
- Showed for the first time that the interannual variations in the stratospheric mean meridional circulation impact tropical tropopause layer clouds

Instrument and platform development

- Developed two new miniaturized instruments for studies of aerosol forcing using Unmanned Aerial Systems (UASs), and completed test flights on the Manta UAS: an optical particle counter (Printed Optical Particle Spectrometer, POPS), and a scanning radiometer (Upward Looking Radiometer, ULR)
- Developed new instruments for making accurate and sensitive airborne measurements of ozone, black carbon, and water vapor, as well as for measuring climate-relevant properties of atmospheric aerosols
- Developed and integrated turbulence sensors for the Global Hawk UAS; also provided scientific and technical leadership in using the Global Hawk UAS for the first time for Earth System science research in the GloPac campaign (2010), and again in the ATTREX campaign (2011-2014)
- Leading in development of space-based instruments in support of weather and climate (ongoing)

## 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:

# I. CLIMATE RESEARCH

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, $R^2$Drone; 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$^4$RS], 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.

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

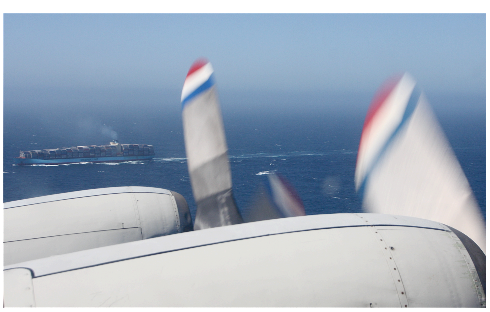
| NOAA Goals and Enterprise-Wide Capabilities | NOAA Objectives |
|---|---|
| Weather-Ready Nation | Healthy people and communities due to improved air and water quality services<br><br>A more productive and efficient economy through environmental information relevant to key sectors of the U.S. economy |
| 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.

## Some Recent Highlights of CSD Research on Air Quality

- CSD measurements during the 2010 California Nexus: Research at the Nexus of Air Quality and Climate Change (CalNex) field study gave an independent confirmation that California's new regulations—which require ocean-going vessels to "fuel switch" to cleaner fuels when nearing the coastline—are working as intended to reduce pollutant emissions from shipping. Researchers used state-of-the-art instrumentation developed at CSD to measure black carbon, sulfur dioxide, and other pollutants as a cargo ship switched from high-sulfur to low-sulfur fuels. This research has enabled the California Air Resources Board (CARB) to verify the effectiveness of current regulations in that state, which ultimately will bolster future actions at the national level to improve air quality for coastal residents and those living along inland waterways.



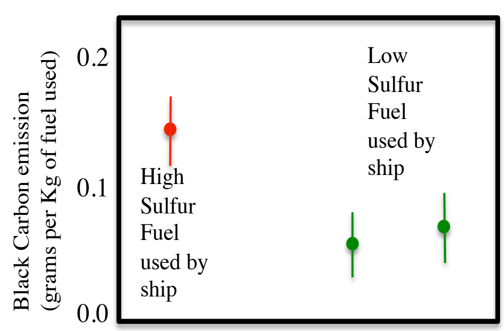



**Figure II-1.** Emissions from a cargo ship, shown in the distance as the NOAA WP-3D research aircraft flew overhead, were measured before and after the ship switched to cleaner fuel.

- An international study led by CSD found that the highest levels of ozone pollution have dropped at many rural eastern sites, as expected due to declining emissions of the chemicals that contribute to ozone formation. Precursor emissions have also declined in the West; however, in rural areas of the West, ozone trends tend to be steady or increasing, with the strongest increases occurring in spring. Trends in the West are consistent with the potential impact of increasing baseline ozone flowing into the U.S. West from across the North Pacific Ocean.

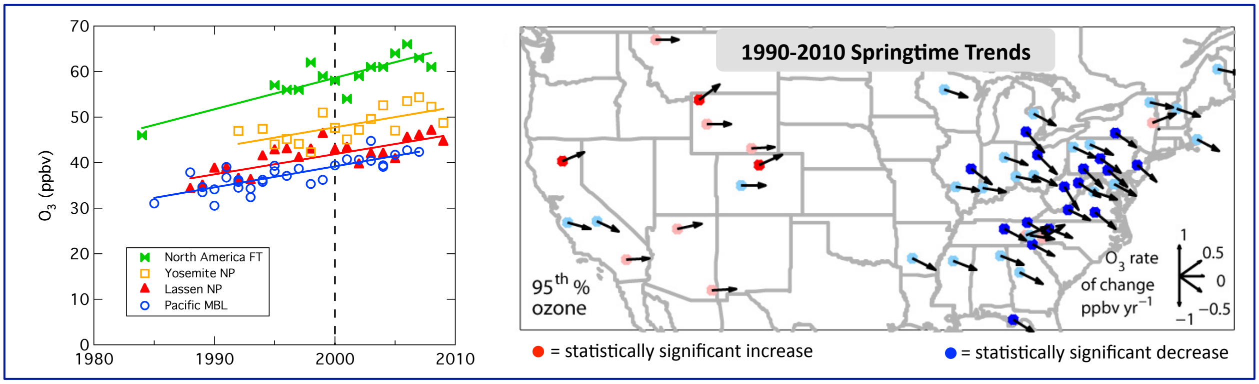



**Figure II-2.** *Left*: Ozone trends (in springtime) at stations indicative of baseline air masses impacting the western U.S. *Right*: Spring daytime ozone trends (1990-2010) at 52 locations in the U.S.

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- CSD-led research showed that in California's Los Angeles Basin, levels of some vehicle-related air pollutants (notably volatile organic compounds (VOCs)) have decreased by about 98 percent since the 1960s, even as area residents now burn three times as much gasoline and diesel fuel. The emissions reductions implemented in the region have cut air pollution, but also have altered the pathways of air pollution chemistry in the region. Among the pollutants that have plummeted are ground-level ozone and acetyl peroxynitrate (PAN), which is the compound historically associated with eye irritation (the "sting") in Los Angeles smog.

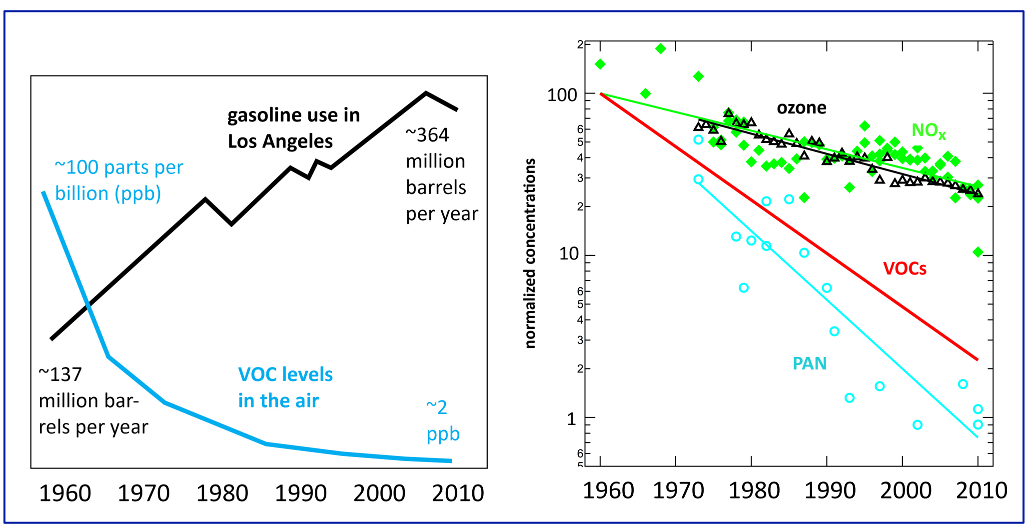


**Figure II-3.** Although gasoline consumption in Los Angeles has nearly tripled since 1960, levels of vehicle-related pollutants (VOCs, NOx, PAN, ozone) have plummeted.

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## Selected CSD Accomplishments in Air Quality Research (January 2008 – February 2015)

Field mission leadership

- Led and participated in the most detailed study available of air quality during the Deepwater Horizon oil spill, showing that: secondary aerosols were the most important air pollutant from the spill; the amounts of air pollutants in the plume generated by the spill were similar to those found in large cities and likely affected a limited area of the Gulf coast; the oil spill fires released more than one million pounds of black carbon into the atmosphere; and airborne measurements could be used to make an independent determination of the subsurface oil leak rate and describe the distribution of spilled oil in the environment
- Led airborne field studies in a variety of U.S. regions experiencing poor air quality (Northeast U.S., Los Angeles, Utah, and the Southeast U.S.), identifying factors unique to each region's air pollution challenges
- Led and participated in three ground-based field missions (2012, 2013, 2014) to study air quality processes involved in the formation of unusual wintertime high-ozone episodes near the surface during snow-covered, low-sun-angle wintertime conditions in the oil and gas exploration fields of Uintah County, Utah; used the measurements of ozone, other trace gases, and wind, along with modeling, to demonstrate that the ozone episodes are primarily caused by the very high VOC emissions from the oil and gas sector, persistent stagnation episodes, and high surface albedo and reduced deposition during periods of snow cover
- Co-led and participated in the WINTER-2015 airborne field campaign to gather data that will elucidate the differences in wintertime versus summertime processes that influence ozone, fine particles, and other pollutants in the eastern U.S.
- Co-led and participated in field campaigns at the Boulder Atmospheric Observatory to characterize air quality impacts of oil and gas activities in the Denver region and to study the effects of nighttime chemistry on air quality

Ozone and trace gases

- Quantified the role of nighttime chemical processing in the polluted troposphere, with a focus on nitrate radicals and chlorine-atom sources, in studies that: showed that nighttime chemistry not only affects air quality directly, but also allows the nighttime accumulation of photolabile species (nitryl chloride ($ClNO_2$), nitrous acid (HONO)) that act as radical sources that contribute to the following day's photochemistry; showed that chlorine-mediated chemistry plays a larger role in inland areas than previously thought; and elucidated the mechanism for $ClNO_2$ formation from $N_2O_5$ uptake on aerosols
- Used lidar data to show that ozone transported from Houston, Los Angeles, Denver, and other major urban areas can impact rural air quality far downwind, and to characterize the atmospheric boundary layer
- Used lidars to study the formation of the nighttime atmospheric boundary layer; to investigate the relationship between peak ozone values and boundary layer height in Texas and California; and to determine the structure of the boundary layer over complex terrain in Utah's oil and gas fields
- Investigated urban air quality in a global context and in megacities (Beijing, Mexico City), identifying the dominant role played by vehicle fleets in degraded air quality
- Made the first atmospheric measurements of isocyanic acid (HNCO), a trace gas that is emitted during wildfires and other forms of biomass burning; also measured its solubility in water and its emission during cigarette burning, factors that indicate the potential for health effects
- Showed that glyoxal (CHOCHO) plays a small role in organic aerosol formation in Los Angeles, in contrast to its larger role in other cities (e.g., Mexico City)
- Obtained the first direct evidence of high levels of molecular chlorine in the polar marine atmosphere, in measurements made at Barrow, Alaska, and found that the snow-covered land or ice surface likely plays a role in the formation of molecular chlorine, and chlorine atoms are likely the dominant oxidant in the Arctic lower atmosphere
- Demonstrated that reductions in $NO_x$ emissions from power plants are enhanced by nighttime chemistry in the plumes, and that $NO_x$ removal is more efficient in lower-$NO_x$ plumes

- Participated in the Denver deployment of the NASA DISCOVER-AQ mission (Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality), to advance understanding about the factors that create poor air quality in the Denver metro region and to help improve the capability of future satellites to monitor air quality around the world; also conducted ozone lidar measurements during the Houston, Texas, deployment of DISCOVER-AQ
- Provided detailed chemical measurements of the specific sources of VOCs emitted in oil and gas production fields, identifying the types of equipment and different production methods that lead to the greatest emissions, and thereby providing information that will help the industry identify how to reduce emissions as inexpensively and effectively as possible
- Led a model study that found that methane and VOCs from oil and gas operations in the Uintah Basin, Utah, are significantly underestimated in the most recent U.S. EPA national emission inventory, while emissions of $NO_x$ are overestimated by nearly a factor of four
- Conducted several inverse modeling studies of the temporal evolution of CO, $NO_x$, $SO_2$, and $CO_2$ at the urban scale, and used the technique to evaluate anthropogenic emissions (Los Angeles, Houston)
- Conducted research to improve emissions inventories:
  - analyzed observations of VOCs and $NO_x$ from the 2000 and 2006 aircraft campaigns in Texas, showing that emissions from the Texas petrochemical industry are declining but are still higher than inventories used by industry and regulators; found that using airborne and satellite measurements can improve emissions inventories for Texas and thereby improve model predictions of ozone
  - analyzed observations of ammonia made during the CalNex mission, showing that inventories of agricultural emissions are underestimating the dairy-related sources
  - measured area-wide agricultural emissions of nitrous oxide and methane and found that inventories underestimate the fluxes by about a factor of three
  - developed a new data set providing surface emissions of gases and aerosol for the 1850-2000 period on a decadal basis at the global scale
  - made initial measurements of ammonia, nitrous oxide, and methane from Colorado feedlots
- Demonstrated the importance of local meteorology, including convective venting, on concentrations of ozone measured in 2006 in the Houston area, and showed that ozone concentrations have declined since 2000, presumably as a result of pollution controls adopted in the region in response to CSD’s findings in the 2000 and 2006 Texas Air Quality Studies

<u>Aerosol</u>

- Found that the exhaust fumes from gasoline vehicles contribute more than diesel vehicles to the production of secondary organic aerosols in the Los Angeles area
- Demonstrated, using data from aircraft-based field studies, that nighttime oxidation of isoprene makes a significant contribution to the formation of secondary organic aerosol in the northeastern U.S. in summer
- Showed that the production of sulfate aerosols in the plumes of coal-fired power plants is highly dependent on preexisting aerosol pollution as well as the amount of sunlight and nitrogen oxides

<u>Transport and mixing</u>

- Showed with CalNex data that downward transport of ozone-rich air from the free troposphere and lower stratosphere into the planetary boundary layer contributes to the ozone burden at the surface in the Los Angeles area
- Examined the impact of transported background ozone inflow on summertime air quality in a California ozone exceedance area, finding that that $O_3$ transported on hemispheric scales substantially impacts air quality in some areas of the U.S.
- From lidar measurements made during the 2006 Texas Air Quality Study, found that either deep convection or steady onshore flow lead to improved surface air quality in Houston, but that the latter can significantly increase regional ozone levels as the pollution from the Houston area is transported downwind

Development of instruments, techniques, models

- Developed a new mobile platform (an instrumented van) for measuring agricultural emissions such as ammonia, nitrous oxide, and methane
- Developed the broadband cavity-enhanced spectrometer (BBCES), a high-sensitivity instrument for fast time response measurements of ambient aerosol optical properties
- Advanced the development of NOAA's chemical transport model (WRF-Chem) by improving the parameterization of secondary organic aerosol (SOA), and applied it to analyses of the southeastern U.S. and the Deepwater Horizon oil spill

## 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:

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.

## 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<br>Mitigation and adaptation choices supported by sustained, timely, and reliable climate services<br>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.

## Some Recent Highlights of CSD Research on the Stratospheric Ozone Layer

- A CSD study presented the first explicit calculation of the ozone depletion potential (ODP) of nitrous oxide ($N_2O$), and evaluated the ODP-weighted emissions of anthropogenic $N_2O$ using the same approach as for other ODS emissions, such as CFCs and halons. The research showed that $N_2O$ emission currently is the single most important anthropogenic ODS emission and is expected to remain the largest throughout the 21$^{st}$ century if anthropogenic $N_2O$ emissions continue unabated. The predominant anthropogenic emission of $N_2O$ arises from agriculture-related activities, a widely distributed and growing source. Although $N_2O$ is unregulated by the Montreal Protocol, it is in the Kyoto Protocol's "basket of greenhouse gases." The contribution to ozone depletion from future anthropogenic $N_2O$ emissions is larger than that from other gases (HCFCs, methyl bromide) and ODS banks (ODSs that are already produced but not yet emitted).

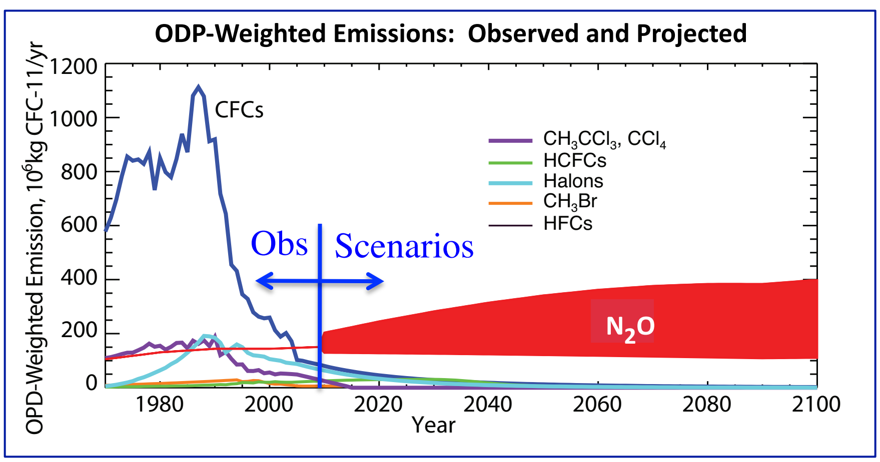


**Figure III-1.** Past observations and future projections of ODP-weighted emissions of various halocarbons and $N_2O$, showing the increasing relative importance of $N_2O$ emissions.

- CSD conducted a detailed laboratory study of the ultraviolet (UV) photolysis of $Cl_2O_2$ (dichlorine peroxide, also referred to as the ClO dimer), a key step in the catalytic destruction of polar stratospheric ozone. This work was in response to another research group's results that indicated the $Cl_2O_2$ photolysis rate was much lower than calculated in current models of stratospheric chemistry using recommended cross section data. The CSD study used multiple methods to re-measure the absolute cross sections over the wavelength range 200−420 nm and refuted the lower rates. The results resolved a major scientific debate, thereby restoring confidence in our understanding of atmospheric chemical mechanisms of polar ozone depletion.

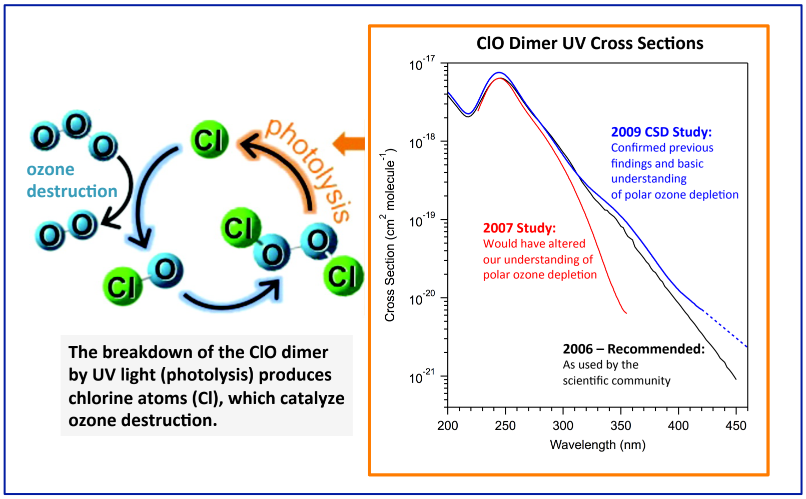


**Figure III-2.** *Left*: The breakdown of the ClO dimer by ultraviolet light (photolysis) produces chlorine atoms (Cl), which catalyze ozone destruction in the stratosphere. *Right*: CSD's 2009 study of the UV cross sections of the ClO dimer confirmed the recommended value and resolved a scientific dispute raised by a 2007 study. The 2009 CSD study was the basis of the subsequent (2010) JPL recommendation.

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- A CSD-led study concluded that initial signs of the recovery of the Antarctic ozone hole will be detectable in the South Pole atmospheric data record within ten years (between about 2017 and 2021). The study focused on the observed ozone loss rates during the 25-year data record. The largest loss rates occur between the end of August and end of September between 50 hPa and 30 hPa. Loss rates at these pressure levels increased by approximately 40% from the late 1980s to the late 1990s and have remained stable within estimated uncertainties since then. To estimate when a reduction in ozone loss rates would be observable outside the range of dynamical variability at the South Pole, the researchers scaled the estimated loss rates to the future projected concentrations of equivalent effective stratospheric chlorine (EESC) and assumed a linear relationship between ozone loss rates and EESC.

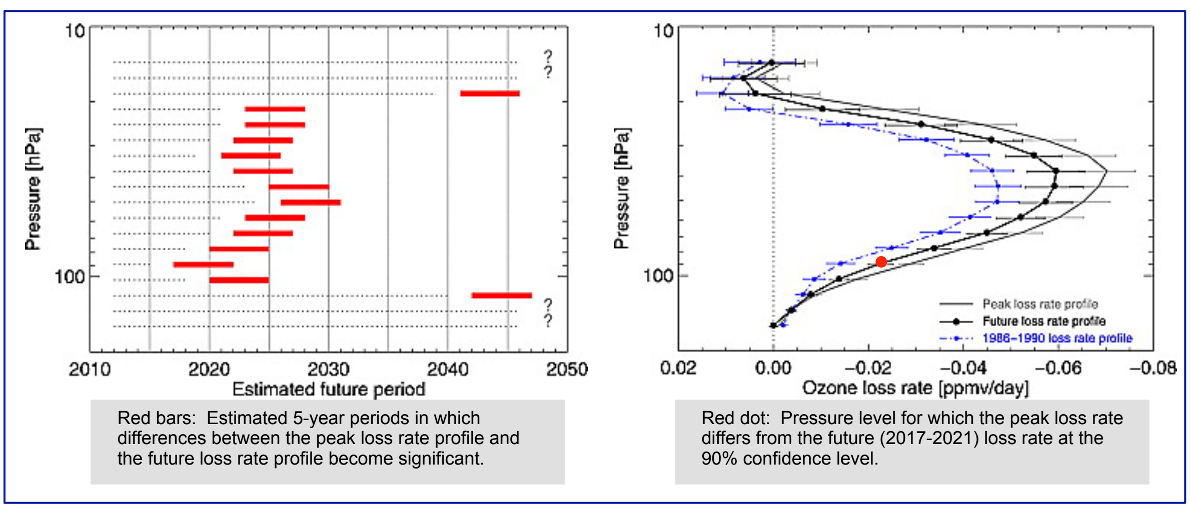


**Figure III-3.** CSD research shows that at most altitudes with the ozone layer, recovery of the Antarctic ozone hole is expected to be detectable between 2017 and 2030, with earliest detection between 2017 and 2021.

## Selected CSD Accomplishments in Stratospheric Ozone Layer Research
**(January 2008 – February 2015)**

Chemical and dynamical processes

- Analyzed ozone trends for the period 1998-2012, finding that measurements do not yet show statistically significant evidence of stratospheric ozone increases
- Demonstrated that differences in three available reconstructions for tropical stratospheric ozone levels lead to uncertainties (up to a factor of two) in the derived temperature trends for the tropical lower stratosphere
- Used an interactive chemical-dynamical model of the stratosphere to show that the nonlinear interactions between halocarbons, $CO_2$, $CH_4$, and $N_2O$ preclude unambiguously separating their effects on ozone, and also to show that by 1980 all of these gases were significantly affecting ozone levels
- Used a tropical pipe model to study factors that affect the "age of air" in the stratosphere, finding that the best quantitative agreement with the observed mean age and ozone trends over the last three decades occurs by assuming a small strengthening of the mean circulation in the lower stratosphere, along with a moderate weakening of the mean circulation in the middle and upper stratosphere and a moderate increase in the horizontal mixing into the tropics
- Analyzed satellite temperature data to assess long-term changes in the mean meridional circulation of the stratosphere that transports ozone; anticorrelated relationships were found, implying statistically significant trends in the stratospheric mean meridional circulation for some months during the year
- Participated in an international ozone trends assessment ($SI^2N$), leading the overview study on data sets, and contributing to the overview studies on trends and on merged data sets
- Built the CSD UAS ozone instrument and flew it on the GloPac, ATTREX, and SEAC4RS aircraft experiments.

Evaluation of ozone-depleting substances (ODSs) and ODS substitutes

- Made laboratory measurements to define the atmospheric degradation chemistry of several current or proposed replacement compounds for ozone-depleting substances, including several relatively short-lived hydrofluorocarbons (HFCs) that are being considered as alternatives to long-lived HFCs as refrigerants in mobile air conditioning applications; and R-316c (1,2-$C_4Cl_2F_6$ (E,Z)), an ozone-depleting and potent greenhouse gas that was being proposed for commercial use but has been withdrawn from consideration because of CSD's findings on its harmful effects on the environment
- Conducted laboratory studies to improve stratospheric lifetime estimates and reduce budget uncertainties: measured UV absorption spectra of $CCl_4$, $N_2O$, $NF_3$, several halons (Halon-1202, -1211, and -2402), and CFC-11 (a major ODS), resolving a longstanding discrepancy for the latter compound; studied the $O(^1D)$ kinetics of several long-lived chlorofluorocarbons (CFCs) for which either limited or no previous data existed (including CFC-113, -113a, -114, and -114a); and studied the $O(^1D)$ kinetics of 11 key CFCs, HCFCs, and HFCs
- Used a new approach that considers seasonal and regional dependence when calculating the fraction of very short-lived ozone-depleting substances (VSLS) that reach the stratosphere, and applied it to calculate how the ozone depletion potentials of very short-lived substances vary with season and emission region. Results showed that there is large regional and seasonal variability in the effective transport of VSLS and that the effect of emissions from the Indian subcontinent is an order of magnitude larger than those from Europe or other middle-latitude source locations.

Science and leadership for Montreal Protocol assessments

- Led and participated as Co-Chair, Lead Authors, Coauthors, Reviewers, and Coordinating Editor of the 2010 and 2014 ozone assessments for the Montreal Protocol
- Provided scientific publications that were cited in the reports' detailed chapters on ozone, ozone-depleting substances, and ozone-climate interactions
- Served as Co-Chair of the Montreal Protocol Scientific Assessment Panel and provided scientific information to the Parties to the Montreal Protocol (all nations have signed the Montreal Protocol)

## 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:

<u>Laboratory studies</u>

- 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.

<u>Dynamical studies</u>

- 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.

<u>Chemical and radiative studies</u>

- 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.

## Some Recent Highlights of CSD Research on Interconnections

- CSD has conducted a number of studies of air quality and climate effects from oil and gas exploration and development activities. (1) Atmospheric measurements near Boulder, Colorado, showed definitively that energy exploration and development activities are the source of very high levels of volatile organic compounds (VOCs), which are precursors for the formation of surface-level ozone pollution. Fugitive emissions from operations include methane, a potent greenhouse gas. CSD research showed that VOCs from oil and gas operations can be clearly differentiated from other fossil fuel-related sources common to urban areas. (2) The results of field studies conducted in the winters of 2012, 2013, and 2014 in Uintah Basin, Utah, demonstrated how unusual episodes of extremely high surface-level ozone were occurring in sparsely populated regions due to emissions from extensive energy development. A CSD-led effort using the air quality model WRF-Chem was the first 3-D model study to accurately simulate the high wintertime ozone events in Utah. (3) A modeling study using an updated Master Chemical Mechanism chemistry scheme with over 10,000 chemical reactions showed that the high levels of VOCs act as the spark for ozone formation during stagnant winter periods when snow cover is present.

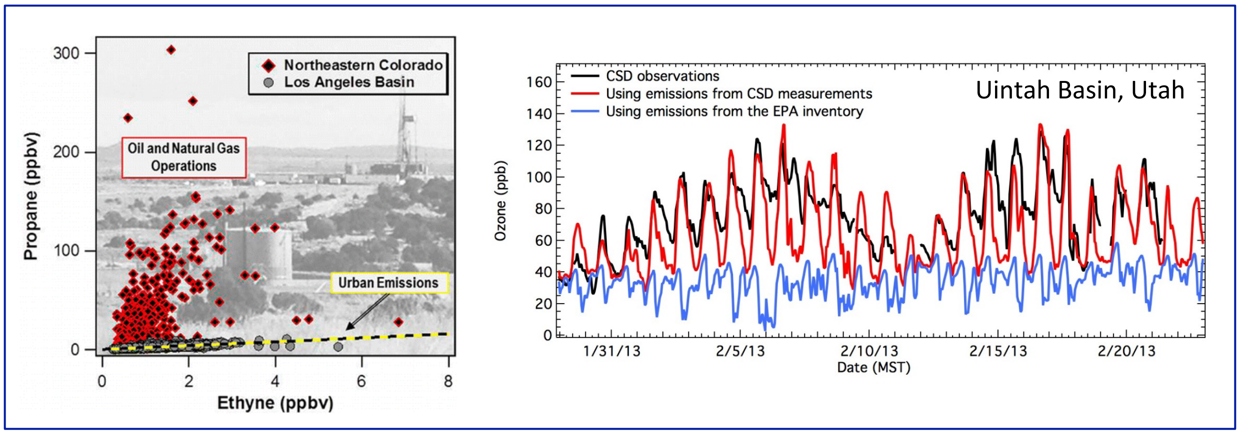


**Figure IV-1.** *Left*: Distinctive signatures of hydrocarbon emissions from oil and natural gas operations versus urban emissions, as measured at the Boulder Atmospheric Observatory in Colorado. *Right:* Three-dimensional model simulations capture the high ozone events observed in Utah in winter when emissions derived from CSD measurements are used.

- CSD research showed for the first time how aerosol controls the two-way transitions between highly reflective closed cellular clouds and much less reflective open cellular clouds. Precipitating clouds prefer the open state while non-precipitating clouds prefer the closed state; the aerosol helps to select the state by controlling precipitation. The frequency of these cloud states has significant influence on the amount of heat absorbed by the planet and is therefore of importance for climate change predictions.

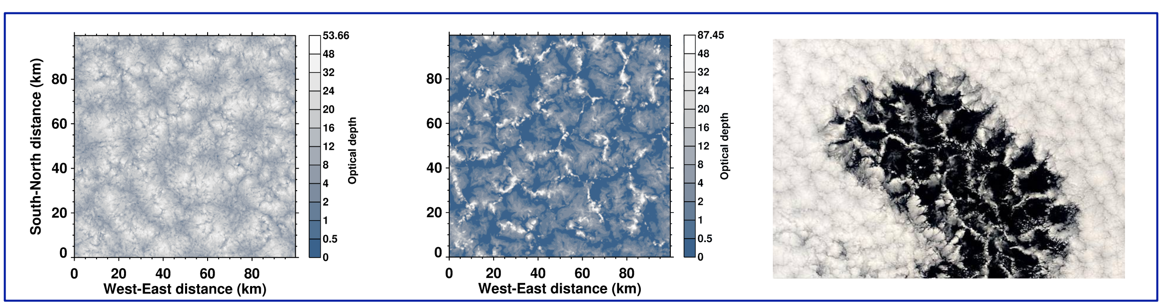


**Figure IV-2.** Snapshots of a model-generated reflective closed cellular cloud state (*left*) and a much less reflective open cellular state (*center*). Similar structures can be seen in NASA/MODIS satellite images (right). CSD research showed that the marine boundary layer aerosol controls which of these states the cloud system will prefer.

- CSD-led research used observations and modeling to show that increases in the abundances of stratospheric aerosols may have offset about a third of the current climate warming influence of carbon dioxide ($CO_2$) change during the past decade, despite an absence of major volcanic eruptions. These results highlight the importance of background variations in the stratospheric aerosol layer for understanding past and future changes in global climate. The increase in aerosols from 2000 to 2010 implies a cooling effect of about 0.1 Watts per square meter – approximately a third of the 0.28 Watts per square meter warming effect from the carbon dioxide increase during that same period. Subsequent CSD research (also mentioned in Climate accomplishments list) showed that aerosols from small to medium-sized volcanic eruptions played a role in the aerosol increase.

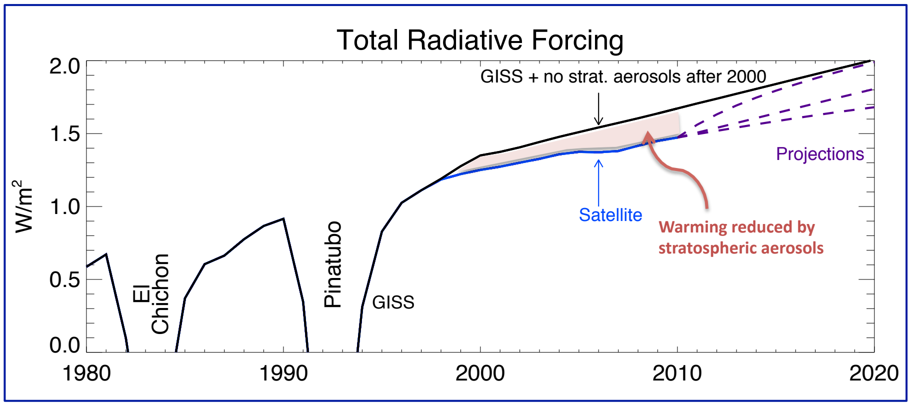


**Figure IV-3.** A 2011 CSD study used climate models to probe how recent and possible future changes in stratospheric aerosol affect global climate forcing. The difference between forcing from the Goddard Institute for Space Studies (GISS) model without stratospheric aerosol changes after 2000 (black line) and the GISS model constrained by satellite aerosol optical depths (blue line) shows the warming reduced by stratospheric aerosol (red shading). After 2010, the model curve with aerosols splits into three future projections (purple dashed lines).

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- CSD research has provided case studies of the interconnection of stratospheric intrusions and air quality: (1) Measurements in the Los Angeles air basin during the 2010 CalNex field mission showed that stratosphere-to-troposphere transport can influence surface ozone in a megacity located at sea level. Several major stratospheric intrusions increased ozone at the surface by 10 to 15 parts per billion by volume (ppbv), and when combined with locally produced ozone led to several exceedances of the current National Ambient Air Quality Standard (NAAQS) on the following day. (2) Measurements near Las Vegas in 2013 (the Las Vegas Ozone Study, LVOS) showed that stratospheric intrusions contributed 10 to 20 ppbv of ozone during the three days that the region exceeded the NAAQS during the study. CSD's research showed that the number of exceedances would increase 4-fold if the NAAQS was lowered from 75 to 70 ppbv, and would increase 20-fold if the standard was lowered to 65 ppbv.

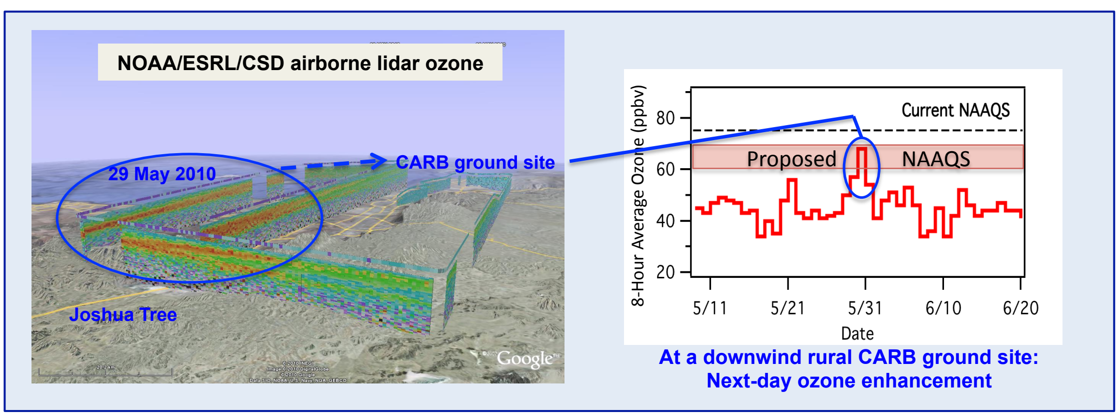


**Figure IV-4.** Vertically resolved lidar observations of identified ozone intrusions (red) from the stratosphere. A downwind ground observation site of the California Air Resources Board detected high levels of ozone at the surface the next day; the levels exceed the proposed new air quality standard.

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## Selected CSD Accomplishments in Research on Interconnections (January 2008 – February 2015)

*Process studies interconnecting air quality, climate, and the stratosphere*

- Led three major field missions to study atmospheric composition at the nexus of climate and air quality: Aerosol, Radiation, and Cloud Processes affecting Arctic Climate (ARCPAC) (2008, Arctic); CalNex (2010, southern California); and SENEX (2013, southeastern U.S.)
- Conducted the 2013 Las Vegas Ozone Study (LVOS) that demonstrated how transport from the stratosphere sometimes contributes to the high surface ozone measured in the Las Vegas area during late spring and early summer, affecting the region's ability to meet National Ambient Air Quality Standard; conducted other studies that showed that stratosphere-troposphere transport influences surface ozone in the Denver region and in a megacity (Los Angeles) located at sea level *(see highlight above)*
- Participated in the 2012 Deep Convective Clouds and Chemistry (DC3) experiment based in the mid-U.S., to investigate how thunderstorms impact ozone in the upper troposphere, where ozone acts as a greenhouse gas
- Used a modern data record to show that ozone in the lower atmosphere has been rising from 1950 to 2010 in the northern midlatitudes, and found that models captured the qualitative but not the quantitative features of the increases
- Analyzed multiple U.S. data sets and found that fine-particle pollution (both total aerosol and black carbon) decreased significantly—by 30% for the annual average—in a broad region across the entire U.S. from 1990 to 2004; showed that the trend is beneficial for air quality, but for climate the net effect of these changes is an additional warming (i.e., not a "win-win")
- Used satellite data coupled to a radiative transfer model to show that on a global scale, there has been little net change to radiative forcing arising from the shift in aerosol pollution sources; namely, the decreased emissions in North America and Europe, and increased emissions in Asia
- Showed that lidar measurements of aerosol properties can be used to classify aerosol types and distinguish different sources of aerosols, such as biomass burning or mineral dust
- Demonstrated that clouds can provide the environment for the transformation of biogenic emissions (isoprene) into secondary organic aerosol (SOA), with implications for both climate and air quality
- Used lidar measurements to show that neither power plant emissions nor long-range transport or stratospheric intrusions cause the high surface ozone episodes in wintertime in the Uintah Basin; and to derive, using a mass-balance approach, urban-scale flux measurements of greenhouse gases and air quality pollutant emissions in California, Indiana, and Texas
- Integrated lidar wake observations into a wind-energy forecasting model, which helped to reduce the forecast uncertainty and improved modeling of wind turbine wakes for single turbines and wind farms
- Developed cavity-enhanced broadband instruments for measuring trace gases (such as glyoxal (CHOCHO), nitrous acid (HONO), and nitrogen dioxide ($NO_2$)) and characterizing atmospheric aerosols, and open-path techniques for measuring aerosol extinction, all of which have been applied in field studies in California and Colorado
- Improved a new commercial instrument to measure bioaerosols (the Wide-band Integrated Bioaerosol Sensor, WIBS) and participated in the 2013 CloudLab airship study to complete the first characterization of bioaerosol from coast to coast across the U.S.
- Developed the broadband cavity-enhanced spectrometer (BBCES) to measure aerosol optical properties, and used it in the southeastern U.S. field campaign (SENEX); showed that decreases in aerosol sulfate relative to organics because of emissions reductions have produced decreases in both aerosol water and aerosol extinction, with both effects leading to reduced aerosol impacts on local climate forcing and visibility

*Process studies interconnecting climate and the stratosphere*

- Showed that the hydrofluorocarbons (HFCs) being used as substitutes for ozone-depleting compounds—and whose use is growing especially in developing countries—may become an increasingly larger factor in future climate warming, and could offset a significant portion of the climate benefits of the Montreal Protocol (*see Climate highlights*)

- Showed that water vapor in the stratosphere increases in tandem with increases in the Earth's surface temperature, generating a climate feedback that adds to climate warming; provided the first quantification of the feedback, finding that it is comparable to the albedo feedback and could be as much as 10% of all the feedbacks that affect climate warming
- Found that the observed pattern of recent Antarctic surface temperature trends (cooling over the high plateau, accompanied by warming in the region of the Peninsula) is largely due to a change in Southern Hemisphere circulation that is related to the ozone hole

*Emissions interconnecting air quality and climate*

- Provided leadership for the Global Emissions InitiAtive (GEIA), a new international community approach to the inventory and modeling of emissions that aims to assimilate information about emissions for use by scientists and decision makers (ongoing)

## 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

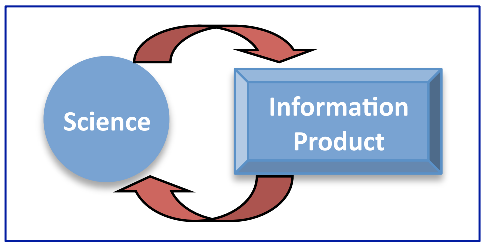
- Within the framework of GEIA (Global Emissions Initiative), improve inventories of air quality-related and climate-relevant emissions through a combination of different approaches that include bottom-up methodologies, new applications of in-situ and remote-sensing observations, and inverse modeling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

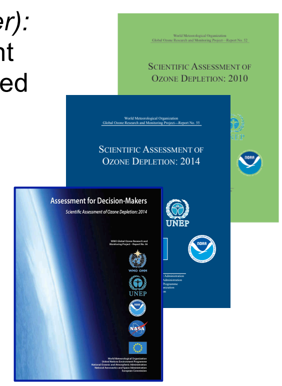
These information products and interactions provide key scientific input to policy and management decisions of industry and local, state, national, and international governments regarding three societally relevant topics:
Climate • Air Quality • Stratospheric Ozone Layer

### Recent Contributions (January 2008–February 2015)

[*See also the Supporting Information document for more detail on these contributions.]*

***National and International Assessment Reports***

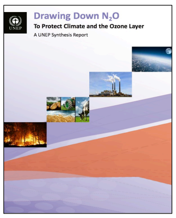
*CSD plays extensive roles in leading, authoring, and reviewing international and national scientific state-of-understanding assessments on the climate system, air pollutants, and the stratospheric ozone layer:*



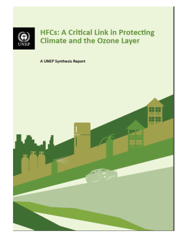
- *WMO/UNEP Assessments for the Montreal Protocol (stratospheric ozone layer):* Served as one of four international Cochairs who led the Scientific Assessment Panel's 2010 and 2014 Ozone Assessments for the Montreal Protocol, prepared under the auspices of the World Meteorological Organization and the United Nations Environment Programme (WMO and UNEP); served as chapter Coordinating Lead Authors, Lead Authors, Coauthors, Contributors, and Reviewers of the 2010 Ozone Assessment, and served as chapter Coauthors and Contributors, and Reviewers, for the 2014 Ozone Assessment. Served as Coordinating Editor for both the 2010 and 2014 Ozone Assessments. Co-led, authored, reviewed, and coordinated the 2014 *Assessment for Decision-Makers*, a new model for the communication of the ozone assessment to policymakers. Impact: Since its inception in 1987, the Scientific Assessment Panel has provided state-of-scientific-understanding assessments to underpin the decisions associated with the protection of the Earth's ozone layer through the United Nations Montreal Protocol on Substances that Deplete the Ozone Layer.

# RESEARCH TO APPLICATIONS


- *IPCC Climate Assessment, Working Group I (Science) (2013):* Served as Chapter 8 Review Editor, Chapter 7 Lead Author, Contributing Authors (5 CSD scientists), and chapter reviewers (11 CSD scientists) of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report. Impact: Since its inception in 1988, the IPCC Working Group I has provided assessments and special reports that have informed policymakers worldwide on the topic of climate change.

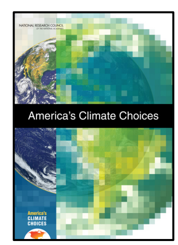



- *UNEP Synthesis Report on “Drawing Down $N_2O$ to Protect Climate and the Ozone Layer” (2013):* Served as two of the ten Lead Authors and as one of two coordinators of this report, which assesses the science behind $N_2O$’s role in climate and ozone depletion, and ways to mitigate its ever-increasing emissions. Impact: This report provides timely information for international discussions, under the Montreal Protocol (Vienna Convention on the Ozone Layer) and the Kyoto Protocol (United Nations Framework Convention on Climate Change), on possible approaches to address anthropogenic nitrous oxide emissions.

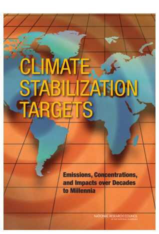



- *UNEP Synthesis Report on “HFCs: A Critical Link in Protecting Climate and the Ozone Layer” (2011):* Served as one of four international scientists who were Lead Authors of the report; two of 19 Scientific and Technical Reviewers; and two of five Contributors of Information/Data. Impact: This report has provided timely information for international discussions on possible approaches to curtail the use of HFCs. This is a major topic under consideration by the Parties to the Montreal Protocol.

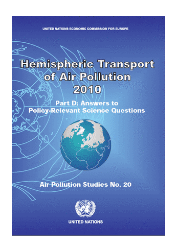

- *USGCRP Synthesis and Assessment Reports (climate):* (1) Served as Agency lead (one CSD scientist), chapter Convening Lead Authors (two CSD scientists), chapter Lead Authors (two CSD scientists), and reviewers (two CSD scientists) of Synthesis and Assessment Product 2.4, “Trends in Emissions of Ozone-Depleting Substances, Ozone Layer Recovery, and Implications for Ultraviolet Radiation Exposure,” 2008; (2) Served as Lead Author of several chapters (one CSD scientist) and Reviewer (one CSD scientist) of Synthesis and Assessment Product 2.3, “Atmospheric Aerosol Properties and Climate Impacts,” 2009. Impact: The USGCRP’s 21 Synthesis and Assessment Products provided a synthesis of the cumulative knowledge on climate to inform U.S. policymakers in their efforts to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change.




- *U.S. National Research Council report on America’s Climate Choices (2011):* (1) Served on the overall Committee of America’s Climate Choices; (2) Served on the panel of the report on “Advancing the Science of Climate Change.” Impact: The America's Climate Choices project was the National Research Council's most comprehensive study of climate change to date. Its report on “Advancing the Science of Climate Change” provided a concise overview of past, present, and future climate change, including its causes and its impacts, and focused on scientific advances needed both to improve understanding of the integrated human-climate system and to devise more effective responses to climate change.

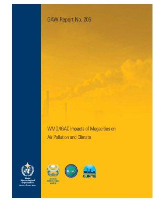



- *US National Research Council report on “Climate Stabilization Targets” (2011):* Served as Chair and leading author of the report. Impact: This report quantifies the outcomes of different stabilization targets for greenhouse gas concentrations, using analyses and information drawn from the scientific literature, and provides information for societal choices regarding future greenhouse gas emissions.




- *UNECE Task Force on Hemispheric Transport of Air Pollution (TF HTAP) Assessment Report (2010):* Participated as Chapter Lead Authors (two CSD scientists) of the first comprehensive assessment of the intercontinental transport of air pollution in the Northern Hemisphere. Impact: This report informs the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution, a 1979 international agreement that fosters cooperation on actions to mitigate air pollution emissions.

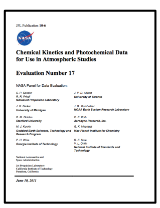
- *"WMO/IGAC Impact of Megacities on Air Pollution and Climate" (2012)*: Served as one of the eight international Lead Authors of this document, which assesses the research about megacities and their role in local to global atmospheric chemistry. Impact: An assessment of the megacities is important for both scientific communities and policymakers dealing with urbanization, air quality management, and climate change.



**Assessment activities that primarily serve the scientific community, but underpin the efforts of other assessments:**

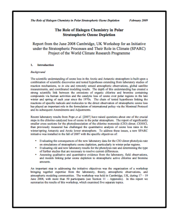
- *IGAC Black Carbon Assessment, "Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment" (2013):* Served as one of three Coordinating Lead Authors and one of the Contributing Authors of this international assessment of the role of black carbon in climate, carried out under the auspices of the International Global Atmospheric Chemistry Project (IGAC) of the International Geosphere-Biosphere Programme. Impact: This assessment informs research efforts, climate modeling, and policy discussions regarding black carbon.

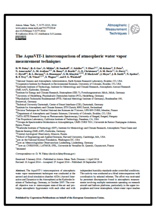
- *SPARC Lifetimes Report (2013):* Served as one of the Lead Authors of this report, as a Coauthor, and as four of the reviewers. This report updates the state of understanding on the atmospheric lifetimes of trace gases that are important to climate and stratospheric ozone. Impact: This assessment provides key input for international (IPCC and WMO/UNEP) scientific assessments on climate and the ozone layer.



- *Jet Propulsion Laboratory Kinetic Data Evaluation Panel:* Served as one of twelve international Panel Members of this periodic data evaluation (latest evaluation: 2011). Impact: This evaluation dates back to 1977; it provides evaluated chemical kinetics and photochemistry information used in modeling of atmospheric chemistry, and underpins international assessments on the ozone layer and climate.

- *SPARC Report on "The Role of Halogen Chemistry in Polar Stratospheric Ozone Depletion" (2009)*: Served as two of the Steering Group members and three of the reviewers of this assessment, which evaluated new research regarding the photochemistry of the chlorine monoxide dimer. Impact: This evaluation resolved a major issue regarding the chlorine monoxide dimer and confirmed the scientific community's understanding of halogen chemistry related to the polar ozone layer. It figured prominently in the 2010 WMO/UNEP Ozone Assessment.





- *Water Vapor Techniques Intercomparison (2014)*: Served as Lead Author, two Coauthors, and two Referees of the Aqua-VIT water vapor techniques assessment. Impact: This assessment supports improved climate projections by helping to resolve discrepancies among water vapor measurements on different platforms and made by different instruments.

***Governmental (National and International)***

*CSD has actively participated in synthesizing information for decision makers at national and international levels:*

- *Parties to the Montreal Protocol:* Service as Cochair of the Montreal Protocol Scientific Assessment Panel, and providing ozone-layer science and understanding at meetings of the Montreal Protocol (A.R. Ravishankara)

- *U.S. State Department:* Provided scientific information and expertise on climate, as well as on ozone-layer science and understanding (the latter in the context of the Montreal Protocol)
- *U.S. Environmental Protection Agency:* Provided scientific information and expertise on climate, ozone-layer depletion, and air quality (stakeholders at national and regional levels of EPA)
- *Capitol Hill briefings and testimony:* (1) Provided briefings to Congressional staff and members on topics in air quality and climate, as well as briefings regarding CSD's research findings and capabilities developed during the Deepwater Horizon oil spill (A.R. Ravishankara); (2) Gave testimony to the Subcommittee on Aviation of the House Committee on Transportation and Infrastructure, at a hearing on the topic of "Aviation and the Environment: Emissions" (D.W. Fahey).
- *Congressional staff briefings:* Gave briefings to various staffers, during visits as well as teleconferences, on topics such as air quality, climate, and atmospheric issues related to oil and gas development

***Governmental (State and Local): Regional Assessments for Air Quality, Climate***

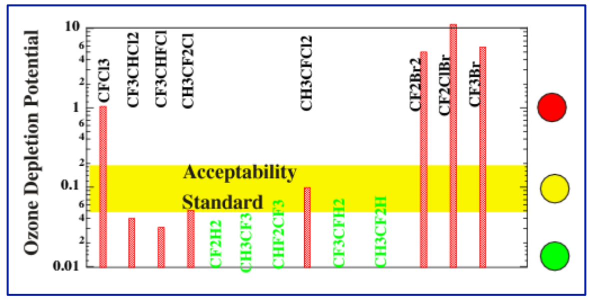
*CSD also provides focused U.S. regional assessments to support air quality and climate decision making at state and local levels. Working with stakeholders, CSD identifies information needs, and then designs and carries out research studies to meet those needs. CSD works closely with stakeholders to provide the information in forms that will be most useful, including reports and briefings. Some recent examples:*

- *California:* Worked with stakeholders in the California Air Resources Board and EPA Region 9 to design and carry out the 2010 CalNex field mission; communicated findings in a science synthesis report, workshops, scientific meetings, and several publications in the peer-reviewed literature
- *Deepwater Horizon Oil Spill:* Provided a rapid-turnaround report on air chemistry during the 2010 Deepwater Horizon Oil Spill; the report gave unique and urgently needed information about air quality in the vicinity and downwind of the DWH spill site
- *Texas:* Continued to provide information and analyses to stakeholders in the Texas Commission on Environmental Quality regarding findings from the 2000 and 2006 Texas Air Quality Studies
- *Utah:* Worked with the Utah Department of Environmental Quality and EPA Region 8 to design and carry out three field campaigns (2012, 2013, 2014) to study the air quality implications of oil and gas exploration activities in Uintah County, focusing especially on determining the processes involved in episodes of high surface ozone in wintertime
- *Nevada:* Worked with Clark County Department of Air Quality to carry out a 2013 field study to investigate the role of stratospheric intrusions during episodes of high surface ozone near Las Vegas
- *Colorado:* Provided scientific information to the Regional Air Quality Council, the lead air quality planning agency for the Denver Metropolitan area; EPA Region 8; the Colorado Department of Public Health and Environment; and local municipalities regarding CSD measurements near oil and gas fields north of Denver

***Industry and Non-Governmental Organizations***

- *Oil & gas organizations*: Concerning our research related to atmospheric implications of activities related to oil and gas exploration/extraction, CSD is interacting with several organizations related to energy development, including the Colorado Oil and Gas Conservation Commission; Western Energy Alliance; and the Western Regional Air Partnership. In the period since the 2008 science review, CSD has published several papers on emissions related to oil and gas activities, based on data gathered in its field missions in Colorado, Utah, California, and the eastern U.S.
- *International Maritime Organization:* CSD has provided information to the IMO on the emissions of black carbon and other atmospheric pollutants from shipping, especially in the context of potential future impacts of shipping on the Arctic. In the period since the last CSD review, CSD has published several papers on shipping emissions, based on data gathered in its field missions in Texas and California.
- *International Civil Aviation Organization*: CSD has a long history of providing scientific information and expertise to the ICAO regarding emissions from aviation, particularly as they relate to climate.

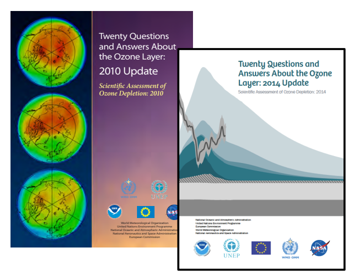
- *Chemical industry*: For over 25 years, CSD has been the honest broker of information about the climate and ozone-layer impacts of substances that industry proposes for a variety of societal uses such as refrigeration, air conditioning, electronic manufacture, and fire protection. CSD has carried out laboratory and modeling evaluations of dozens of substances and gained the reputation among industries and governments as the go-to laboratory for such information.




In the period since its 2008 science review, CSD assessed several potential replacement compounds:

| Compounds Evaluated in the 2008-2014 Time Frame | Potential Use | Safe for climate? | Safe for stratospheric ozone layer? |
|---|---|---|---|
| Methyl perfluoro heptene ethers, MPHEs: $C_7F_{13}OCH_3$ (6 isomers) | Heat transfer fluid | Yes | Yes |
| Hydrofluoro-olefin, HFO-1234yf: $CF_3CF{=}CH_2$ | Refrigerant for automobile air conditioners (replace R-134a) | Yes | Yes |
| Hydrofluoro-olefin, HFO-1225ye(Z): $CF_3CF{=}CHF$ | Industrial refrigerant; medical propellant | Yes | Yes |
| Hydrofluoro-olefin, HFO-1233zd (E,Z): $CF_3CCl{=}CH_2$ | Foam blowing agent; refrigerant | Yes | Yes |
| Sulfuryl fluoride: $SO_2F_2$ | Fumigant insecticide ($CH_3Br$ replacement) | No | Yes |
| $CH_2{=}CF_2$, $CH_2{=}CHF$ | Indicative of fluoroalkenes | Yes | Yes |
| (Z)-$CF_3CH{=}CHCF_3$ | Foam blowing agent | Yes | Yes |
| R-316c (E,Z): c-$C_4Cl_2F_6$ | Medical and commercial uses | No | No |

***The Public/Students/Educators***




- *Stratospheric Ozone Depletion:* Led in authoring the 2010 WMO/UNEP Ozone Assessment's "Twenty Questions and Answers about the Ozone Layer" document, and coauthored its 2014 update. These documents are distributed worldwide to decision makers, educators, students, and the public.
- *NOAA Fact Sheets:* Provided expertise in NOAA's efforts to produce informational fact sheets on topics of wide interest; contributed to fact sheets on air quality, aerosols, and geoengineering
- *Web stories and press releases:* Contributed to dozens of stories for NOAA, OAR, CSD, and CIRES websites, as well as to several NOAA and CIRES/University of Colorado press releases
- *Outreach events:* Contributed to numerous outreach events for the public and students, and provided leadership for NOAA committees that deal with outreach, diversity, and Equal Employment Opportunity (EEO)
- *Education/career development:* Contributed expertise and information for next-generation atmospheric scientists, including giving invited presentations at international focused trainings and lecture series for graduate students, and serving on thesis committees for graduate students in the atmospheric sciences

### *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.

A special case (currently in progress) that illustrates the transition of CSD research to applications (RtoA) is described below.

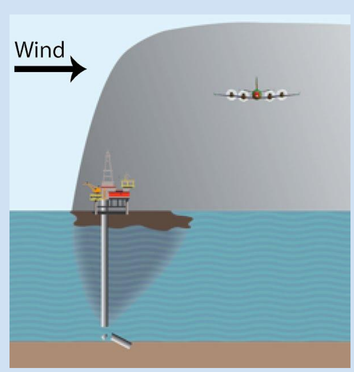
**A Special Case of Research to Applications *In Progress*:**
**CSD's Groundbreaking Work During the Deepwater Horizon Oil Spill**

CSD scientists made detailed air chemistry measurements during the 2010 Deepwater Horizon oil spill and used them to develop a new, independent method for accurately estimating the subsurface oil leak rate (results agreed well with other estimates), and for determining the fates of the spilled oil in the ocean and atmosphere. The measurements also provided insights about air pollution implications for the recovery/cleanup workers and coastal residents in the Gulf, as well as new discoveries related to air quality and climate regarding the formation of organic fine particles (aerosols) in the atmosphere.

Based on the successful first demonstration of the technique during Deepwater Horizon, and a second successful application during the 2012 Elgin spill in the North Sea, CSD has proposed that NOAA invest resources to develop a standing capability for the airborne assessment of future oil spills.

Detailed air chemistry measurements by CSD provided key information on air quality to NOAA, EPA, and OSHA within hours of the response flights during the Deepwater Horizon oil spill. Other payoffs included:

- new understanding of how organic aerosols form in the atmosphere
- an independent estimate of the subsurface oil leak rate
- successful first demonstration of the potential for a rapid-response assessment capability for future offshore oil spills in remote locations



## Partnerships and Collaborations
### *Synergies through Vital Partnerships*

*[See also the Supporting Information document for more detail on collaborations.]*

***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).

**For journal articles in 7 recent years (January 2008 to February 2015):**

Papers with co-authors outside of CSD: 86%

Papers with co-authors from elsewhere in NOAA: 20%

Papers with co-authors from non-U.S. institutions: 44%

Papers with co-authors from academia: 72%

Papers with co-authors from private sector research organizations or industry: 11%

In addition to these basic scientist-to-scientist collaborations, CSD has been involved in many jointly planned and jointly conducted field campaigns, in which inter-organizational breadth was one of the key factors in the capability to carry out the campaign. Recent examples include missions in which CSD has taken the lead and involved multiple partners (e.g., ARCPAC in 2008; CalNex in 2010; Uintah Basin Winter Ozone Study (UBWOS) in 2012, 2013, and 2014; and SENEX in 2013); NASA-led missions for which CSD provided significant scientific leadership and contributions (e.g., GloPac in 2010; MACPEX and ATTREX in 2011; and SEAC4RS and Discover-AQ in 2013-2014); and other U.S. and internationally led endeavors in which CSD participated (e.g., VOCALS in 2008; DYNAMO and HIPPO in 2011).

***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 for Science**

- 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)
- Academia
- Private Sector / Industry
- International

**Key Partnerships for Decision-Support Information**

- U.S. Agencies (e.g., EPA, State Department)
- WMO / UNEP
- State/Local Organizations (e.g., CARB, TCEQ, Utah DEQ)

NOAA ESRL Chemical Sciences Division Review
30 March – 1 April 2015
Boulder, Colorado