National Oceanic and Atmospheric Administration
Air Resources Laboratory

Strategic Plan for Climate Research and Development

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PREFACE

The purpose of this plan is to identify general directions and potential opportunities for climate research and development at the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL). ARL's climate team met with a variety of stakeholders to discuss current and future climate research needs and then considered these needs and the Lab's capabilities. From a broad range of possibilities, the team identified the topic areas in which ARL could make the greatest contributions consistent with resource constraints. ARL will be pursuing work in the described areas and developing more detailed plans as appropriate.

The intended audiences for this plan include current and future ARL staff; NOAA line office, program, and goal staff; and current and future collaborators. It is hoped that this plan will help those groups better understand the themes and directions of ARL's climate research activities, leading to better recognition of ARL's activities, better integration with and support of NOAA's mission, and enhanced collaborations. ARL expects the ideas presented in this plan to evolve as climate issues and needs and NOAA's plans for a National Climate Service evolve.

ARL appreciates the valuable input the following people provided during the development of this plan:

Dr. Krisa Arzayus , National Oceanic and Atmospheric Administration, Climate Program Office
Rona Birnbaum, U.S. Environmental Protection Agency, Office of Atmospheric Programs
Dr. Antonio Busalacchi, University of Maryland, Department of Atmospheric and Ocean Science and Earth System Science Interdisciplinary Center
Neil Christerson, National Oceanic and Atmospheric Administration, Climate Goal
Howard Diamond, National Oceanic and Atmospheric Administration, National Climatic Data Center
Alan Cohn, U.S. Environmental Protection Agency, Office of Atmospheric Programs
Dr. Wayne Higgins, National Oceanic and Atmospheric Administration, Climate Prediction Center
Dr. Carey Jang, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards
Dr. Thomas Karl, National Oceanic and Atmospheric Administration, National Climatic Data Center
Craig Long, National Oceanic and Atmospheric Administration, Climate Prediction Center
Dr. Alexander MacDonald, National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research
Dr. Chris Miller, National Oceanic and Atmospheric Administration, Climate Program Office
William Murray, National Oceanic and Atmospheric Administration, Climate Program Office
Sharon Phillips, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards
Dr. Richard Rosen, National Oceanic and Atmospheric Administration, Climate Program Office
Jason Samenow, U.S. Environmental Protection Agency, Office of Atmospheric Programs

EXECUTIVE SUMMARY

Climate change will likely be the most serious and far-reaching environmental challenge of the 21st century. The National Oceanic and Atmospheric Administration's (NOAA) climate program, in collaboration with other agencies, provides the scientific underpinning of the Nation's climate policies and plans. NOAA's goal is to "understand climate variability and change to enhance society's ability to plan and respond." In achieving that goal, NOAA provides the observations, analyses, research, data and information products, projections and decision support required by climate policy-makers and planners. Many NOAA components support that goal in various ways. NOAA's Air Resources Laboratory (ARL), working with other NOAA labs and centers and with external partners, provides unique and important contributions that complement and support multiple NOAA and national activities and that help satisfy many of NOAA's climate mission requirements.

ARL has a long history of climate research with significant accomplishments spanning more than 40 years. The Lab's future contribution to the overall NOAA research effort has two primary foci: (1) **Observing Climate Variability and Change** and (2) **Assessment of Regional Climate Impacts**. Both research activities result in data and information products that support other components of the NOAA Climate Goal. These activities are well aligned with NOAA's and the Nation's needs for climate information and services and with ARL's resources and historic strengths. ARL conducts all of these activities in close cooperation with a number of government and academic partners.

ARL's capabilities and plans for **Observing Climate Variability and Change** fall into two program areas: Reference Observations, focused on the design, establishment, operation, maintenance and analysis of *in situ* atmospheric climate reference observations in the U.S. and internationally, and Climate Variability and Change Analysis, aimed at documenting and understanding diurnal to multi-decadal climate variations and at detecting long-term climate changes in the context of both shorter-term variability and observational uncertainty. Both activities support the development of data sets and insights required to understand the climate system and to evaluate other observing (e.g., satellites) and modeling systems.

Work on reference observations is primarily organized around several networks. ARL plays a key role in the U.S. Climate Reference Network and U.S. Historical Climatology Network Modernization project, both of which will provide long-term observations of key climate parameters at the Earth's surface. ARL and its partners have also developed the Surface Energy Budget Network, which provides a detailed examination of the land-surface and related radiative processes that can drive regional climate. In addition, ARL has provided leadership for the development of the Global Climate Observing System Reference Upper-Air Network, which will ensure that future climate scientists will be able to identify upper-air climate change signals in observational data more confidently than is now possible. ARL's activities in these and related networks are expected to expand in the future.

The prime objective in Climate Variability and Change Analysis is to advance understanding of climate variability and change by continuing to document and analyze diurnal to multi-decadal variations in the global climate system, with emphasis on analysis of upper-air observational data and data quality issues. ARL has more than three decades of experience in analysis of observed climate variability and change and has made significant contributions to understanding past atmospheric changes at the surface and in the upper-air. In the future, ARL will extend its work in this area to further investigate long-term

changes in clouds, particularly as they may relate to climate feedback mechanisms and to air quality changes, and possible changes in aspects of atmospheric circulation, including jet streams and storm tracks. The program will also involve study of the relationships between circulation changes, temperature changes in the troposphere and stratosphere, and tropopause region changes.

ARL's capabilities and plans for **Regional Climate Impacts** involves development and evaluation of modeling tools for simulating climate and related processes on regional scales for application to climate problems involving air quality, water resources, ecosystems, and extreme events. This work falls into two program areas: (1) Climate Modeling at the Weather-Resolving Scale, which links global scale climate to regional-scale mesoscale conditions, (2) Assessment of Regional Climate and Air Quality Interactions, which is focused on the potential impacts of regional-scale climate variability and trends and of climate and air quality mitigation measures on future air quality conditions.

The prime objective of the Climate Modeling at the Weather-Resolving Scale activity is to provide regional climate tools and projections to support well informed decision making on climate policies and plans. ARL's role currently in this area is coordination and support of external development of the Climate extension of the Weather Research and Forecast model. The model has been applied or is being considered for studying multiple issues, such as water availability. In the future, availability and development of the modeling system and ARL's technical activities will be enhanced.

The prime objective of Assessment of Regional Climate and Air Quality Interactions is to develop modeling tools and information for climate and air quality decision-makers on the interactions of climate and air quality and mitigation measures for each. Those issues have mutual interactions. For instance, aerosols are a key issue for both air quality and climate. Decision-makers need to understand such interactions to find approaches that achieve both air quality and climate benefits. After a recent reorganization, ARL is working towards rebuilding its capabilities to provide models and related information to address such issues.

STATEMENT OF NEED

Climate change will likely be the most serious and far-reaching environmental challenge of the 21st century. The Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) concluded that "warming of the climate system is unequivocal" and that "observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes." While these strong statements underscore the scientific consensus that climate change is real, there remains much to learn about the details of past and projected future change.

Weather and climate influence every sector of society. Weather and climate sensitive industries, both directly and indirectly, account for about one-third of the Nation's GDP[1]. Changes in the climate can influence economic prosperity, human[2] and environmental[3] health, and national security[4]. The annual variation in U.S. economic activity attributable to weather variability exceeds $260 billion[5]. AR4 stated that "Altered frequencies and intensities of extreme weather, together with sea level rise, are expected to have mostly adverse effects on natural and human systems." Citizens, communities, businesses, governments at all levels, and international organizations are demanding climate information and products to cope with climate variability and to adapt to and mitigate climate change.

The National Oceanic and Atmospheric Administration's (NOAA) climate program, in collaboration with other agencies, provides the scientific underpinning of the Nation's climate policies and plans. NOAA's goal is to "understand climate variability and change to enhance society's ability to plan and respond." In achieving that goal, NOAA provides the observations, analyses, research, data and information products, projections, and decision support required by climate policy-makers and planners. Many NOAA components support that goal in various ways. As described below, NOAA's Air Resources Laboratory (ARL), working with other NOAA labs and centers and with external partners, provides unique and important contributions that complement and support NOAA's and the Nation's activities.

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[1] Dutton, John A., *Opportunities and priorities in a new era for weather and climate services,* Bulletin of the American Meteorological Society, September 2002, volume 83, no. 9, pp 1303-1311.

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[3] CCSP, 2008: The effects of climate change on agriculture, land resources, water resources, and biodiversity. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. P. Backlund, A. Janetos, D. Schimel, J. Hatfield, K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, D. Wolfe, M. Ryan, S. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, W. Schlesinger, D. Lettenmaier, D. Major, L. Poff, S. Running, L. Hansen, D. Inouye, B.P. Kelly, L Meyerson, B. Peterson, R. Shaw. U.S. Environmental Protection Agency, Washington, DC., USA, 362 pp . http://www.climatescience.gov/Library/sap/sap4-3/final-report/default.htm

[4] National Intelligence Assessment on the National Security Implications of Global Climate Change to 2030, House Permanent Select Committee on Intelligence House Select Committee on Energy Independence and Global Warming, 25 June 2008, Statement for the Record of Dr. Thomas Fingar. http://www.dni.gov/testimonies/20080625_testimony.pdf

[5] Harrod, Megan, Peter H. Larsen, Jeffrey K. Lazo, and Donald M. Waldman. 2007. "Sensitivity of the U.S. Economy to Weather Variability" NCAR Societal Impacts Program, Boulder, Colorado, working paper.

AIR RESOURCES LABORATORY GOALS

ARL has a long history of climate research with significant accomplishments spanning more than 40 years (see Appendices A and B for selected publications and milestones). The Lab's future contribution to the overall NOAA research effort has two primary foci: (1) **Observing Climate Variability and Change** and (2) **Assessment of Regional Climate Impacts**. These research activities produce data, information products, and tools that support other components of the NOAA Climate Goal. Both ARL programs have a foundation in expertise and capabilities in atmospheric modeling, observations, and analyses developed over the laboratory's 60-year history. Observing climate variability and change has two components, one addressing climate observations per se and developing reference observing systems to meet climate requirements, and a second analyzing long-term observational datasets to understand climate variability and change on diurnal to multi-decadal time scales. Assessment of regional climate impacts involves development and evaluation of modeling tools for simulating climate processes on regional scales for application to climate problems involving air quality, water resources, ecosystems, and extreme events.

By working closely with partners throughout NOAA and by collaborating with U.S. and international colleagues in other agencies, academia, and the private sector, the ARL climate research program has leveraged a relatively small effort to yield significant results with broad impact. Within NOAA's overall climate research capabilities, ARL's strengths include collection and analysis of *in situ* climate observations, and regional modeling of atmospheric constituents and near-surface characteristics. Plans for the future involve building on this experience to more fully support the emerging NOAA National Climate Service.

Outreach and education are an integral part of climate research and development at ARL, where we believe that the results of publicly-supported scientific research are only of value to the extent that they have been understood by others and integrated into their thinking, planning, and decision-making. A first step in this communication process involves connecting with the scientific community through publication of research results in peer-reviewed journals and participation in scientific conferences, seminars and workshops. Communication with decision-makers and stakeholders in government and the private sector is a coordinated activity, often focused on scientific assessments that integrate results from many research teams. Opportunities for outreach to the general public, and in particular with students, are numerous, varied, and challenging, but ultimately very fulfilling and critically important. By reaching out to non-scientific audiences and to young people, ARL helps NOAA realize its overarching vision: An informed society that uses a comprehensive understanding of the role of the oceans, coasts, and atmosphere in the global ecosystem to make the best social and economic decisions.

Rationale for Selecting Those Goals

ARL selected the above goals based on the following factors:

- They each address important unmet societal needs for information about climate trends, variability, and projections.
- They support NOAA's goals and mission requirements and complement climate research and development performed at NOAA, other agencies, and academic institutions.

- They are aligned with ARL's lab-wide focus and expertise on *in situ* observing systems, regional and local modeling, and the two-way interactions between the atmosphere and the land surface, including society and ecosystems.
- They are consistent with reasonable assumptions about resources. There are many other areas where ARL could make key contributions given additional resources. The Lab's climate planning team felt that spreading ARL's limited staff too thinly would harm the success of the research.
- They are logically related. For instance, knowledge about reference observing system characteristics is necessary to identify discontinuities and other issues with the climate record that complicate analysis of climate variability and change. Those observing systems are also key sources of measurements used to compute trends and variability. Further, research on climate variability and trends can provide insights on requirements for new observing systems. Deploying research networks to study surface energy budgets provides the expertise required to design instrument suites for "operational" climate networks, which can then provide additional opportunities for conducting research. In addition, reference observations and analyses of climate trends and variability are essential for the development and evaluation of regional impact models. Finally, work on climate-air quality interactions complements ARL's ongoing research and development on models for air quality forecasting.

Connections with NOAA's Requirements and Goals

ARL's goals directly support multiple NOAA mission requirements and goals as expressed in NOAA's program charters and strategic and research goals. These connections are summarized in Appendix C.

BENEFITS

ARL's climate research and development provides essential observations and analyses for monitoring climate variability and change and understanding why they are occurring. National and international climate scientists and decision-makers use this information to understand climate trends and the need for mitigating and adapting to climate change. ARL's research has contributed to a number of climate change assessments, including the work of the Intergovernmental Panel on Climate Change and the U.S Climate Change Science Program.

ARL has also contributed to models that can be used to project weather patterns that would be associated with climate change. For instance, models may show how water availability, air quality, and severe weather would be affected by climate change, information that regional managers need to make informed decisions.

CAPABILITIES AND PLANS

Observing Climate Variability and Change

ARL's capabilities and plans for **Observing Climate Variability and Change** fall into two program areas: Reference Observations, focused on the design, establishment, operation, maintenance and analysis of *in situ* atmospheric climate reference observations in the U.S. and internationally, and Climate Variability and Change Analysis, aimed at documenting and understanding diurnal to multi-decadal climate variations and at analyzing long-term climate changes in the context of both shorter-term variability and observational uncertainty.

Reference Observations

Until recently, data for analysis of climate change were essentially compilations of archived weather observations, sometimes with additional quality control applied, but without the long-term quality and continuity essential for unambiguous identification of climate trends. Changes in instruments, observing methods, station locations, and data processing methods all introduce time-varying biases that could be mistaken for, or mask, real climate changes. Now it is recognized that reference observing networks, dedicated to meeting climate needs, are needed both to monitor climate change *in situ* and to calibrate measurements from other observing systems (particularly satellites) to make them more suitable for climate work. Providing a consistent reference network across the U.S. will likely be a core component of a National Climate Service and contribute to a fully global climate observing system.

Objectives

The prime objective of this activity is to support the design and implementation of some key components of the Global Earth Observation System of Systems (GEOSS) and Global Climate Observing System (GCOS), under the auspices of the United Nations Framework Convention on Climate Change. ARL's specific contributions are founded on demonstrated expertise and experience. They aim to ensure that reference-quality *in situ* observations are available for climate monitoring and research and to provide calibration for spatially more complete satellite and *in situ* observations. Four networks are the focus of the ARL reference observations program.

Current Capabilities and Key Accomplishments

ARL has a proven track record in providing instrument development, testing, and deployment for the *US Climate Reference Network*; operating a *Surface Energy Budget Network* for climate and micrometeorological studies; and providing leadership for the establishment of the US Historical Climate Network—Modernization and the *GCOS (Global Climate Observing System) Reference Upper-Air Network*.

U.S. Climate Reference Network

NOAA has established the US Climate Reference Network (USCRN) to provide climate quality benchmark observations for air temperature and precipitation that fulfill the national commitments to monitor the U.S. climate for the next 50-100 years. What sets this climate monitoring network apart from others is

the careful attention to site selection, triple sensor redundancy (for air temperature and precipitation), calibrations to National Institute of Standards and Technology standards, careful documentation and archiving of site metadata, and a strong coupling to the science and research components of the program. ARL partners with the National Climatic Data Center (NCDC) on this project. ARL has provided leadership on sensor measurements and calibration, data acquisition, data communications, and analysis and testing of emerging sensor technology for future climate applications and services. ARL also maintains the network, which achieves a data availability rate in excess of 99%. In 2008, ARL completed CRN deployment in the continental U.S., started adding soil moisture/temperature sensors to those sites, began installation of additional stations in Alaska, and developed plans for installation of similar equipment at some international sites.

US Historical Climatology Network-Modernization

The Historical Climatology Network Modernization (HCN-M) project was initiated in response to the need for the most accurate, unbiased, modern climate record for detecting climate change in various U.S. regions over the next 50 –100 years. The HCN, a sub-network of 1221 Cooperative Observer Network (COOP), are maintained by the NOAA's National Weather Service, and the HCN data set is maintained by NCDC. Approximately 1000 of the HCN stations will be modernized using similar technology and calibration standards from the U.S. CRN program. In the first phase, the technology teams from ARL will be utilized to complete the initial 150 pilot deployments in the Southwestern U.S. ARL's partners in this are NCDC and the National Weather Service. This activity builds on the initial 17 HCN-M prototype sites which ARL installed in Alabama from 2005-2008 in partnership with NCDC.

Surface Energy Budget Network (SEBN)

ARL is partnering with NOAA's Earth System Research Laboratory Global Modeling Division's (ESRL/GMD) to provide a detailed examination of the land-surface and related radiative processes that can drive regional climate. The Surface Energy Budget Network (SEBN) combines prior separate efforts for the Global Energy and Water Cycle Experiment (GEWEX) and the Surface Radiation (SURFRAD) network to holistically measure the response of terrestrial ecosystems to climate forcing at the earth's surface. This is quantified by measuring not only the sensible heat flux and evapotranspiration, but also the magnitude of CO_2 uptake by the land surface. Understanding the land-surface feedbacks as climate changes will be the critical underpinning of parameterizations in climate models. A network of seven high-quality SEBN climate stations fully characterizing the components of the surface energy balance (radiation, sensible, latent and ground heat fluxes) is currently deployed within representative ecosystems in the U.S. to improve our understanding of both radiative and non-radiative forcing of climate.

GCOS Reference Upper-Air Network (GRUAN)

ARL's involvement in the *GCOS Reference Upper-Air Network (GRUAN)* is closely linked to ARL Climate Variability and Change Analysis research and is motivated by a desire to ensure that future climate scientists will be able to more confidently identify upper-air climate change signals in observational data than is now possible. Having identified significant deficiencies in operational radiosonde data vis a vis climate needs, ARL has articulated the scientific need for the network, performed analyses of observational requirements, and provided international leadership in the initiation of the GRUAN.

In 2004, ARL developed a whitepaper articulating the need for better upper air observations for support of climate research and monitoring and has continued to be a driving force behind the GRUAN. Now GRUAN is a reality with a Lead Center in place and network operations slated to begin in 2009. Through the international Working Group for Atmospheric Reference Observations, ARL continues to provide leadership for this network.

Products

Data from the existing reference observations systems are publicly available. These data support the analysis of climate variability and trends. Observations from SEBN support development of improved understanding about the physical processes the influence climate. These observations are also used by modelers to evaluate land surface and other parameterizations.

CRN observations are available from

http://www.ncdc.noaa.gov/oa/climate/uscrn/index.html

High quality climate data and products for all sites in near-real time for the following SEBN components can be found at the following locations:

http://www.srrb.noaa.gov/surfrad/ (NOAA SURFRAD)
http://www.atdd.noaa.gov/gewex.htm (NOAA flux sites)

Partners

ARL's partners in these activities include the following:

- NOAA National Climatic Data Center is a partner on USCRN and HCN-M projects and archives USCRN, HCN-M, and SEBN data and metadata.
- NOAA Regional Climate Centers provide site surveys and contact information for existing and potential climate stations for HCN-M and USCRN.
- NOAA Climate Program Office supports ARL's research activities and the development of plans for climate activities.
- NOAA Earth System Research Laboratory Global Monitoring Division is a partner in SEBN and provides calibration activities for other radiation observations.
- State climatologists assist in selecting and maintaining sites for USCRN and HCN-M.

Plans for Future Work

Over the next few years, ARL's USCRN activities will be focused on deployment strategies for climate stations in Alaska, where the signatures of climate change are believed to be appearing more quickly than in other regions. Also, the existing USCRN network is also being leveraged to provide soil moisture and soil temperature data and relative humidity as a contribution to the National Integrated Drought Information System (NIDIS).

GRUAN is an international effort, with US agencies (NOAA and the Department of Energy) and academic institutions contributing in such areas as site support and operation; reference radiosonde development and testing; data management, quality assurance and distribution; and international support for both the Working Group and work in developing nations. Potential future ARL activities in support of GRUAN include:

- Network design and observing system simulation studies to refine the planned GRUAN network and observation schedule.
- Analyses of GRUAN data for signals of climate variations.
- Testing and development of reference radiosondes and component sensors.

With more than half the world's population now living in urban areas, urban climate footprints and impacts could spread well beyond the immediate vicinity of cities, affecting local to global scale atmospheric composition, surface energy budgets, water and carbon cycle processes, and local ecosystems. Although most climate monitoring networks avoid urban areas because of the potential impact on the climate signature, the extent of the urban impact can only be determined if similar reference systems are located in urban areas. As the percentage of people living in urban areas continues to increase, the need arises for climate quality reference observations in these areas. As part of a pilot study, ARL will acquire some preliminary reference observations of air temperature and precipitation using similar components as those in the USCRN and HCN-M programs. These observations will support analysis of requirements for future urban climate observations.

Potential Extensions

With additional resources, an expansion of SEBN has the potential to provide an unprecedented level of detailed information about physical and chemical process that influence climate through the selection of sites based not only on various climate regimes, but on local land use and vegetation dynamics that result in regionally representative surface temperatures, surface albedo, and energy partitioning of sensible, latent and ground heat fluxes. The scientific rationale and the number and placement of SEBN sites are described in NOAA Technical Memorandum OAR GMD-17.

Climate Variability and Change Analysis

Projecting future climate changes depends on two things. One is an understanding of the nature and causes of past climate variability and change, and the second is climate models that can accurately simulate the past and therefore be trusted to make credible future projections. Analysis of climate variability and change, and comparison of observed changes with model simulations, deepens understanding of the climate system and improves our ability to model its evolution.
Robust climate change analysis and attribution requires quantitative estimates of climate trends and their uncertainty. A major source of trend uncertainty is problematic data, particularly for upper-air observations, making analysis of data quality a necessary aspect of climate trend estimation. Such long-term changes in climate, in both the past and future, must be understood within the context of climate variability, so analysis of a wide range of time scales is critical, as is analysis of a suite of different climate variables and indicators.

Objectives

The prime ARL objective in Climate Variability and Change Analysis is to advance understanding of climate variability and change by continuing to document and analyze diurnal to multi-decadal variations in the global climate system, with emphasis on analysis of upper-air observational data and data quality issues. Over the next few years, the laboratory will maintain and further develop capabilities for analysis of upper air observations, focusing on data homogeneity adjustments, changes in temperature profiles, planetary boundary layer characteristics, tropopause region characteristics, atmospheric responses to forcings (e.g., volcanoes), and intercomparisons of various *in situ* and satellite upper-air data sets.

Current Capabilities and Key Accomplishments

ARL has more than three decades of experience in analysis of observed climate variability and change and has made significant contributions to understanding past atmospheric changes at the surface and in the upper-air. As highlighted in the appended timeline of key accomplishments, the group has built on the pioneering efforts of Jim Angell to develop a program of careful monitoring of surface and upper-air atmospheric variability, mainly focused on *in situ* observations, and analysis of a variety of climate signals. ARL expertise in temperature, humidity and ozone observations has contributed to understanding of such issues as

- the role of data uncertainty in climate trend analysis;
- solar, volcanic, El Niño, and quasi-biennial signals in temperature and ozone; and,
- detection of significant trends in such climate parameters as surface and upper-air temperature, tropospheric water vapor, heat stress and heat waves, sunshine duration, cloudiness, tropopause height, and the width of the tropical belt.

These studies are published in top journals and have earned NOAA, Department of Commerce and World Meteorological Organization prizes. ARL scientists have contributed to the work of the Intergovernmental Panel on Climate Change, from the start of that effort in the early 1990s through to the most recent 2007 assessment, as well as other national and international scientific assessments of climate and stratospheric ozone.

Products

The primary product of this research is improved understanding of climate variability and change. This is communicated to the scientific community and general public via journal publications, presentations at conferences and in seminars, and through informal professional mechanisms and outreach to the general public, including schools. To a large extent, this improved understanding is enhanced, consolidated, and given broad perspective when included in scientific assessments of climate change, and ARL intends to contribute to such efforts whenever appropriate. Research-quality climate datasets are important additional products of this activity, and ARL makes strong efforts to make such datasets widely available to both the scientific community and the public at large.

Partners

ARL's Climate Variability and Change Analysis activity is small and depends on close collaboration with colleagues from around the climate science community, particularly climate change detection and

attribution researchers, to leverage the ARL effort. ARL partners with scientists from other parts of NOAA, other agencies, universities and international institutions in the development of combined *in situ*/satellite data products, model evaluation studies, and impact studies. Our NOAA partners include the Geophysical Fluid Dynamics Laboratory (GFDL), ESRL and NWS/National Centers for Environmental Prediction (NCEP) (on collaborative climate research projects), NCDC (on climate dataset development, analysis, operationalization, and dissemination), and NOAA's Climate Program Office, and we expect to participate in NOAA Climate Service activities.

Plans for Future Work

Over the five year time frame, ARL plans to extend its Climate Variability and Change Analysis research programs to further investigate long-term changes in clouds, particularly as they may relate to climate feedback mechanisms and to air quality changes, and possible changes in aspects of atmospheric circulation, including jet streams and storm tracks. The program will also involve study of the relationships between circulation changes, temperature changes in the troposphere and stratosphere, and tropopause region changes.

Potential Extensions

Current ARL Climate Variability and Change Analysis work is resource-constrained, particularly with regard to staffing. Additional resources would allow for a significant acceleration of the pace of ongoing work, so that the resulting climate information would be available in a more timely manner. The scope of current projects could be expanded to included areas that cannot currently be addressed. In particular, the program would expand the range of observational data sources examined to include more satellite datasets, including Global Navigational Satellite System Radio Occultation data, and would involve more analysis of climate model simulations, both for climate model evaluation and for climate change attribution studies.

Assessment of Regional Climate Impacts

ARL's capabilities and plans for **Regional Climate Impacts** fall into two program areas: (1) Climate Modeling at the Weather-Resolving Scale, which links global scale climate to regional scale mesoscale conditions, (2) Assessment of Regional Climate and Air Quality Interactions, which is focused on the potential impacts of regional-scale climate variability and trends and of climate and air quality mitigation measures on future air quality conditions.

Climate Modeling at the Weather-Resolving Scale

Until recently, research on the weather-climate connection, i.e., bridging the gap between weather and climate systems, was mainly focused on historical data diagnostics. The emerging challenges of providing information at regional and local levels necessary for deciding how to adapt to climate variability and change, often involves aspects of weather. Therefore, the need to develop climate modeling capability that can adequately resolve weather systems has become much more pressing. NOAA recognizes the need for a move to a more seamless approach to weather and climate prediction which operates at weather-resolving scales in the atmosphere.

Objectives

The prime objective of this activity is to provide regional climate tools and projections to support well informed decision making on climate policies and plans. For instance, a modeling system that could predict changes in precipitation or storm patterns as a result of climate change would provide valuable information for planners.

Current Capabilities and Key Accomplishments

Significant advances in simulating regional climate signals have been made in the development of the Climate extension of the Weather Research and Forecast (CWRF) model. ARL has coordinated and supported development and evaluation of this modeling system, with most of the technical work performed by external partners. Development of the CWRF will provide improved regional modeling capability for climate prediction/simulation, future climate change projection, assessment of climate change impacts on air quality, and study of the weather-climate connection, with the following features: 1) realistic surface characteristics that are the most comprehensive among current climate models; 2) an advanced land surface albedo parameterization based on satellite observations; 3) a state-of-the-art Common Land Model with numerous recent updates; 4) an improved boundary layer model with nonlocal effect of transport by large eddies; 5) an improved grid-scale topography and sub-grid orographic effects; 6) an interactive mixed layer ocean model; 7) a cloud microphysics bulk parameterization; 8) an ensemble cumulus parameterization; 9) a parameterization for cloud cover and optical properties; 10) a comprehensive radiation transfer based on the latest solar and thermal infrared schemes; 11) an advanced terrestrial hydrology module with a 1-D dynamic surface routing model and a 3-D volume averaged soil moisture transport model, which is a unique characteristic of the CWRF, the most comprehensive among the existing global and regional climate models, for improved modeling of the conjunctive surface and subsurface flow and runoff and stream-flow geographic distributions.

ARL's expertise in Observing Climate Variability and Change will support this modeling work. SEBN will provide a unique data set for evaluating and improving the quality of the model—based on retrospective simulations. Also, insights from analyses of climate variability and trends and model evaluation capabilities will be directly applicable to ARL's regional climate modeling work.

Products

The CWRF system will be submitted for inclusion in the WRF repository, which will increase the availability and maintenance of the system.

Partners

ARL's partners in these activities include the following:

- Illinois State Water Survey is the primary CWRF developer, providing upgrades and code maintenance using NOAA computing resources. NCEP is interested in evaluating CWRF capabilities for inclusion in its National Environmental Modeling System for various weather and climate applications/operations.
- NOAA's Regional Climate Centers are potentially interested in adapting CWRF capability for their specific local/regional applications.

Plans for Future Work

The prime objective of this activity is to provide regional climate projections to support well informed decision making on climate policies and plans. Over the next 1-3 years, ARL and its partners will continue to develop capabilities in applications using the CWRF system, with increased technical work occurring at ARL. NOAA's Climate Program Office is providing support to include CWRF in a regional climate model inter-comparison project, which is targeted for improvement of NOAA's Climate Testbed regional climate products development and information services delivery. In addition, the Joint Center for Satellite Data Assimilation (JCSDA) will be using CWRF for regional data assimilation. Additional partnerships will also be developed, such as with the Regional Integrated Sciences and Assessments Program and other NOAA groups. Results from this work could provide the basis for climate assessments and the development of regional adaptation strategies.

Potential Extensions

Additional resources would enable the acceleration of the development and application of CWRF and would support extended applications, such as projections of extreme weather.

Assessment of Regional Climate and Air Quality Interactions

Changes in temperature, heat extremes, atmospheric concentrations and deposition of pollutants, precipitation and water supply can impact both human and ecosystem health. Recent modeling studies suggest that future climate trends could have a substantial impact on air quality extremes, and to a lesser certainty deposition of pollutants. There is a societal need to better understand these interactions between climate and air quality for environmental management. This research is directed toward advancing our current scientific understanding of climate impacts on atmospheric pollutant concentrations and atmospheric deposition. Using regional climate scenarios, similar to the CWRF effort described above, air quality modeling tools are used here to investigate and explore the potential responses of atmospheric sources, sinks, and chemistry to future climate trends. These regional scale modeling tools and future climate scenario archives will be made available to environmental managers, so they may account for regional interactions between future climate and air quality in their decision making process.

Objectives

The prime objective of this activity is to develop modeling tools and information for climate and air quality decision-makers on the interactions of climate and air quality and mitigation measures for each. It is likely that climate change will have an impact on air quality, which is highly dependent on weather conditions. It is also likely that air quality mitigation measures will have an impact on the climate and that climate mitigation measures will have an impact on air quality. For instance, aerosols are a key issue for both air quality and climate. Decision-makers need to understand such interactions to find approaches that achieve both air quality and climate benefits.

Current Capabilities and Key Accomplishments

While ARL has conducted significant work in assessment of regional climate and air quality interactions in the past, a recent reorganization involved transfer of an ARL division to the Environmental Protection Agency (EPA), and ARL currently has no capabilities in this area. However, this work is a logical extension

of ARL's other regional impact assessment work and its ongoing air quality research and development in support of NOAA's operational air quality forecasting capabilities. EPA is likely to continue research on climate-air quality linkages to support its evolving regulatory responsibilities, but may not provide the general information and tools state and Federal decision-makers require to address broader issues regarding climate-air quality interactions.

Potential Extensions

ARL is pursuing resources to restore capabilities in this area. Continued evaluation of regional climate simulations generated from downscaling modeling tools (e.g., CWRF, potential model simulation tests using WRF and the NOAA GFDL model) is needed to assess key air quality-sensitive parameters under a range of regional climate scenarios. Work would be conducted in collaboration with GFDL, ESRL, and EPA. Linkages will be established between advanced global climate/chemistry models and advanced regional climate and air quality models. Applications will study the impact on air quality of various climate scenarios and climate management strategies and develop tools for the climate and air quality management communities.

APPENDIX A: SELECTED AIR RESOURCES LABORATORY PUBLICATIONS

Seidel, D.J., F.H. Berger, H.J. Diamond, J. Dykema, D. Goodrich, F. Immler, W. Murray, T. Peterson, D. Sisterson, M. Sommer, P. Thorne, H. Vömel, J. Wang, 2009: Reference upper-air observations for climate: Rationale, progress, and plans. Bull. Amer. Meteorol. Soc. in press.

Gu, L., P.M. Hanson, W.M. Post, D.P. Kaiser, B. Yang, R. Nemani, S.G. Pallardy, and T. Meyers, 2008: The 2007 eastern US spring freeze: Increased cold damage in a warming world? Bioscience, 58(3):253-262.

Seidel, D.J., Q, Fu, W.J. Randel and T.J. Reichler, 2008: Widening of the tropical belt in a changing climate. Nature Geoscience, doi:10.1038/ngeo.2007.38

Kato, H., M. Rodell, F. Beyrich, H. Gleugh, E. van Gorsel, H. Liu, and T.P. Meyers, 2007: Sensitivity of land surface simulations to model physics, land characteristics, and forcings, at four CEOP sites. J. Meteorological Society of Japan, 85A:187-204.

Wilson, T.B., and T.P. Meyers. 2007: Determining vegetation indices from solar and photosynthetically active radiation fluxes. Agricultural and Forest Meteorology, 144:160-179.

Angell, J. K., 2006: Changes in the 300-mb north circumpolar vortex, 1963–2001. J. Climate, 19, 2984-2994

Seidel, D.J., and M. Free, 2006: Measurement requirements for climate monitoring of upper-air temperature derived from reanalysis data. J. Climate, 19, 854-871.

Seidel, D.J., and W.J. Randel, 2006: Variability and trends in the global tropopause estimated from radiosonde data, J. Geophys. Res., 111, D21101, doi:10.1029/2006JD007363.

Liang, X.-Z., J. Pan, J. Zhu, K. E. Kunkel, J. X. L. Wang, and A. Dai, 2006: Regional climate model downscaling of the U.S. summer climate and future change, J. Geophys. Res., 111, D10108, doi:10.1029/2005JD006685.

Free, M., D.J. Seidel, J.K. Angell, J. Lanzante, I. Durre, T.C. Peterson, 2005: Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC): A new data set of large-area anomaly time series, J. Geophys. Res., 110, D22101, doi:10.1029/2005JD006169.

Jacob, D.J., and A.B. Gilliland, 2005: Modeling the impact of air pollution on global climate change, *EM*, October, 24-26.

Free, M., M. Bister, K. Emanuel, 2004: Potential intensity of tropical cyclones: Comparison of results from radiosonde and reanalysis data, J. Climate, 17, 1722-1727.

Fu, Q., C.M. Johanson, S.G. Warren, and D.J. Seidel, 2004: Contribution of stratospheric cooling to satellite-inferred tropospheric temperature trends, Nature, 429, 55-58: doi: 10.103/nature02524.

Seidel, D.J., J.K. Angell, J. Christy, M. Free, S.A. Klein, J.R. Lanzante, C. Mears, D. Parker, M. Schabel, R. Spencer, A. Sterin, P. Thorne, and F. Wentz, 2004: Uncertainty in signals of large-scale climate variations in radiosonde and satellite upper-air temperature datasets, J. Climate, 17, 2225-2240.

Lanzante, J.R., S.A. Klein, and D.J. Seidel, 2003: Temporal homogenization of monthly radiosonde temperature data. Part II: Trends, sensitivities, and MSU comparison. J. Climate, 16, 241-262.

Li, J., and J.X.L. Wang, 2003: A modified zonal index and its physical sense. Geophysical Research Letters, 30(12):1632, doi:10.1029/2003GL017441.

Free, M, and J. K. Angell, 2002: Effect of volcanoes on the vertical temperature profile in radiosonde data. J. Geophys. Res., 10.1029/2001JD001128.

Levitus, S., J.I. Antonov, J. Wang, T.L. Delworth, K.W. Dixon, A.J. Broccoli, 2001: Anthropogenic warming of Earth's climate system. Science, 292, 267-269.

Meyers, T., 2001: A comparison of summertime water and CO_2 fluxes over rangeland for well watered and drought conditions. Agricultural and Forest Meteorology, 106:205-214.

Ross, R.J., and W.P. Elliott, 2001: Radiosonde-based Northern Hemisphere tropospheric water vapor trends. J. Climate, 14, 1602-1612.

Seidel, D.J., R.J. Ross, J.K. Angell, and G.C. Reid, 2001: Climatological characteristics of the tropical tropopause as revealed by radiosondes. J. Geophys. Res., 106, 7857-7878.

Wang, J.X.L., and D.J. Gaffen, 2001: Late-twentieth-century climatology and trends of surface humidity and temperature in China. J. Climate, 14, 2833-2845.

Gaffen, D.J., B.D. Santer, J.S. Boyle, J.R. Christy, N.E. Graham, and R.J. Ross, 2000: Multi- decadal changes in the vertical temperature structure of the tropical troposphere. Science, 287, 1239-1241.

Wang, J.X.L., and J.K. Angell, 1999: Air stagnation climatology for the United States(1948-1998). NOAA/Air Resources Laboratory ATLAS No. 1, Silver Spring, MD, 73 pp.

Baldocchi, D.D., and T. Meyers, 1998: On using eco-physiological, micrometeorological and biogeochemical theory to evaluate carbon dioxide, water vapor and trace gas fluxes over vegetation: A perspective. Agricultural and Forest Meteorology, 90:1-25.

Gaffen, D.J., and R.J. Ross, 1998: Increased summertime heat stress in the United States. Nature, 396, 529-530.

APPENDIX B: SELECTED AIR RESOURCES LABORATORY MILESTONES IN CLIMATE RESEARCH AND DEVELOPMENT

1948

- Air Resources Laboratory established as the Special Projects Branch of the US Weather Bureau

1960's

- Identification of the quasi-biennial oscillation in stratospheric temperature and winds (Angell and Korshover 1962), ozone (Angell and Korshover 1964), stratospheric water vapor, tropopause height and the centers of action (Angell and Korshover 1974)

1970's

- Beginning of global upper-air temperature monitoring (Angell and Korshover 1975) and U.S. cloudiness and sunshine research (Angell and Korshover 1975)
- ARL begins support for C. David Keeling's CO_2 monitoring efforts at Mauna Loa Observatory (1971)
- Establishment of the Geophysical Monitoring for Climatic Change stations (now under ESRL) (1972)
- Beginning of stratospheric ozone monitoring research (Angell and Korshover 1973)
- Initiated monitoring of US cloudiness and sunshine (Angell and Korshover 1975, Angell 1990)
- Quantification of volcanic influence on atmospheric temperature and ozone (Angell et al. 1971, Free and Angell (2002)

1980's

- Identification of solar signal in a variety of climate records (Angell 1988, 1991, 1992, 2001)
- Began research on interannual variability of US stagnation episodes with relation to air quality (Korshover and Angell 1982, 1985)

1990's

- ARL authors contribute to the first assessment report of Intergovernmental Panel on Climate Change and have continued to contribute to each successive report (IPCC 1992, 1995, 2001, 2007).
- ARL scientists contribute to World Climate Research Programme (WCRP) Stratospheric Processes and their Role in Climate (SPARC) scientific assessments of stratospheric ozone, water vapor and temperature, and to WMO/UNEP Scientific Assessments of Ozone Depletion.

- Compilation of first-ever radiosonde station history dataset (Gaffen 1993) and identification of significant problems in use of radiosonde data for long-term climate studies (Gaffen 1994)
- Identification of utility of monitoring global water vapor changes as a surrogate for temperature (Elliott et al. 1995)
- Two AGU Chapman Conferences on Water Vapor in the Climate System convened by ARL scientists (1994, 1999)
- Development of global tropospheric water vapor dataset (Ross and Elliot 1996)
- Detection of long-term increase in surface humidity (Gaffen and Ross 1999, Wang and Gaffen 2001) and tropospheric water vapor (Ross et al. 2001)
- Detection of increase the frequency of extreme heat events in the US (Gaffen and Ross 1998) and China (Wang and Gaffen 2001)
- Release of digital U.S. air stagnation atlas (Wang and Angell 1999), updating earlier work by Korshover and Angell (1982)

2000's

- ARL authors contribute to US Climate Change Science Program's assessment of temperature trends in the lower atmosphere (CCSP 2006)
- ARL author contributes to US Climate Change Science Program's assessment of long-lived and short-lived species influence on climate (CCSP 2008)
- Release of Radiosonde Atmospheric Temperature Products for Assessing Climate (Free et al. 2005)
- Symposium honoring and celebrating the career of Jim Angell on his 80th birthday (2003)
- Detection of increase in tropopause height (Gaffen et al. 2001, Seidel and Randel 2006)
- Identification of widening of the tropical belt (Seidel et al. 2008)
- Regional-scale modeling study of air quality sensitivity to future climate (Nolte et al. 2008)
- Evaluation of large-scale transport patterns in downscaled regional climate simulation methods (Cooter et al., 2008)

APPENDIX C: CONNECTIONS WITH NOAA'S REQUIREMENTS AND GOALS

ARL's goals directly support multiple NOAA requirements and goals as expressed in NOAA's mission requirements and strategic and research goals. These linkages are summarized below.

Requirements Drivers and Mission Requirements

Requirements drivers are external mandates that NOAA is expected to satisfy. Mission requirements are NOAA responsibilities that are derived from the requirements drivers. The following list contains NOAA mission requirements that are supported by ARL's goals. The underlying requirements driver is listed in parentheses. (This information is extracted from charters of NOAA programs.[6, 7, 8])

- Provide climate data and information that meets rigorous scientific standards for quality. (Data Quality Act, Coastal Zone Management Act, and U. S. Ocean Action Plan)
- Provide monitoring, assessment, and analysis of the climate system through high quality observations and measurements of atmospheric, oceanic, and select terrestrial variables, as well as modeling capabilities (Global Change Research Act, National Weather Service Organic Act, Coastal Zone Management Act, US Ocean Action Plan).
- Improve quantification of the forces and feedback systems bringing about changes in the earth's climate and related systems. (Global Change Research Act, Global Climate Protection Act of 1990, Oceans Act 2000, Climate Change Science Program, U. N. Framework Convention on Climate Change, Global Earth Observation System of Systems)
- Improve knowledge of observed variability and change of the Earth's past and present climate and environment (Strategic Plan for the Climate Change Science Program).
- Understand and predict climate variability on timescales ranging from intraseasonal through seasonal to decadal and beyond (Global Change Research Act).
- Monitor, assess, and forecast climate (National Weather Service Organic Act).
- Provide air quality decision-makers key information about the atmospheric processes responsible for poor air quality and related tools to support the development of effective policies and emissions management programs (examples of decision-makers include Federal, state, and local policy-makers and regulators, industrial planners, and other air quality stakeholders) (Congressional appropriations)

NOAA Climate Goals

In supporting NOAA's mission requirements, ARL's climate research contributes to multiple NOAA climate goals and objectives. These include the following:

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[6] Program Charter for Climate Monitoring and Observation, http://www.ppi.noaa.gov/PPI_Goals&Programs/charters/climate/CL-COM_Program_Charter_03-28-08.pdf .
[7] Program Charter for Climate Research and Modeling, http://www.ppi.noaa.gov/PPI_Goals&Programs/charters/climate/CL-CRM_Program_Charter_03-28-08.pdf .
[8] Program Charter for Air Quality, http://www.ppi.noaa.gov/PPI_Goals&Programs/charters/weather&water/WW-AQL_Program_Charter-11-29-05.pdf .

- From NOAA's Strategic Plan, FY2006-2011 [9]
    - Together with our partners, we will accelerate the development of information to support climate policy decisions and plans that consider both climate variability and long-term climate change.
    - We will direct our efforts and actions toward delivering trusted, timely information services to those who need and can use them.
    - Describe and understand the state of the climate system through integrated observations, analysis, and data stewardship.
    - Improve climate predictive capability from weeks to decades, with an increased range of applicability for management and policy decisions.
    - Reduce uncertainty in climate projections through timely information on the forcing and feedbacks contributing to changes in the Earth's climate.
    - Increase number and use of climate products and services to enhance public and private sector decision making.
- From "Research in NOAA: Toward Understanding and Predicting Earth's Environment A Five-Year Plan: Fiscal Years 2008 – 2012" [10]
    - During the next five years, NOAA's Climate Goal will focus on improving the utility of its observations by integrating climate observations, enhancing data management, and analyzing data derived from these observing systems for improved integrated information products
    - Completing the ocean and Arctic observing systems, and integrating surface and upper air measurements
    - Collecting and delivering regular, systematic, and reliable climate data and information—with rigorous scientific standards and easy data access by customers—that document and describe the current and evolving state of the climate system through the development of integrated observing systems
    - Producing reference data sets that provide improved climate information; using these data sets to develop integrated historical analyses of the global climate system through integration of all reference data sets into state-of-the-science global climate models, and using the integrated analysis to carry out detection and attribution studies that link observed climate changes (including changes in extreme events) and climate extremes to specific climate forcing and feedbacks
    - Conducting observational, diagnostic, and modeling research to improve understanding of physical mechanisms and processes of climate variability and predictability that will lead to improved climate models and climate predictions
    - Conducting laboratory and field studies of … the oceanic and terrestrial processes that control the natural emissions and uptake processes in the global carbon cycle
    - Contributing toward the incorporation of [improved climate] understanding into predictive models
    - Delivering peer-reviewed information products, coidentified with stakeholders that assess the state of understanding of climate-change forcing

[9] http://www.ppi.noaa.gov/PPI_Capabilities/Documents/Strategic_Plans/FY06-11_NOAA_Strategic_Plan.pdf
[10] http://www.nrc.noaa.gov/plans_docs/5yrp_2008_2012_final.pdf .