RESEARCH APPLICATIONS LABORATORY

Science in Service to Society

Strategic Plan for the Research Applications Laboratory
National Center for Atmospheric Research
2013-2018

NCAR

1. Background on the Research Applications Lab

About this Plan

This document is the strategic plan of the Research Applications Laboratory (RAL), one of five laboratories in the National Center for Atmospheric Research (NCAR). It describes RAL's mission, vision, broad goals, and priorities for the next five years. This plan is used in the ongoing process of program management and program development, and provides the basis for more detailed program and budget decisions that occur on an annual basis.

This strategic plan updates and extends previous plans written in 2006, 2009, and 2011. It is well aligned with the strategic plans of NCAR, UCAR, and the National Science Foundation (NSF), and shows how RAL contributes to the goals of the parent organizations. The plan builds on RAL's demonstrated success in directed research and in executing efficient procedures for technology transfer, on the experience of its staff over the past thirty years, and on advice provided by its Advisory Panel and by colleagues both internal and external to NCAR.

This plan is not a comprehensive description of RAL projects and activities; rather, it attempts to show the Laboratories overall direction, an overview of key program elements and objectives, and a description of frontier areas that represent developing programs and opportunities over the next five years. Much more detailed descriptions of the items addressed here – and of many other RAL research, technology transfer, education, and service activities – can be found on the RAL web site (www.ral.ucar.edu) and in the RAL Annual Reports.   To aid the reader, a list of acronym definitions is included at the end of the document.

RAL Mission and Structure

NCAR is a Federally Funded Research and Development Center of the National Science Foundation (NSF), and all parts of NCAR conform to the NSF mission "*To promote the progress of science; to advance the national health, prosperity, and welfare; and to secure the national defense*." In addition to serving as the Nation's premier agency for promoting fundamental research, NSF programs are also intended "*to foster and encourage the translation of new knowledge generated through basic research into processes, products, and methodologies with significant economic or societal impact*."

In conformance with the NSF statements above, the RAL mission closely follows the NCAR mission and may be stated as:

- ***To conduct directed research that contributes to the depth of fundamental understanding of the atmosphere and its interaction with society***

- ***To support, enhance, and extend the capabilities of the scientific community, nationally and internationally***

- ***To develop and transfer knowledge and technology that contributes to the betterment of life on Earth***

The latter area is closely connected to the Broader Impacts Criterion of NSF and the "translation of new knowledge" for the benefit of society. RAL makes important contributions in each of the three elements listed, though it places an emphasis on carrying advances from the first two elements into the third as a matter of course. Such emphasis is sometimes called an "end-to-end" approach.

While NCAR is largely supported by NSF, RAL receives roughly 90% of its funding from other sources including other Federal agencies, the private sector, and foreign entities. In addition to use-inspired fundamental research, a hallmark of RAL's effort has been building programs directly with the operational agencies, stakeholders, and end users, and by keeping their requirements in focus at all times, developing and transferring capabilities to them that are put into practical use.

RAL has grown from its origins as a small research program at NCAR in the early 1980s to its current status as one of the five laboratories of NCAR, with six divisions as shown below. The staff is comprised of approximately 200 persons with a diverse set of skills and experience in the physical sciences, social sciences, mathematics, software engineering, project management and administration.

Research Applications Laboratory
Brant Foote, Director
Bill Mahoney, Deputy Director
Liz Hoswell, Administrator

Aviation Applications Program (AAP)
Bruce Carmichael, Director

Climate Science and Applications Program (CSAP)
Lawrence Buja, Director

Hydrometeorology Applications Program (HAP)
Roy Rasmussen, Director

Joint Numerical Testbed Program (JNTP)
Barb Brown, Director

National Security Applications Program (NSAP)
Scott Swerdlin, Director

Weather Systems and Assessment Program (WSAP)
Sue Haupt, Director

Organization chart for the Research Applications Laboratory.

The Laboratory is managed through its Executive Committee, which is comprised of the RAL Director (who also serves as an NCAR Associate Director), the Deputy Director, the RAL Administrator, and the

Directors of the programs listed above. This management team provides oversight and direction to a strong cadre of middle-level managers who are given both authority and responsibility for leading the many projects within RAL.

A companion document to this Strategic Plan, the RAL Compendium (also available at www.ral.ucar.edu) provides a more extensive description of RAL's background and activity, and how its emphasis on an end-to-end approach fits into the missions of NSF, UCAR, and NCAR. A more complete discussion of what is meant by "directed research" is included there, along with its relationship to the concept of "use-inspired basic research." The Compendium also provides discussion of how specific projects are chosen (or rejected), the interactions of RAL staff with other parts of NCAR and the external community, the compilation of a large number of program metrics, and other related topics.

Vision and Values

RAL Vision

RAL seeks to be a world-class leader in performing collaborative end-to-end research, development, and technology transfer that expands the reach of atmospheric and related sciences by addressing important problems that impact society.

Achieving this vision requires the willingness and ability to work in an interdisciplinary way with teammates inside the Laboratory, with other units of NCAR, with stakeholders, and with a host of colleagues in universities, federal laboratories, and the private sector. Ensuring that people, projects, and programs are woven into a diverse, but coherent whole is a primary objective of RAL management.

Operating Principles and Associated Values

The operating principles that contribute to a group's success and that define its fabric and culture may be considered to reflect the values that it holds. For RAL these include:

- Recognition of the importance of excellence and maintaining the highest possible scientific and engineering standards
- Recognition of the importance of specialized knowledge and expertise, as well as breadth of interest and experience and ability to see the big picture
- Recognition of the value of multidisciplinary teamwork, both within the Laboratory and more broadly with members of the research and operational communities, as well as with stakeholders on specific projects
- Recognition of the importance of systematic validation of all our products; this includes a rigorous scientific evaluation of the inherent skill of the product; it also includes an evaluation of the operational benefits that can be derived from the product
- Creation of opportunities for staff to grow professionally and to contribute to the development, application and transfer of fundamental scientific and technological understanding
- Creation and maintenance of a workplace in which openness, transparency, respect and trust are fostered, and in which diversity of background and diversity of approach are respected

- Creation and maintenance of a working environment in which people can be creative, ask hard questions, and take risks
- An entrepreneurial approach to program development that continually seeks new ways to apply knowledge and expertise to societal needs
- A strong connection with sponsors and stakeholders extending from the initial stage of identifying their needs, capabilities, and constraints through the delivery of solutions
- Conduct of programs with a diverse set of government and non-government sponsors both nationally and internationally

Building Advocacy

In pursuing its vision, RAL sees the important need to advocate on behalf of both the science and operational communities for research, development, and transfer of weather- and climate-related technologies that serve end-user needs. For many years RAL has emphasized the transportation, national defense and water resources communities; these efforts will be continued and in some cases expanded. Newer advocacy efforts include renewable energy; climate, weather, and health; urban issues including air quality; the public service sectors; economic valuation of weather information; and communication of weather information. An effort is made to convince members of these communities that advanced weather- and climate-related R&D can lead to societal benefits such as increased safety and efficiency of their operations. Increased attention will be given to social science aspects that provide an underpinning for decision makers in these communities.

Liaison to Stakeholders

RAL maintains strong relationships with decision-makers in business and industry, with local, national, and international governmental bodies and agencies, and with non-governmental organizations. RAL seeks to remain a catalyst in connecting science and society. Policy questions and information needs will be considered as research plans are developed. RAL will investigate decision-making processes and develop decision-support mechanisms to help ensure efficient and effective application of science to societal needs. Both research and operational goals will be pursued in model development. RAL will seek engagement with those interested in the atmospheric, social and Earth-system sciences, will conduct its work in an open and transparent manner, and will pro-actively inform the public about its programs and results.

Context of RAL's work

In a Rapidly-Changing World

RAL's success over the past three decades has been related in part to its efforts to focus on problems that evolving communities and technologies face as they are exposed to weather hazards. Two decades ago it was common for organizations like the Federal Aviation Administration (FAA) to design very large systems without factoring in the effects of weather hazards. That is not true today in large part because of RAL's ability to convince FAA managers that such systems could not operate with sufficient safety or efficiency without incorporating weather information. Surface transportation planners and designers have adopted similar practices, again largely due to RAL and its partner organizations playing an early role in developing weather-resilient systems and infrastructure. Similar efforts have led to RAL's involvement in the atmospheric side of homeland security and public safety, societal impacts, adaptation, and vulnerability associated with global change, and research and development related to wind and solar energy prediction capabilities.

An End-to-End R&D Process

NCAR's founder, Dr. Walter Orr Roberts, promoted "Science in Service to Society" from the earliest days of NCAR's history. RAL adopted that theme to describe its primary mission. In order for this mission to be carried out successfully, a process that is sometimes referred to as "end-to-end R&D" must be employed. The process begins with basic science (physical and social), which is always the foundation of any successful effort to transfer technology. The process continues with directed research and development aimed at finding tailored solutions to specific weather and climate problems. The end point is the delivery of a new technology that increases productivity, safety, mobility or efficiency within some operational environment, or social science results that provide a basis for making difficult decisions. RAL participates in all phases of this cycle, with careful assessment of the science and its readiness for application, thoughtful discussions with the user community about real needs and the readiness to accept and exploit new capabilities, and focused attention on the necessary human and computational resources (on both the developer and recipient sides) required to test, validate and deliver the technology. In the last step, it is usually critical that operational stakeholders receive suitable training to use the new technology.

While the phrase "end-to-end" is commonly used, a term like "spiral development" more accurately portrays the iterative development process between researcher/developer and user that is almost always necessary for successful technology transfer. Careful attention to user needs always needs to be a hallmark of such work.

Need for On-Going Program Development

With its overwhelming fraction of soft money support, RAL will remain dedicated to an on-going effort in program development. Given the uncertain timing in which these efforts bear fruit, the Laboratory is of necessity opportunistic in addressing specific issues, and must remain agile in its ability to design, propose, and take on new projects. At the same time, RAL is increasing its interactions every year with the other management units at NCAR, and its expertise is sought out and cross-utilized by other groups in the same way that RAL programs seek to entrain colleagues in other parts of NCAR and in the universities. RAL scientists and engineers will continue to contribute to, and occasionally to lead, large flagship programs bringing multidisciplinary teams together at NCAR.

Involvement with Sponsors and Other Stakeholders

RAL is committed to ensuring that its research and the products it delivers to its sponsors reflect the highest quality science and technology allowed by project budgets and timetables. This requires RAL to develop a detailed knowledge of a sponsor's needs and requirements. This takes some time and patience on the part of both parties, but has proven to be a key element in completing a successful transfer of technology while keeping an accurate focus on relevant societal issues. We will continue to make this investment of time and energy as we develop new programs as part of this strategic plan.

Dialogue in the "Art of the Possible"

Experience has shown that as a new project is designed in partnership with a sponsor, neither party tends to have a clear understanding of the exact nature of the scientific or technological package to be delivered, or, in fact, the problem to be solved. Many times people simply "don't know what they don't know." To design a project as effectively as possible, RAL attempts to engage the sponsor in a dialogue concerning the "art of the possible." By this is meant an interactive process whereby each party, with its pre-conceived notion of the problem and the deliverable, begins to exchange information regarding what

might be possible on the science and technology side and what changes in operating procedures might occur if these changes were deployed for the sponsor. This normally results in a much more detailed understanding of the sponsor's real needs as compared to perceived needs, and an in-depth understanding of the sponsor's decision process. In going through this process, both parties shift their thinking to a set of common ideas regarding requirements and deliverables.

Sponsor's Role in Guiding the R&D

Having established the goals of the program as outlined above, the next essential step is to guide the research and development carefully so that the deliverable is focused (and sometimes re-focused, within the constraints of time and budget) to meet the needs of the sponsor. Two mechanisms are employed to allow the sponsor to guide the R&D from beginning to end: a) formal feedback from user groups (typically operational stakeholders from the sponsor's community) who work regularly with RAL developers and provide input on interim developments; and b) frequent program reviews with senior managers in the sponsoring organization who can approve work done and make mid-course corrections. This collaborative development approach helps to ensure sponsor satisfaction with the deliverable and a successful technology transfer process leading to operational use of the results.

Evaluating Program Success

Scientific and Operational Validation of Work

The scientific validation of meteorological forecast products is an essential step in determining their utility and represents an important part of our work. Developing improved techniques for forecast validation is a scientific research topic in its own right, and one in which RAL strives to maintain a strong program. In recent years, major new evaluation tools have been developed by RAL and its collaborators, and have been made available to the community through the activities of the Joint Numerical Testbed Program.

From the viewpoint of technology transfer and the end user, the operational evaluation of forecast products is as important as the scientific evaluation. How useful is the capability to the customer? What are the actual efficiency and safety gains attained? What is the anecdotal feedback from the "front lines" regarding whether the product is helpful to their decision process? Is the weather information communicated effectively?   What is the value of the weather information to the user? Such subjective evaluations are often as informative as formal benefit/cost studies, are more readily obtained, and are commonly the primary basis for establishing customer satisfaction. The operational evaluation is critical in that it literally takes the science and technology out of the laboratory and puts it into a societal, operational setting.

Other Specific Metrics of Performance

In the research applications arena one may consider metrics related to the research itself, metrics related to support to the community, and others related to the applications, the technology transfer, and the societal benefit parts.

The first two are quite familiar to the traditional research community, and consist of things like:

- The advancement of scientific knowledge as measured by refereed publications
- Citation indices
- Patents

- Visitor interactions (numbers of visitors, co-authored papers)
- Support to the community through
  - Development and support of community models and community software tools
  - Service on national and international advisory panels, editorial boards, AMS Committees, National Academy of Science committees, etc
  - Planning and chairing national and international conferences, and leading or participating in field campaigns
  - Organizing and conducting community tutorials and workshops
  - Education and outreach to national and international groups
  - Service on academic thesis committees

Regarding the applications-oriented part of our work there are, in addition, measures like:

- Longevity of relationship with the sponsor as a metric of the sponsor's satisfaction with the work being conducted (for example, has the work led to a higher level of safety, productivity, efficiency, or public health to point that the sponsor seeks to continue the relationship?)
- Numbers of scientific and operational evaluations conducted as described above
- Adoption of the product or capability by the sponsor, or by other economic sectors (public, private, or academic)
- Development of international standards and their subsequent adoption
  - Examples are turbulence, snowfall measurement, "check time", work on OGC standards, RTCA standards
- Technologies licensed

2. Introduction to Strategic Goals and Priorities

The following sections describe six areas in which RAL will focus its efforts. The goals and priorities here have been defined in ongoing discussions between RAL managers and technical staff, our collaborators in other parts of NCAR, the RAL Advisory Panel, our external colleagues, and interested public and private-sector stakeholders. The process of defining goals and priorities has also been informed by careful consideration of:

- RAL's mission and vision for the future within the context of the strategic plans of NCAR and of the National Science Foundation
- National and international needs and opportunities in science and technology as reported, for example, in reports of the National Research Council
- The expertise, interests, and capabilities of RAL staff and research partners

Throughout this process, every attempt has been made to balance RAL's responsibility to attack large-scale, difficult problems with its judgment about the tractability of such problems and prospects for progress (see the more complete discussion regarding project selection in the RAL Compendium).

The work described in the following six sections corresponds roughly to work that is concentrated in the six RAL Program units described in Section 1. However, by design, the correspondence is only approximate. It is important to recognize that many scientific and development topics that are being pursued contribute to a broad spectrum of applications goals. There is thus no attempt to "pigeon hole" a piece of research into only one applications topic, or to confine a subject to only one of RAL's six management units. For example, the cross-cutting topic of forecast verification and product quality assessment is an activity that naturally affects each of the programs, though it is centered in the JNTP. The topic of precipitation forecasting, though it is clearly a strong aspect of hydrometeorological research and a key aspect of understanding the water cycle, is also highly relevant to the Laboratory's work involving numerical weather prediction (NWP) advances, coupled model applications, and a host of other topics dealing with water resource management, transportation, agriculture, climate, etc. It is believed that the research overlap between application themes and the cross-strapping of scientists and research topics across RAL program units are strengths of the program. RAL seeks out and maintains similar collaborations and overlapping subject areas with other parts of NCAR, as well as with the universities and other government labs. In the NCAR context it is worth noting that RAL currently leads a number of cross-laboratory programs including the Water System Program, NCAR Vulnerability, Impacts and Adaptation Program associated with the Integrated Science Program, the Short-Term Explicit Prediction program, and the Developmental Testbed Center.

The discussion here is intended as a summary, as noted earlier. More detailed descriptions of RAL science and technology transfer can be found in the project plans of the laboratory's six management units and the RAL Annual Report on the Web at www.ral.ucar.edu .

The strategic planning elements that follow are grouped into six general goal areas that are regarded as imperatives for the laboratory. In each of these areas the high-level goal is first stated as an Overarching Priority, followed by a discussion of the motivation for this effort. The specific plans are then presented in terms of Near-Term Objectives. These are followed by other long-term objectives termed Frontiers. Generally the former involve the continuation of important work presently underway, along with follow-on projects that expand the scope and capabilities developed. The Frontiers describe research projects that only recently began, or those in the formative or planning stages. They often involve strong elements of program development, building of new collaborations, and interactions with potential or expected sponsors.

3. Goal Area: Weather Technologies for the Global Air Transportation System

Overarching Priority

Provide national leadership, research, and technical innovation toward development of advanced weather technologies that enable a vastly improved air transportation system.

Motivation

RAL has spent the past three decades addressing and supplying the needs of aviation stakeholders in the U.S. and other countries. This work has yielded fundamental improvements in the scientific understanding of aviation weather hazards as well as a broad array of practical tools and systems that reduce the vulnerability of aviation to such hazards.

Current and projected growth in the volume, complexity, and economic importance of air and space transportation clearly demonstrates the need for a new paradigm supporting the organization and control of air traffic services in the 21st century. Since weather conditions seriously impact air traffic operations and the levels of service available to system users, the manner by which weather is observed, forecast, disseminated and used within air traffic decision processes and systems is of critical national importance.

"The paradigms we have relied on for 50 years cannot accommodate the massive change that has already begun."
- Robert Pearce, Acting Director, Next-Gen, in Journal of Air Traffic Control, 2006

Many new factors compound the challenge to safe and efficient air and space operations during the first twenty five years of this century. Among these factors are the following:

- Aircraft passenger and freight load requirements will be 2-3 times higher
- No new airports are planned during the next decade
- Airport expansion is limited at some major airports
- New aircraft types such as very light jets and unmanned aerial vehicles (UAVs) are proliferating
- Commercial space vehicles are beginning operations
- Increasing use of polar routes will introduce new hazards to crews and passengers
- New navigational technologies that allow more flexible routing and separation of aircraft are not fully compatible with the current air traffic control system
- Increasing concerns about environmental impacts

Capacity will become an increasingly limiting factor at many airports. Efficiency of flight operations en-route will become more critical. Predicting traffic loading accurately at all locations within the airspace system several hours in advance will be critical to efficient operations. Space operations with commercial passengers will require many safeguards for launch, sub-orbital flight, orbital flight and recovery. Weather affects all of these operations and in most cases, precise weather information integrated into

decision support systems will be critical for maximizing the performance of the 21st century system. The Next Generation Air Transportation System (NextGen) is beginning to take shape through the acquisition process of several federal agencies.

Near-Term Objectives

Advanced Weather Products for the Next Generation Air Transportation System

Play a leadership role within the atmospheric research community to provide the necessary scientific underpinning and technology to support the weather- and climate-related needs of NextGen including: a) collaboratively determining the role of weather in aviation operations with operational stakeholders, b) tailoring solutions to operational user's needs via focused and integrated (weather and operational parameters) decision information to address safety, capacity and efficiency issues, c) with other NextGen partners, build and test the weather component of NextGen, and d) collaboratively build and test fully integrated components of NextGen.

The NextGen System is a national priority to meet the air transportation needs of the U.S. in the 21st century – in particular, a significant growth in demand for air traffic services. Since weather conditions can seriously restrict aircraft operations and levels of service available to system users, the manner by which weather is observed, forecast, disseminated, and used in decision-making is of critical importance.

Storm Prediction for Aviation

For the past several years the focus of storm prediction has been on a collaborative development of a national scale 0 – 8 h forecast of storm hazards for aviation (dubbed CoSPA), based upon feature extraction and extrapolation techniques, numerical weather prediction models, and intelligent blending of multiple forecast fields. During the past year the CoSPA forecast technology has entered the FAA acquisition process to be incorporated in the NextGen Weather Processor in support of strategic air traffic management.

Research and development efforts continue to better grasp convective storm initiation and model performance, and advance model development through improved initialization and data assimilation procedures. Furthermore, information from new sources, such as advanced radar technology and satellite observations, will be harvested to benefit storm prediction for aviation. Recent efforts have begun to focus on impacts of thunderstorms and lightning on airport operation safety and efficiency. Moreover, global ensemble forecast models and satellite observations are explored toward development of a probabilistic convective storm guidance product for strategic transoceanic flight planning.
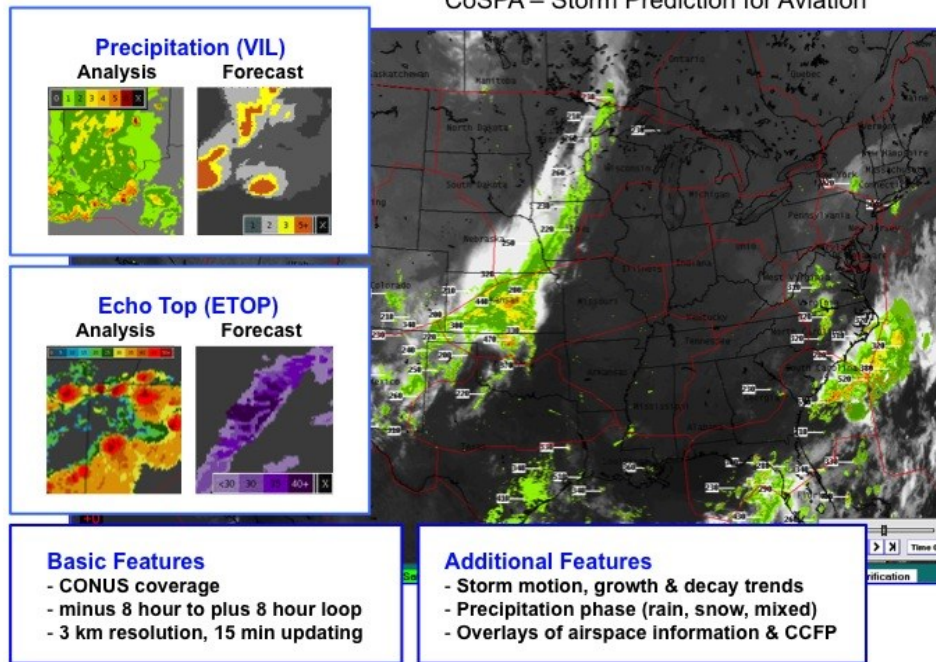
CoSPA Forecast Display of Precipitation Intensity and Echo Top.

Icing

RAL will continue to work on improved diagnosis and forecast methods for in-flight structural icing, engine icing, and ground de-icing. Automated in-flight icing algorithms will be improved through the incorporation of high-resolution NWP model output, new data sets (including GOES-R satellite products and NEXRAD dual-polarization data), and using existing data sets more intelligently (such as extrapolating radar and satellite features). A focus on the terminal area will address potential problems with new regulations regarding flight in freezing drizzle and freezing rain conditions. For this, improvements in detection of precipitation type and amount are needed, as well as more accurate predictions. Better parameterization of cloud processes in numerical weather models for 0-12 h forecasts will focus on the impact of cloud-active aerosols and parameterizations of size distributions for water drops and ice crystals. Our goal is to accurately predict the full drop size spectrum and liquid water content to enable aircraft and flight-path specific icing severity estimates. Engine icing will continue as an interest area and RAL is developing an algorithm, based on NWP model, satellite and radar information, to predict regions of high ice water content (HIWC) associated with deep convection. Improved radar techniques, including NEXRAD dual-polarization capability and the national Multi-Radar-Multi-Sensing system (MRMS) will be explored to assist in diagnosing icing conditions. Global applications using combinations of global weather models and satellite information will be developed to support oceanic flight routes, as well as to provide guidance for re-entry of space vehicles. RAL will also seek opportunities to work with NASA and industry on improved terminal-area in-flight icing detection systems (such as the NASA Icing Remote Sensing System) incorporating previous research results into operational facilities.
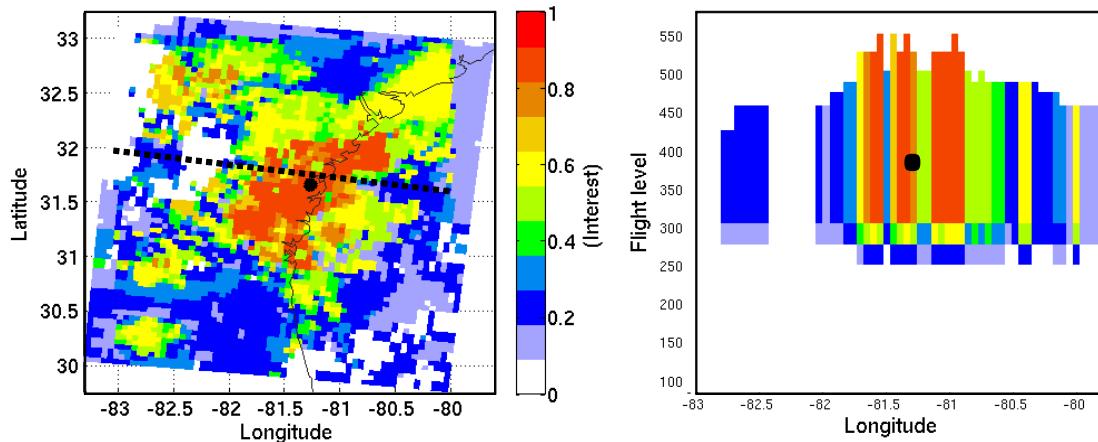
Output from Algorithm to Predict High ice water content Hazard Regions (ALPHA) for Aug 24, 2006 at 2345 UTC in the southeastern US. Black dot indicates the location of an engine icing event.

Turbulence

RAL will continue to develop and implement methods for making both *in situ* and remotely-sensed observations of turbulence, and to further refine turbulence nowcasting and forecasting algorithms for use by the aviation community.   All measurements, inferences, and forecasts of turbulence will be based on the eddy dissipation rate (actually $\varepsilon^{1/3}$ or EDR) metric, which is aircraft independent.

The forecast product, Graphical Turbulence Guidance (GTG), has operational and experimental versions that predict aviation-scale turbulence based on diagnoses of NWP model output related to upper-level fronts and jet streams and mountain waves out to 12 hr. An example output of EDR is shown in the figure below. Future versions will include terrain-induced turbulence and turbulence associated with convection, and provide forecasts out to 18 hr, thus expanding the altitude range covered as well as the utility of the product. Research will also be conducted on improved turbulence parameterizations, better use of increased model resolution, increased understanding of all turbulence generation and downscaling mechanisms, and incorporation of new observational data. This will be done through high-resolution model simulations of observed events and by pursuing opportunities for collecting and analyzing research quality *in situ* aircraft data. A nowcasting product, GTGN, is also being developed to provide rapid updates (every 15 min) of GTG background analyses that incorporate and utilize all available turbulence observations (from *in situ* or remote measurements).   This product is necessary due to the rapidly evolving nature of atmospheric turbulence, especially in the vicinity of storms. A global turbulence forecast product is also under development that combines NWP model output results with satellite imagery to detect and predict turbulence from clear air and convective sources.

Improvements to the quality and quantity of turbulence observations will continue. The turbulence detection network based on NEXRAD radars will be expanded and incorporated into GTGN. *In situ* turbulence measurements (from commercial airlines and possibly TAMDAR sensors) will supplement pilot reports (PIREPs) and airborne radar forward-looking turbulence detection algorithms (in cloud). The feasibility of using forward-looking IR sensors as well as GPS scintillation to detect turbulence will be assessed as these new technologies continue to mature.
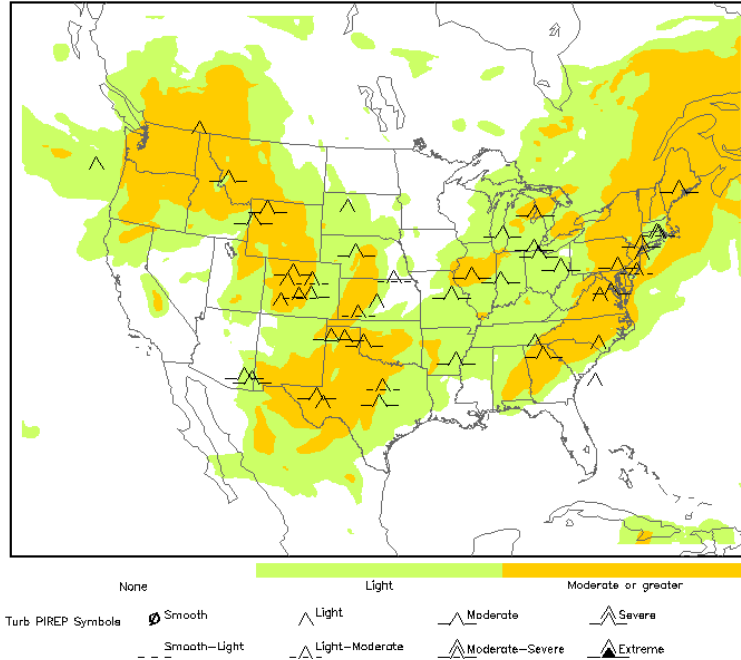
Sample GTG output as it appears on the NOAA's Aviation Digital Data Service (ADDS).

Ceiling and Visibility

RAL's work toward development of real-time products for the analysis and forecasting of ceiling and visibility conditions uses FAA and NOAA funding toward R&D that will yield improvements in both the efficiency and safety of aviation across the continental U.S. As shown in the figure below, work to date has pursued two products:

- The real-time analysis product (CVA) supports improved situational awareness critical to the safety of general aviation (GA) and helicopter emergency medical services (HEMS) operations. FAA approval for operational use of CVA was granted in July, 2012.
- RAL's probabilistic 1-10 h ceiling and visibility forecast (CVF) will improve forecasting of C&V conditions responsible for commercial air traffic delays and will further aid GA and HEMS pilots anticipate expected changes in conditions. CVF development targets operational readiness by FY2016.

Future work will extend application of these techniques to the Alaska domain. A new effort beginning in FY2013 will address unmet needs related to dissemination and forecasting of runway visual range (RVR), a critical visibility measure controlling air carriers' landing procedures.
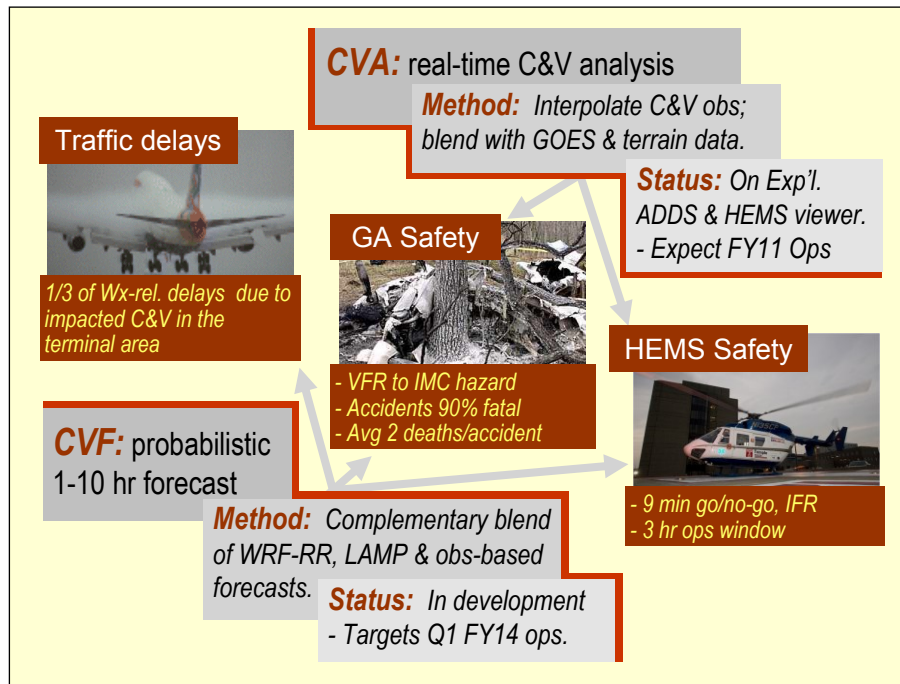
Principal impacts of ceiling and visibility hazards within U.S. national air space (in red): delays of commercial traffic and reduced safety of general aviation and helicopter emergency medical services (HEMS) operations. Arrows show areas where CVA and CVF

Common Support Services - Weather (CSS-Wx)

RAL is heavily engaged with the FAA, NOAA, and MIT/Lincoln Laboratory in the development of a capability called Common Support Services - Weather (CSS-Wx). This capability will provide a global four-dimensional database of all weather information relevant to aviation decision-making. This so-called "4D weather data cube" will be a distributed entity that exists through the application of modern information technology to store and retrieve data. To facilitate this effort, RAL is involved with the Open Geospatial Consortium to motivate the development and extension of open standards and technology that will make CSS - Wx possible.

Frontiers

Integration of Weather Information into Air Traffic Management Decision Support Systems

Incorporate deterministic and probabilistic weather information into real-time decision support tools for managing the national airspace.

Historically the FAA plans for management of the U.S. national airspace system (NAS) have simply ignored the existence of weather impacts. When hazardous weather occurred, the system entered what could be called a reactive mode. As the volume of air traffic has increased, the impact of weather on the system has also increased. It is recognized that new, pro-active solutions are required. While progress has been made over the last decade in presenting weather information to non-meteorologist end users in the NAS (that is, dispatchers, air traffic controllers/managers, pilots) this will not by itself lead to the efficiencies required. The NAS is too complex. Automated air traffic management tools are needed that optimize decisions while taking probabilistic weather information into account. The concept of "risk management" verses "risk avoidance" recognizes the fact that weather information will never be totally

certain (hence the integration of probabilities) but at some point the decision must be made based on deterministic thresholds. Options for human intervention in the system will still be required.

The figure below portrays the process of translating weather information into air traffic impacts and constraints, and finally into thresholds for taking action. Risk management using probabilistic weather information is expected to lead to a reduction in weather impact by not having to fully close airspace in many cases, but rather by managing the air traffic flow around weather constraints that have varying degrees of hazard. How to effectively accomplish this process with the human in or over the control loop, adding value where appropriate, is the challenge and the future of weather information R&D.
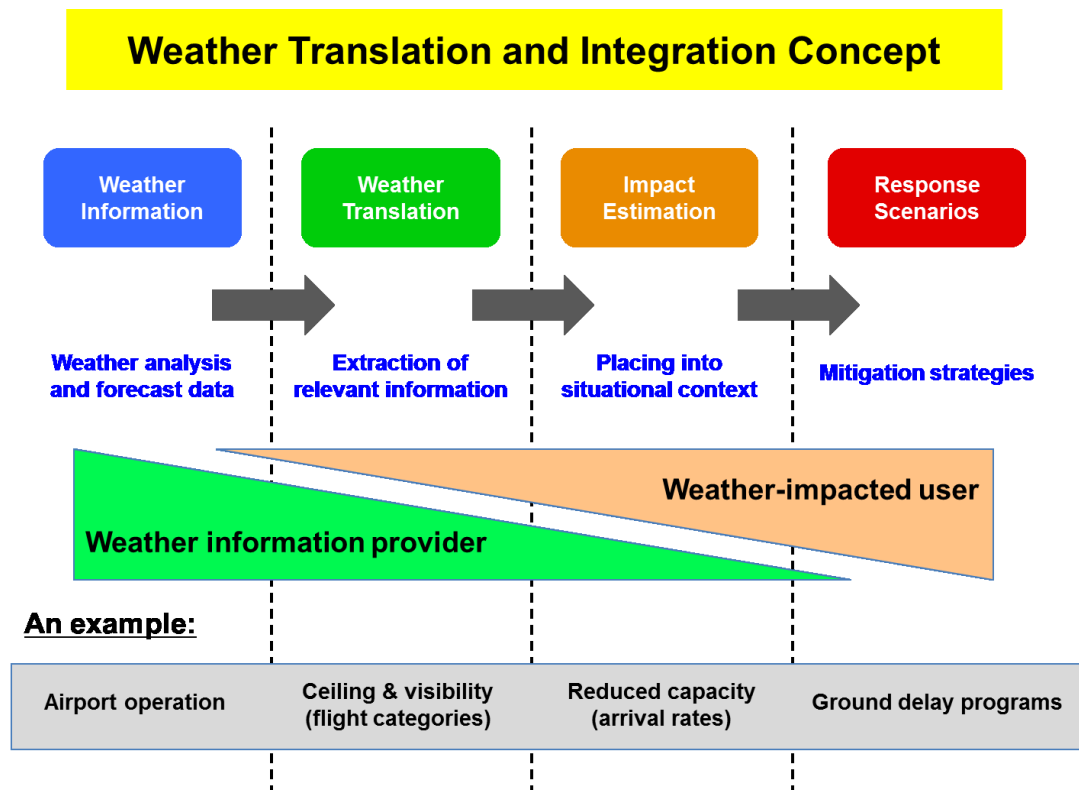
Weather Integration into Air Traffic Management Decision Support Tools.

An essential element of the R&D plan continues to present prototypical deterministic and probabilistic weather information to end users during every opportunity possible, including pilots while in flight. There are two reasons why this is so important. First, user feedback tells us how well we are doing toward reducing the uncertainty of weather forecasts and diagnoses. And second, this gives us a chance to better understand how the human integrates weather into his/her decision-making.

Through collaboration with NASA, NOAA, academia, and the community of aviation weather users, we are learning how to translate ensemble storm forecasts into probabilistic information about the airspace capacity available to the air traffic system when impacting weather is expected. This is information that aviation planners may use in the future to provide for a more orderly flow of air traffic, without actually having to look at or try to interpret weather forecasts. RAL will continue efforts in this area, by incorporating more sophisticated analysis techniques and also by applying them to real-world conditions. Exploration of similar approaches to other aviation weather hazards, such as turbulence and in-flight icing, will be conducted as well.

En Route Wake Vortex Hazard Research

Identify the potential hazard to air traffic from en route wake vortices as aircraft separation is reduced in the NextGen environment.

In the airport environment, much is known about wake vortex longevity and transport, but much less is known about wake vortex characteristics in the en route environment: for example, the longevity of wake vortices in the vicinity of the tropopause. For today's aircraft separations, en route wake vortex encounters are not considered to be a safety or capacity problem. However, there have been turbulence reports that may have been caused by en route wake but attributed to clear air, convective, mountain wave or other forms of turbulence.

In the NextGen timeframe, aircraft en route separations will be reduced vertically, laterally, and longitudinally. Additionally, there is an on-going increase in fleet diversity, including a large number of lighter jets, which may be strongly impacted by wake encounters. However, it is not definitively known whether these paradigm changes will result in an increased likelihood and severity of en route wake encounters, or increased risk of injury and fatality.

Detection and Transport of Volcanic Ash

NCAR will undertake research to improve dispersion models on scales appropriate for volcanic ash tracking, satellite detection of ash clouds, and early detection of eruptions.

Due to the extreme vulnerability of aircraft to volcanic ash, NextGen has a requirement for detection and forecasting of ash clouds to drive the air traffic flight planning process.

Space Weather Support for Aviation

Develop fully operational predictive models and current space weather observations that can be blended to provide a consolidated probabilistic space weather forecast that is available through the NNEW 4D data cube to support NextGen.

In NextGen, the air transportation system can be adversely impacted by space weather events. The volume of polar flights is projected to increase. NextGen will rely on satellite-based systems for communication, positioning, navigation, timing, and surveillance. A real-time forecast of the impact of space weather events along a particular route of flight is critical to system safety. Furthermore, it is becoming clear that there can be health hazards to flight crews who are repeatedly exposed to the higher than normal radiation levels inherent in flights along polar routes. A real-time forecast of human health effects along a flight path is needed. This capability will require the completion of research efforts and algorithms.

Environmental Forecasts

Develop a forecast system for assessing the environmental impacts of aviation operations in real time.

Real-time mitigation of environmental impacts of aviation requires an understanding of those environmental impacts and their dependencies on real-time weather. NextGen's fully operational

predictive models (including climatology) and current weather observations will be fused to provide a consolidated probabilistic environmental forecast that is available to users over a Network-Enabled Infrastructure. This capability will build on a body of research and algorithms that will forecast real-time noise propagation, dispersion of airborne pollutants (including from a terrorist attack or accidental release), and forecasts of the sensitivity of atmospheric volumes to exhaust emissions, including greenhouse gases and formation of cirrus clouds.

Cockpit Display of Hazardous Weather

Facilitate targeted weather hazard product development and dissemination to support evolving industry standards for integrated cockpit weather displays and pilot decision-making

This new Frontier links the development of Advanced Weather Products for the Next Generation Air Transportation System to pilot decision support on the flight deck. It also links the Integration of Weather Information into Air Traffic Management Decision Support Systems, focusing on flight deck needs. The research we envision for this Frontier has a large human factors component which focuses RAL expertise in developing and evaluating advanced display concepts for the flight deck, which in turn recognizes that future display of weather information spans both Portable and Installed Displays (PaIDs) for the pilot. We have identified four main R&D thrusts:

- Partnerships with manufacturers of integrated cockpit weather displays that will target operational improvements in the NextGen environment, including both primary flight displays and electronic flight bags (EFBs).
- Rapid prototyping of weather displays that can be initially evaluated in aircraft flight simulators, including both airline and FAA facilities. These systems have served well as robust platforms for evaluating the human factors and utility of new display concepts.
- Prototyping of weather displays for portable devices that will be used as EFBs or stand-alone weather information displays that are integrated with planned and actual flight profiles.
- Continued substantive involvement with committees that develop aviation standards and recommended practices, such as the RTCA, AIAA, and SAE G-10 Human Factors. This involvement provides the needed two-way linkage between the weather R&D and product development communities and actual operational requirements.

4. Goal Area: Weather and Climate Information for Improved National Security and Public Safety

Overarching Priority

Advance fundamental understanding and the community's ability to predict fine-scale weather and climate processes for the purpose of providing forecasters, decision makers, and emergency managers with accurate information to save lives and property.

Motivation

NCAR has developed several technologies, mostly model-based, over the past decade that are focused on Department of Defense and National Security needs. This work began well before the September 11, 2001 attack on the U.S. but has increased dramatically since that event. Much of this work has been focused on coupled-model concepts, model-based climatologies for data sparse regions, atmospheric scales ranging from neighborhood-scale to mesoscale, and science and technology education and outreach to our operationally minded sponsors. By necessity, urban areas, particularly those with high-valued national assets, have received much attention. Great challenges exist in tuning and operating these models at the scales of large turbulent eddies (Large Eddy Simulation (LES) models), in terms of ensuring that they are representing physically realistic processes, that they are verifying reasonably against observed quantities, and that they run efficiently on cutting edge hardware platforms. Aside from the scientific and technical challenges, the end users who are presented with products at such fine scales require substantial and sustained education on how to interpret the model output. The material must be presented in a manner that properly communicates information that is critical to their operations, where this communication is often very different from how scientists communicate among themselves. This ongoing work provides an excellent scientific and technical basis for strategically planning NCAR research and development over the next five years.

Sponsor-needs for research and development in this work area continue to grow rapidly. As stakeholders gradually incorporate advanced weather and climate-based decision systems, they continually see new application areas. It is imperative that this science base and its associated technologies be pushed even farther in the following areas: a) plume modeling in urban areas with a focus on street canyons effects of flow around buildings, b) overall modeling of the flow regimes and atmospheric conditions in a metropolitan area down to street scale, c) coupling of atmospheric models to other sector models such as agriculture and public health, and d) for sponsors in the realm of homeland security and defense, the production of regional climatologies to provide planning information to decision makers with regard to the effect of climate change on their region.

Near-Term Objectives

Customized Modeling Capabilities

Improve mechanisms of transferring customized modeling capabilities and knowledge, based on fine-scale weather and climate forecasts, to the community, to our sponsors, and to end users that employ these products.

RAL has at its immediate disposal a large array of "outdoor laboratories" in the form of Army Test Ranges managed by the U.S. Army Test and Evaluation Command (ATEC). In RAL's role as the outsourced R&D and educational outreach contractor, tasked with providing eight ATEC ranges across five major climate zones with technology for advanced meteorological analysis and forecast, and with transferring knowledge to personnel ranging from recent college graduates to 20-year operational forecasting veterans, there is a unique opportunity to develop and refine our methods of transferring the fruits of R&D to the community.
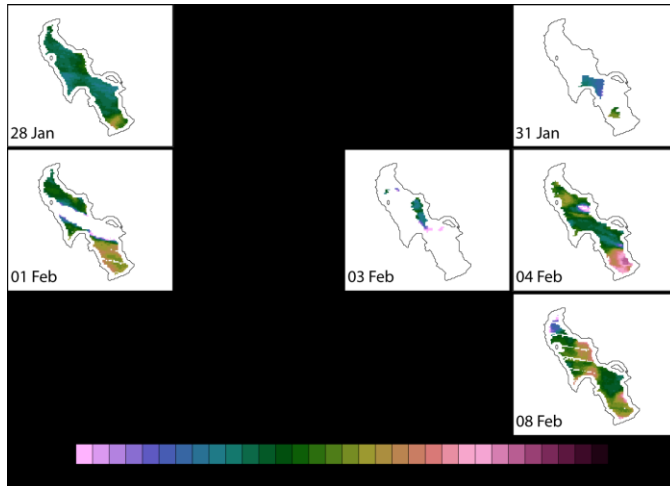
Surface temperature (°C) of the Great Salt Lake in winter 2010, as derived from observations by the MODIS instrument aboard NOAA's satellite Terra (top), and after application of RAL's unique technique for creating multi-satellite spatio-temporal composites from the same MODIS data (bottom). The composites have no missing data and therefore can be used to prescribe the gridded lower boundary in numerical weather prediction models, thereby better simulating complex weather and climate near large inland lakes. Such images also provide forecasters with improved understanding of factors that affect their local weather. These composites, which are more accurate than other available operational datasets used to define gridded lake temperatures, are being supplied to universities and the larger forecast community.
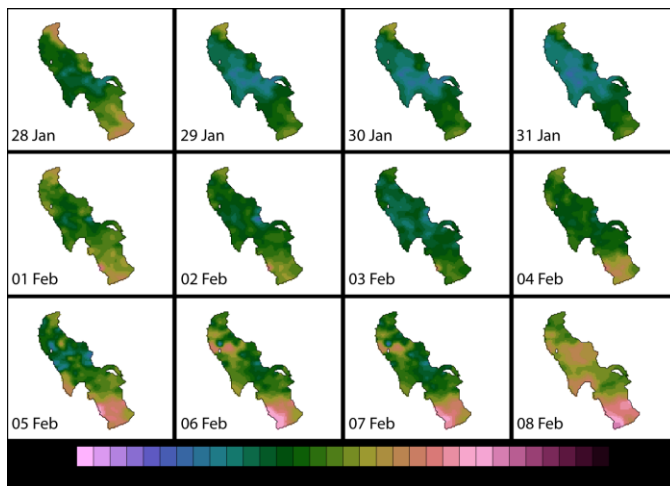
In our role to support the component of the National Science Foundation's mission that addresses "securing the National defense," RAL has the responsibility not only to develop and provide the very best technologies to a number of U.S. and allied agencies that protect the Homeland and our warfighters, but also to effectively transfer knowledge to end users so they can fully exploit what these capabilities have to offer. This includes knowledge of how complex terrain drives the specific mesoscale and microscale phenomena that characterize local weather and climate in different parts of the world. A better understanding of these phenomena fosters better numerical weather prediction models and enables forecasters to develop their own *mental* models of the atmosphere—mental models that are the foundation of a forecaster's skill, and that often inform how forecasters customize their workflow to maximize skill

and efficiency. RAL uses a variety of media and venues for transferring knowledge of weather and numerical weather prediction, including 2.5-day Forecaster Training sessions held twice per year as part of the ATEC-sponsored 4DWX project.

Forecaster Training in RAL is a key component of the ATEC-sponsored 4DWX project. This session was held in 2012.

Each test range that RAL supports with R&D and educational outreach in itself represents a wealth of opportunities to advance important topics in the NWP weather modeling community: heavily instrumented with *in situ* and standoff weather sensors collect many hours of data daily, and numerous tests are conducted from near-surface through the upper troposphere, providing important verification data for coupled weather/test-materiel experiments against which to compare modeling and results. Regularly staged improvements to the range forecast systems resulting from R&D focused at the range-scale provides RAL with frequent opportunities to refine how we deploy cutting-edge research into operations, which supports the community effort to put the best tools possible into the hands of researchers, universities, government, and private industry. In a climate of rapid advances made by emerging technical superpowers such as China and India, the U.S. can ill afford to languish in long delays between when advances are made in research and when they appear in operations at our civilian and defense-based weather prediction centers. RAL hopes to help the nation to maintain its competitive edge in both R&D and operational forecast capabilities

Actions:
Streamline and accelerate the process of moving new NWP capabilities that RAL develops into the community software repository, subject to constraints imposed by federal export-control regulations. Gather technical material that has been applied to numerous formal trainings of operational forecasters for the Test Ranges and for other sponsors, and consolidate into a widely available repository. Increase collaboration with national and international universities. Increase use of probabilistic forecasts and products derived from them.

Development of Customized NWP Solutions

Utilizing the WRF and LES-WRF models, and building-aware diagnostic models, develop modeling technologies that meet the needs of a variety of users for real-time precision weather forecast in focused regions. Provide web-based graphical interfaces for this information which allow rapid interpretation and decision making. Couple the meteorological-model output with secondary models that calculate special variables such as sound and radio-wave propagation, and transport and diffusion. Extend the range of the predictions to inter-seasonal time scales.

RAL has developed and deployed very high fidelity, computer-based weather analysis and forecasting systems for many applications worldwide. For example, new weather-prediction systems have brought the DTC Test Ranges into the 21st century, in terms of advanced weather products. The improved weather

information for test planning has saved taxpayers millions of dollars. Numerous other domestic projects include providing proof of concept advanced weather capabilities, to support Navy operations in California and Hawaii, and for potential Space Shuttle landings at alternate sites. Other such systems focus on urban areas and urban impacts on the weather. In contrast to most NWP models that don't recognize the existence of cities in a meaningful way, recent RAL models resolve the large-scale effects of the cities, and some even represent the complex winds in street canyons. In addition to these domestic applications, weather systems are being deployed worldwide to support special missions. For example, they have been used by the National Ground Intelligence Center (NGIC) during Operations Enduring Freedom and Iraqi Freedom to assess the consequences of the potential release of hazardous airborne material, and thus provide a higher degree of safety to U.S. and allied military personnel potentially downwind of hazard zones. Similar models have also been employed for counter-terrorism support by the Defense Threat Reduction Agency at the Salt Lake City, Athens, and Torino Olympics. This work will continue, meeting the needs of a growing number of sponsors with specialized needs.
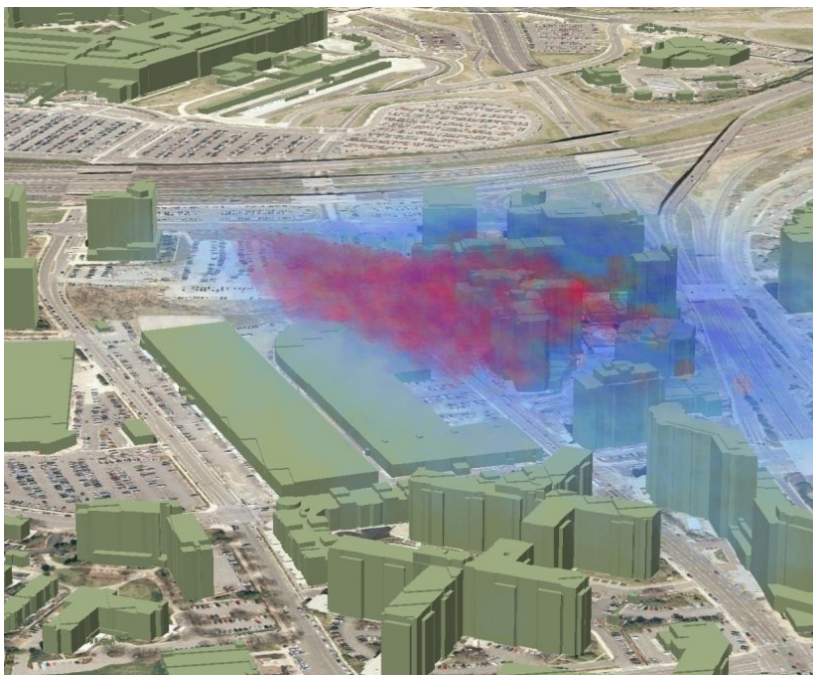
Six-hr forecast from WRF model coupled to the Los Alamos National Lab's (LLNL) QUIC-Urban diagnostic wind field model, and further coupled to the LANL QUIC-Plume Lagrangian particle transport and dispersion model, for predicting the urban transport and dispersion of simulated material released in the vicinity of Crystal City, Arlington, VA

Actions:
Continue to explore new ways in which WRF, LES-WRF, and other diagnostic models can be applied to produce specialized forecasts on short-range to seasonal time scales. Improve the RAL NWP technologies in several key aspects, including radar data assimilation, urban weather modeling, and NWP-hydrological coupled modeling.

Fine-scale Climatologies

Utilizing output from RAL's Climate-Four-Dimensional Data Assimilation (Climate-FDDA) system, further develop software for creatively interpreting the climate statistics in ways that have special relevance for sponsors.

Mesoscale analyses of current climates can be used for many purposes, including optimal siting of wind-energy farms and airports, calculating the most probable direction of the transport of hazardous material

at some future date and time, and scheduling the time and season for events that require specific meteorological conditions. To construct such climatologies for the many areas of the world where there are few routine four-dimensional (4D) observations of the atmosphere, RAL has developed a Climate Four-Dimensional Data Assimilation (Climate-FDDA) system that uses WRF to downscale present-day climates from archived global analyses.

The Climate-FDDA system is able to generate a 4D description of the diurnal and seasonal evolution of regional atmospheric processes, with a focus on the boundary layer. Unlike point measurements, the gridded fields define coherent multi-dimensional realizations of complete physical systems. Not only does the Climate-FDDA system define mean values of variables as a function of season and time of day, extremes are also estimated, and example days are produced.
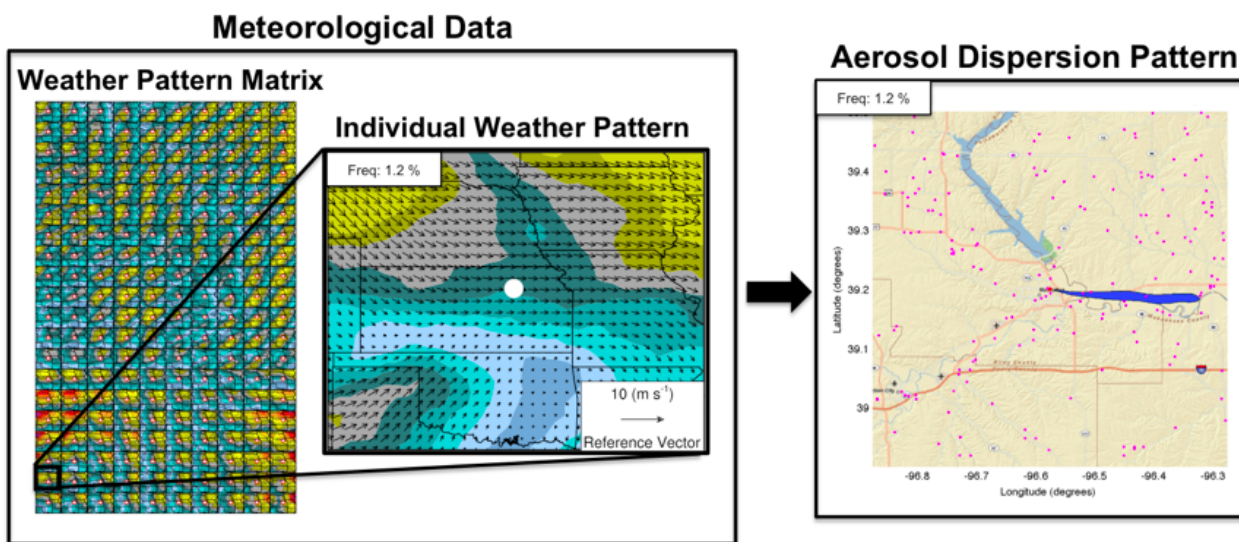
Conceptual diagram of aerosol transport inputs/outputs. The Climate-FDDA model output generated over Manhattan, KS (future site of the National Bio- and Agro-Defense Facility) is pattern-analyzed to extract dominant weather features, which are then passed into a bio-aerosol model to determine likely airborne plume patterns in the event of an accidental release from the facility

As an example of one Climate-FDDA application, the figure above shows a thumbnail map of the prevalent modes of wind speed and direction, and temperature that are expected over the Midwestern United States for a particular time of the year. Individual members of the cluster matrix, representing a typical weather condition expected to occur at a certain frequency, can then be fed into an aerosol model to determine the expected plume characteristics in the event of an accidental airborne release of material from a facility within the depicted area.

Actions:
Evaluate the impact of higher resolution on the quality of the climatologies, and consider the possibility of using ensemble climatology-generation methods. Produce a well-verified global climatology with a grid increment on the order of 4 km, or finer, over continents and littoral zones for use in a variety of applications such as wind-energy prospecting. Re-design Climate-FDDA to be capable of running hybrid dynamical and statistical downscaling techniques, in order to produce model output on increasingly finer grid increments that can address smaller areas of interest. Implement WRF-LES inside the Climate-FDDA system and demonstrate LES-scale downscaling capabilities in areas of high-interest to RAL's defense and homeland security sponsors. Develop the climatology software to creatively interpret climate

statistics in ways that have special relevance for sponsors. Ongoing: Evaluate the impact of higher resolution on the quality of the climatologies. Design and implement hybrid dynamical and statistical method. Implement WRF-LES and generate proof of concept LES-scale climatography.

Characterizing Plumes of Hazardous Material

Extend work on plume transport in stable boundary layers, reverse-locating plumes in urban settings, and coupling indoor and outdoor dispersion models. Extend our LES-model physics so that the resulting winds allow plumes to respond to the "chimney effect" in which anthropogenic and solar heating of buildings cause plumes to rise rapidly.

The mesoscale and urban-scale meteorological modeling activities provide essential input data for multi-scale capabilities that track the movement of plumes of hazardous material. Numerous Department of Defense and civilian (e.g., Environmental Protection Agency) plume models are employed, depending on the need with the models being verified with urban field-program data. As with the LES models, there are quickly executing plume models, such as LANL's QUIC-Plume model that are designed for operational applications such as the previously mentioned Urban Shield project, and there are more complex models that are used for research and for verifying the fast models. One aspect of this work area is the development of methods for characterizing the source of a plume (size, time of release, location, etc.) based on downstream measurements, thus allowing for intervention if material continues to be released. The figure below shows a plume simulation for a hypothetical release over complex terrain, with the skull and crossbones symbol depicting the point of release.
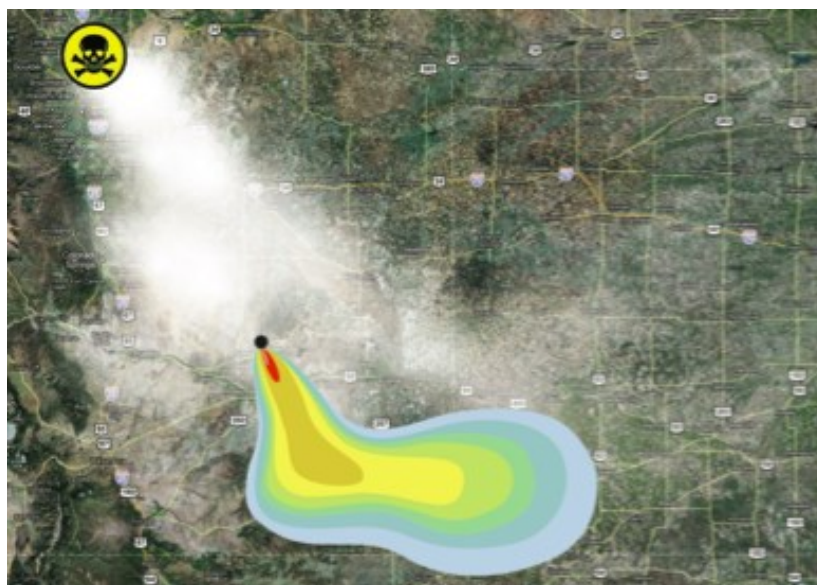
A simulated plume of hazardous material hypothetically released into the atmosphere in complex terrain, superimposed on a measured plume. The standard simulation approach would estimate that the release occurred where the black dot is shown, while in fact the actual release point is located at the skull and crossbones symbol.

The black dot at the origin of the color-coded estimated plume represents the location of a fielded chemical agent collector which detected significant chemical concentrations. The standard operating procedure is to use the collector concentration as the release location, as depicted in this figure, which results in the downstream plume pattern shown, and suggests that the peak concentration area of the event is south of the actual concentration pattern. This results in a grossly inaccurate estimate. If this were a real event, emergency responders following the modeled plume guidance could easily decide to move people to the north of the collector location, effectively exposing them to the maximum agent concentration. Our efforts are improving upon this technology through the incorporation of non-

traditional observations and human intelligence information. The utilization of this information via the NCAR variational source term estimation software enables the transformation of a source term search problem with a complex cost function surface shown in figure (a) below, into a less complex cost function surface shown in figures (b and c). This enables the search algorithm to more accurately identify the actual source term when the meteorological conditions are not well known.
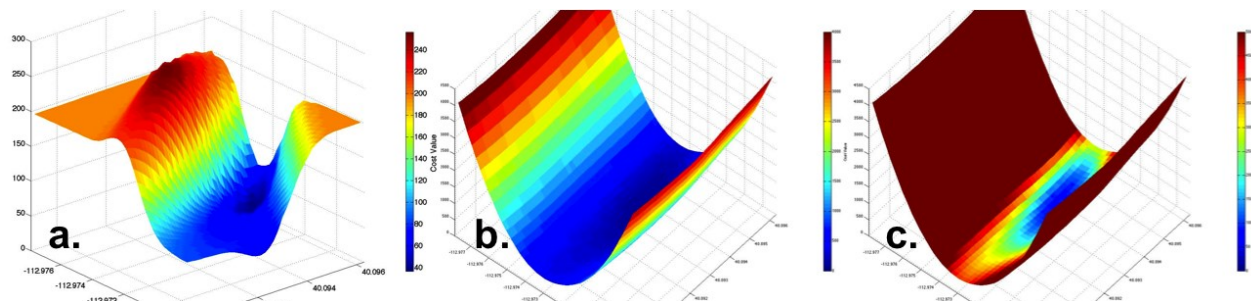
Actions:
Enhance plume modeling capabilities in the following areas: a) plume transport in stable boundary layers, b) coupling of indoor and outdoor dispersion models, and c) reverse-modeling of plume transport and diffusion in urban terrain.

Mesoscale Ensemble Prediction

Conduct research to determine optimal methods for defining ensemble members for fine scale features in the regions of special interest, and in particular, the urban environment. Develop methods for calibrating these new forecasts for operational use by stakeholders. Make the ensemble prediction the standard for routine delivery of forecasts to RAL sponsors, and inform users so they can confidently use the statistical information to optimize their decision process.

Many weather-sensitive agencies and industries make operational decisions based on mesoscale model forecasts; accurate forecasts support many of the other activities in RAL. Quite often decisions can be improved with probabilistic forecast information. Various ensemble filtering algorithms have emerged from academia in recent years, representing the best methods for initializing mesoscale ensemble forecasts while simultaneously providing a nearly-optimal analysis state of the atmosphere. Because of its critical importance to a variety of NSAP activities, a broad effort toward modernizing our mesoscale ensemble capability will continue.

One example is the four-dimensional relaxation ensemble Kalman filter (4D-REKF) FDDA scheme developed by RAL scientists. 4D-REKF combines the advantages of the cutting-edge ensemble Kalman filter (EnKF) data assimilation method with multi-model and multi-approach ensemble perturbations to provide an advanced seamless ensemble data assimilation and ensemble prediction system. During 2013-2017, 4D-REKF will be implemented and further advanced to provide forecasts with improved accuracy and more complete weather information for various weather-sensitive applications. In addition, model output statistical processing for information extraction and display, and value-added error correction and probability calibration will be applied to the ensemble forecasts and customized for end-users' needs.

Develop optimal methods for defining ensemble members and calibrating forecasts for specific user groups. Work with ensemble-forecast users to help them develop improved methods for integrating the statistical information into their decision-making systems

Frontiers

Analog Ensemble Techniques

NCAR has recently developed a novel approach to generate probabilistic predictions and provide uncertainty quantification, called the Analog Ensemble. The analog of a forecast for a given location and time is defined as the observation (or analysis grid point) that verified when a past prediction of a deterministic Numerical Weather Prediction (NWP) matching selected features of the current forecast was valid. The best analogs are combined to form an ensemble and to generate skillful and reliable probabilistic predictions.

As shown in the figure below, the analog ensemble method generates samples of the future observations via three main steps using a history of cases, called the analog training period, in which both a deterministic model prediction and the observations are available. Analogs are sought independently at each location and for each forecast hour (black square in step 1, representing forecast hour 42 in this example), and thus also for each time of day since only forecasts initialized at the same time are used. The best-matching historical forecasts for the current prediction are selected as the analogs (blue squares). An analog may come from any past date within the training period, i.e., a day, week, or several months ago. Next, each analog's verifying observation is selected as a member of the analog ensemble (green squares in step 2). Taken all together, these observations constitute the analog ensemble probabilistic prediction for the current forecast (orange circles in step 3). Details on the analog ensemble algorithm can be found in Delle Monache et al. (2011, 2012).
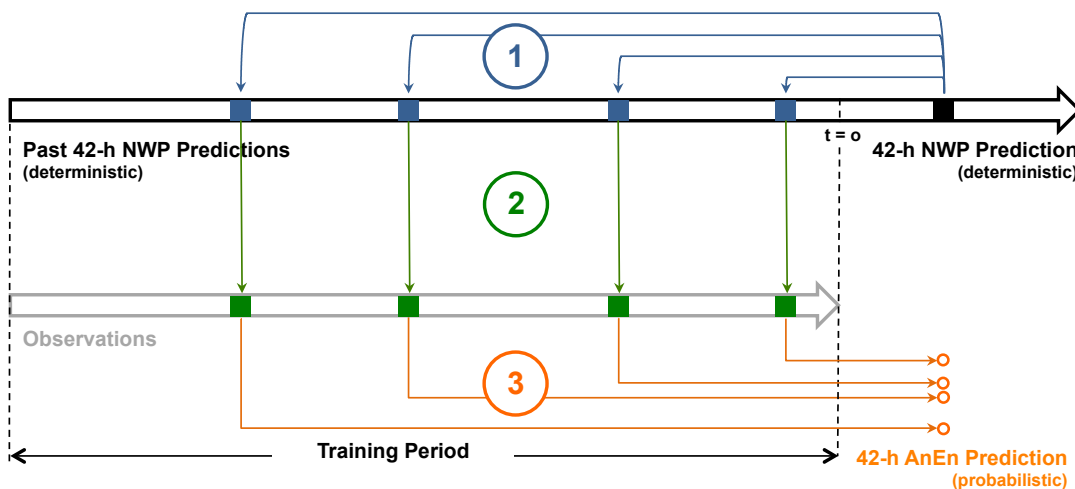
Schematic representation of the process for finding four members of the analog ensemble (AnEn) at forecast hour 42 for a given location.

The Analog Ensemble technique is based on a new paradigm to generate probabilistic predictions, where only a deterministic NWP-based forecast is needed to generate reliable uncertainty estimates, and where future predictions are based on observations from the past. Unlike an NWP ensemble, the Analog Ensemble attempts to sample directly from the true forecast PDF, thus avoiding the challenges of simulating model uncertainty, and providing naturally calibrated probabilistic forecasts. Because only one NWP forecast is needed, all the available computational resources can be dedicated to produce the best deterministic prediction, based on the finest affordable spatial and temporal resolution, and the most advanced numerical and physical schemes. The latter could allow us in the next few years to produce probabilistic predictions at LES or VLES scales.

So far, the Analog Ensemble technique has been applied successfully for general weather predictions and for wind energy power forecasting for point forecasts. Current sponsors and grant agencies include the U.S. Department of Energy (DOE), the U.S. Department of Defense (DOD), the National Renewable Energy Laboratory (NREL), Xcel Energy, Vestas Wind Systems, and Vattenfall.

It is worth noticing that recently the European Centre for Medium-Range Weather Forecasts (ECMWF) has expressed interest in exploring this capability as one of their probabilistic forecast products, and a discussion is ongoing to develop a project of mutual interest to NCAR and ECMWF.

Finally, the Analog Ensemble technique has been also implemented to downscale coarse re-analysis fields, to provide accurate estimates of wind resources at given locations, as well as to reliably quantify the uncertainties associated with such estimates.

References
Delle Monache, L., T. Nipen, Y. Liu, G. Roux, and R. Stull, 2011: Kalman filter and analog schemes to post-process numerical weather predictions. *Monthly Weather Review, 139, 3554–3570.*
Delle Monache, L., T. Eckel, D. Rife, B. Nagarajan, and K. Searight, 2013: Probabilistic weather prediction with an analog ensemble. In press, *Monthly Weather Review*.

Actions:
Refine the technique by developing new metrics to select the best analogs by developing new algorithms to select in an automated fashion the predictors used in the analog search procedure, and possible by weighting strategies for those predictors. Also, so far the technique has been tested with training data sets 15 months long, or less. Tests with multi-year training data sets (e.g., NOAA or ECMWF re-forecast data sets) will quantify the additional benefit and improvement resulting from using a longer training period. Test the technique to generate probabilistic prediction over a 3-D domain, where the ground truth is given by an analysis field, rather than by observations at specific locations.

5. Goal Area: Hydrometeorological Research and Applications across Scales

Overarching Priority

Conduct research to improve integrated understanding of cloud, precipitation and hydrological processes and develop tools that both facilitate community research on the water cycle and improve the societal resilience to changes in the water cycle across a wide range of temporal and spatial scales.

Motivation

Hydrometeorology is the science that combines study of the atmosphere and the hydrosphere, and the processes that control the hydrologic cycle. Understanding the hydrologic cycle is the key to understanding what will happen to water resources in the 21st century in the face of global change. Earth's water supply when considered on a regional basis may not be sustainable relative to agricultural and industrial practices of the last century. RAL's intention in this area is to work toward meeting the associated needs of national (federal, state, county and municipal) and international organizations in the public and private sectors by bringing state of-the-art science and methods to support operational decision making and future scenario planning. Users of such information vary from meteorological services, to flood control districts, to emergency managers, and to a variety of water resource managers.

The many questions that arise in this area can only be addressed by multi-year, multi-scale, interdisciplinary research programs. Two of the programs led by RAL involve significant cross-laboratory research efforts, the Water System program and the Short-Term Explicit Prediction (STEP) program. Both have been very successful in bridging efforts across multiple NCAR management units. A new hydrological prediction system based on WRF supports both these programs and also provides the community with a tool to explore hydrometeorological questions.

Current research foci include the following:

- Short-term storm prediction
- Hydrometeorological processes at the land-atmosphere interface
- Microphysical parameterizations for models
- Water systems under global change
- Winter precipitation and snowpack
- Aerosols and precipitation
- Water resources management

"The impact of water on all aspects of development is undeniable: a safe drinking water supply, sanitation for health, management of water resources, and improvement of water productivity can help change the lives of millions."

Dr. Rajiv Shah
USAID Administrator
World Water Day, 2011

This spectrum of research activities aims to improve understanding of hydrometeorological processes and increase the accuracy and value of related community-based prediction systems. These efforts extend from basic research to highly sophisticated applications.

Near-Term Objectives

Short-Term Storm Forecasting

Address research topics required to improve forecasts with a short time horizon: observations (data acquisition, quality control and data analysis); data assimilation; numerical weather prediction; nowcasting; physical parameterization; hydrometeorological prediction and end-user needs.

An important aspect of hydrometeorological research is to develop and improve the tools for short-term quantitative precipitation forecasts (QPF). Currently, extrapolation of observation data has diminishing skill beyond 2 hr. Numerical Weather Prediction (NWP) 0-8 hr model forecasts of precipitation lack the spatio-temporal accuracy needed by end-users in the prediction of site-specific, convective scale precipitation. This is due in part to delay in model spin-up, use of convective parameterization, and lack of dense observations needed to initialize the models. To overcome these deficiencies, research efforts will focus on determining optimal approaches to blending observations and heuristic system nowcasts with NWP models to produce more accurate QPF, in collaboration with scientists from NESL and EOL under the STEP research program. Research will also focus on techniques to improve storm nowcasts in high-resolution models through the use of data assimilation techniques such as 3DVAR, 4DVAR, and ensemble Kalman Filter. Along with improving short-term prediction of heavy precipitation is the need to obtain accurate quantitative precipitation estimates (QPE) that are a critical component of short-term forecasts and hydrologic runoff models. Research to improve QPE will be conducted using the new dual-polarization capability of U.S. operational radars. Storm precipitation estimation and forecasts will be combined with hydrological models to create a short-term hydrometeorological end-to-end forecast system. A planned field program in the Colorado Front Range will provide a vehicle to demonstrate and test these capabilities over complex terrain.
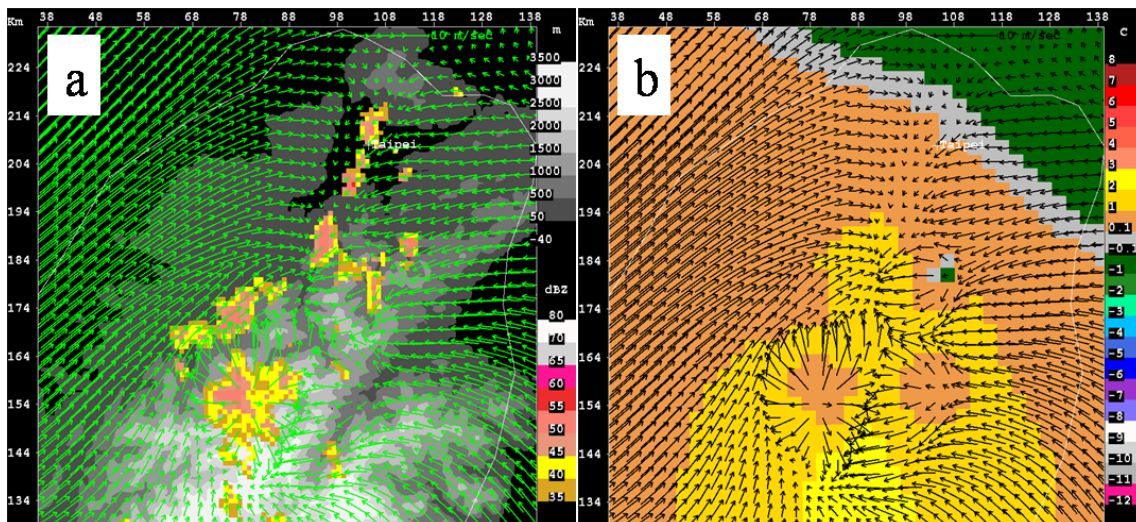
Results from the Variational Doppler Radar Assimilation System (VDRAS) (a) showing wind vectors at a height of 180 m above the terrain. The plot covers a 100 x 100 km area over northern Taiwan. The longest vectors are about 10 m/s. The gray shades are terrain height given by the scale on the right of the plot. Height ranges from sea level to over 2500 m. The colored objects are radar reflectivity in dBZ given by the scale on the right. (b) The same as (a) but the color fill is VDRAS-derived temperature

perturbations (deg C) given by the right hand scale. The temperature perturbations are with respect to the mean temperature at each height at the start of the VDRAS run which was several hours earlier.

Coupled Land Surface/Hydrology Modeling

Develop an integrated community WRF-Hydro modeling system for the hydrometeorological and regional climate research community to provide a framework from which to examine both terrestrial and atmospheric hydrological processes across a range of temporal and spatial scales.

RAL scientists are involved with a variety of projects investigating hydrometeorological processes at the land-atmosphere interface such as snow accumulation and ablation, infiltration, evaporation, soil moisture dynamics, and runoff generation processes associated with flash floods. A major goal is to improve our understanding of land-atmospheric interactions spanning a variety of time and space scales (weather to climate) and their representation in coupled weather and climate models. This includes development of multi-physics capabilities within the community Noah land-surface and coupled WRF-Hydro and WRF-Crop models to facilitate community research on hydrologic processes and land-atmosphere interactions, and, ultimately, help water and agricultural managers to more effectively plan for both flash flood events and future climate change.

Key tools for these process studies include radars, satellites, surface meteorological stations, surface flux measurements, and the WRF-Hydro model and Noah land surface models for both weather and regional climate. WRF-Hydro and WRF-Crop are designed to be a framework for the community to link their hydrological and agricultural models to WRF. RAL has linked a distributed version of the Noah land-surface model to this framework. These community models that include the Noah land surface model and the coupled WRF-Hydro system will serve as the vehicle by which further interaction with the hydrological community will occur. The development and support of WRF-Hydro and its physics components will be a major focus for HAP scientists in the future.

Water Systems Program: Water Resources under Global Change

Investigate how water vapor, precipitation, and land surface hydrology interact across scales to define the hydrological cycle, including under global change. Improve the representation of the water cycle in climate models. Examine the impact of global change on snowfall, snowpack and runoff in headwaters regions by conducting high-resolution WRF simulations. Apply the Water Evaluation and Planning (WEAP) tool in collaboration with users to a variety of issues concerned with climate change impacts on water resources and develop science-based adaptation strategies.

Improving the representation of the water cycle in climate models

An important goal of the Water System Program is to improve the representation of the water cycle in climate models. While climate models typically predict temperature with reasonable confidence, predictions of precipitation are notably weak. Our focus has been on the diurnal cycle of warm season precipitation including diagnoses of rainfall climatology downwind of major mountain ranges over continental regions. These global and regional studies have shown that such regions are frequented by organized convection systems, which propagate and may produce up to 70% of the observed warm season precipitation. These systems, however, are inadequately represented in current global and regional climate models. IPCC4 projections of precipitation trends highlight these regions as having the largest

variability or uncertainty. To address this deficiency, the Water System program will focus on: 1) evaluation and improvement of parameterizations of convective precipitation over continental regions globally; and 2) the impact of climate change on these types of systems.

Colorado Headwaters Project

The Colorado Headwaters project focuses on critical questions concerning the effect of climate change on snow processes in the western cordillera of North America. It employs both high resolution models and observations to investigate the likely impact of climate change on snowfall and snowpack occurring in the headwaters of major rivers originating in Colorado. The project extends across several units of NCAR and to collaborators in the university community. Pseudo-climate change scenarios will be analyzed using fine-scale WRF simulations down to 4-km horizontal resolution for eight years in the past and future. These will be coupled with the distributed hydrological model (discussed above), and the water resources management tool (discussed below) to investigate the impact of climate change on

Diurnal cycle of summertime rainfall frequency of occurrence over the Continental U.S.

streamflow and water management in the Headwaters region. In the future a high resolution simulation of current and future climate will be conducted over North America using the Yellowstone supercomputer to investigate process level changes to the water cycle over various mountain ranges.

Water Evaluation and Planning Tool (WEAP)

WEAP is a sophisticated modeling tool that allows water managers to assess, among other things, the impact of future climate-predicted precipitation on the operation of their watershed or other water resource issues. This model was co-developed by David Yates of HAP and scientists at the Stockholm Environment Institute to address the growing need for new tools and methods to study the impacts and adaptation strategies related to global change. The model couples physical hydrology and water planning and management information within a single framework, allowing users to develop scenarios and strategies for more robust water management decision making in the face of climate change. This tool will be used to evaluate the impact of future climate change on regional and local water resources including the Colorado Headwaters region.

Aerosols and Precipitation

Understand and quantify the relationship between atmospheric aerosol, clouds, and precipitation at the ground. Evaluate intentional modification of aerosols for precipitation enhancement.

Aerosols (natural and anthropogenic) influence clouds through microphysical processes during droplet and ice nucleation. Understanding the basic microphysical properties of natural and pollution particles and relationships between cloud properties and aerosol loading are important parameters in the efficiency

of precipitation development. The Aerosols and Precipitation group in HAP conducts basic and applied research on the impact of aerosols on cloud microphysical processes such as cloud droplet nucleation and formation of rain and snow.

Many countries around the world practice cloud seeding (injecting aerosols into clouds) to enhance precipitation, but in most regions of the world there is little, if any, scientific evidence of its effectiveness. To investigate cloud seeding effectiveness, RAL research will focus on various aspects of advertent and inadvertent modification of clouds and precipitation by aerosols. Past efforts have emphasized cloud and aerosol measurements at a variety of locations around the world (India, Saudi Arabia, UAE, Turkey, Mali, Australia, and Indonesia). A program of "best practices" has been followed that emphasizes airborne and radar measurements and cloud climatology studies as a prelude to conducting any systematic evaluation such as randomized seeding trials. Capacity building through education and training are a major part of the effort.

RAL's current and future work in this area involves three main efforts:

- Statistical and physical evaluation of a randomized cloud seeding experiment in Wyoming for orographic snowpack augmentation with funding from the State of Wyoming. As part of the physical evaluation, RAL is participating in the University of Wyoming led NSF program called ASCII to study the physics of precipitation formation from ground-based silver iodide seeding in the Sierra Madre mountains of Wyoming.
- Research on the effectiveness of cloud seeding in Idaho using high resolution modeling and a new cloud seeding computer code implemented into the Thompson microphysics scheme and a planned field program using aircraft and ground based radars. This effort is funded by Idaho Power.
- Evaluation of the impact of aerosols and cloud seeding on monsoon clouds with funding from the Indian Institute of Tropical Meteorology.

Microphysical Parameterization

Improve forecasts of winter weather conditions at the ground, including quantitative precipitation forecasts.

Research activities related to microphysical modeling are designed to improve the simulation of cloud water (including super-cooled cloud water), rain and drizzle, freezing rain and freezing drizzle, snow, snow pellets, ice pellets and hail in WRF Rapid Refresh and other WRF models. Super-cooled cloud water and freezing drizzle are emphasized due to their importance to aircraft icing. Future work will focus on the improvement of the simulation of convective storms through processes impacted by microphysical processes such as the cold pool.

Winter Precipitation and Snowpack Measurement

Improve the measurement of winter precipitation rate, type, and snow size distribution by direct measurement at the ground and via remote sensors.

Efforts in this area include the development of radar-based algorithms to detect winter precipitation type, winter microphysics studies using a video disdrometer and other data at the Marshall Field Test site, participation in winter field programs, analysis of data from field programs to improve understanding of winter precipitation processes, and snowfall measurements to evaluate the Wyoming orographic snowfall enhancement experiment. Scientists in this area are also heavily involved with the Colorado Headwaters research effort (see earlier section). An X-band dual-polarization radar will be used to map orographic

precipitation in the Colorado Rockies and in southeast Wyoming starting in 2013. A recent development is the decision by the NOAA Climate Reference Network program to move its Sterling, VA test facility to the Marshall Test site. We anticipate that future research opportunities related to snow gauges and other winter surface based instrumentation may develop out of this effort. The World Meteorological Organization (WMO) recently decided to make the Marshal Field Test site the U.S. testbed for its Solid Precipitation Inter-Comparison study for automated snow gauges. Measuring snow on the ground continues to be a difficult problem given the multiple hydrometeorological processes such as precipitation, sublimation, and redistribution by wind. To address this issue we will continue the development of a new technique to map snow depth using a scanning laser at the Marshall and Niwot Ridge test sites. A future focus will be on measuring evapotranspiration at various winter sites such as the Fraser Experimental Forest and Niwot Ridge.

Frontiers

Water and Energy in the West

Define and implement a community-wide initiative to address the pressing problem of water availability and water-related disasters and the exploration of the water-energy nexus in the Western U.S.

Climate model projections suggest that the Southwest U.S. could experience severe drought in the next 25-50 years. NCAR scientists have the requisite skills and tools to address many of the key scientific and societal issues related to understanding and adapting to this change. Climate change also suggests the increased occurrence of extreme events such as floods.

Research is needed that explores the interactions, and possible conflicts, between water-management and energy-management decision making. National-scale guidance is needed on energy policy and decision making that leads to reduced greenhouse gas emission, and avoids unintended consequences related to water management in the context of energy generation.

"Both the availability and use of water are changing. The reasons for concern over the world's water resources can be summarized within three key areas: water scarcity, water quality, and water related disasters."

U.N World Water Development Report, "Water for People, Water for Life"

Different energy management strategies will have different water management implications that extend from the local, to the regional, and ultimately to the national scale. Further, it is recognized that the local importance of these impacts will be defined by the characteristics of individual water systems within which energy management strategies are implemented.

Proposed areas of focus for this initiative are:

- Improve scientific understanding of seasonal changes in precipitation, sublimation, snow water equivalent, snowmelt, soil moisture, and transpiration in the western USA, with particular attention to changes associated with a shift to earlier snowmelt and the potential shift from energy-limited to water-limited systems. A CONUS high resolution WRF simulation will be conducted to support this work.
- Improve scientific understanding of the magnitude of the expected drought through the use of high-resolution climate models (in association with the Colorado Headwaters project).
- Evaluate water resource impacts through use of the WEAP model.

- Implement RAL's flash flood decision support system into the infrastructure of Western water utilities.
- Study societal impacts through interactions with scientists in the Climate Science Applications Program.

Minutes to Seasons Hydrometerological Forecasting System

Many hydrometeorological applications demand probabilistic forecasts at lead times from minutes to seasons. Meeting this demand requires integrating different types of quantitative meteorological analyses and forecasts with state-of-the-art models of environmental processes (e.g., hydrology, crop yield, etc.). Essential technical capabilities include (1) ensemble methods for high-resolution meteorological analyses; (2) ensemble high-resolution meteorological forecasts from merged radar and NWP systems (lead time of 0-72 hours); (3) ensemble downscaling of global-scale numerical weather prediction forecasts (lead time of 1-14 days); (4) ensemble local-scale meteorological time series conditioned on seasonal climate outlooks (lead time of 0-12 months); (5) environmental models with advanced data assimilation capabilities; and (6) statistical post-processing methods to improve the probabilistic information content in environmental forecasts. The figure below provides an example of a minutes-to-seasons forecast system for hydrology; similar systems can be used for other environmental processes (e.g., using WRF-Crop for crop yield).
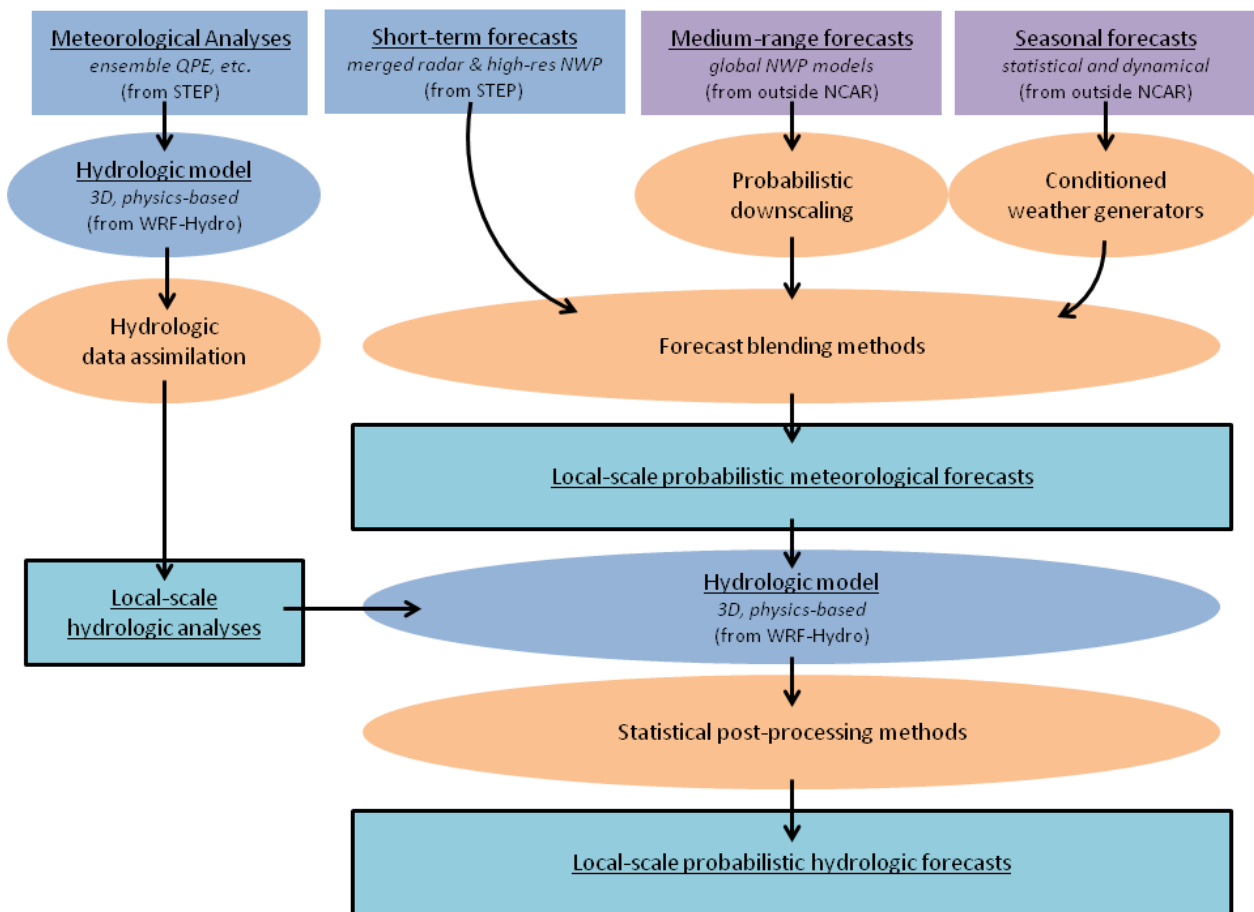
Components of a minutes-to-seasons hydrologic forecasting system, capitalizing on products developed within NCAR (blue shades) and outside NCAR (purple shades).

Research and development in this Frontier area will focus on each of these areas to a level sufficient for integration into a hydro-meteorological forecasting system. Estimating current hydro-meteorological conditions requires improvements to precipitation estimation using dual-polarization radar, gauges and satellite, while short term storm nowcasting will optimally combine (via data assimilation and blending techniques) radar observations with NWP systems. Ensemble research will be required to make the 1-2 week forecast, while longer time scale climate modes involving ocean initialization and atmospheric blocking will be needed for the sub-seasonal and seasonal forecasts. Statistical research will be used to both integrate these components and produce reliable probabilistic forecasts.

6. Goal Area: Research and Applications for Surface Transportation, Energy, and Other Emerging User Sectors

Overarching Priority

Identify, develop, and implement advanced weather decision support systems for new and emerging user sectors such as surface transportation, renewable energy, extreme weather, and other applications.

Motivation

Life and property could be spared and economic performance improved if decision makers used weather information more effectively. This motivates engaging stakeholders in various economic sectors, many of which have not been historically well served by the meteorological community, to explore new solutions to specific problems.

During the next five years, stakeholders in wireless vehicle technology programs, wildland fire management and mitigation, energy and particularly renewable energy, precision agriculture, extreme weather, retail operations (just-in-time delivery concept), and data analysis will be proactively engaged to understand and document their unmet needs for weather and climate information and to address their needs through science and technology development. In addition, applications in boundary layer and complex flow, extreme weather, and seasonal forecasting will be explored

Near-Term Objectives

Surface Transportation Weather

Become the central focus for research and development for the weather component of the United States Department of Transportation (USDOT) wireless vehicle technology program. Accelerate the adoption of the Maintenance Decision Support System technology across the nation and extend this technology by developing transportation decision support systems focusing on traffic, incident, and emergency management and maintenance beyond snow and ice control. Perform research to seamlessly blend the strategic prediction component of the system with tactical short-term weather and road condition technologies.

Since the late 1990s, RAL has played a pivotal national role bringing the surface transportation and weather communities together to improve the performance of surface transportation weather services. RAL will continue this community building process, as the concept of advanced weather information for the surface transportation sector holds great promise. RAL will continue to work with the surface transportation stakeholders in a proactive manner to implement a research agenda that addresses national and international needs for improved surface transportation weather services for the surface transportation community and the traveling public. Surface transportation research efforts include the further development of: the Maintenance Decision Support System (MDSS) that focuses on pavement condition modeling, precipitation prediction, data fusion techniques, snow and ice control rules of practice, and summer maintenance operations rules of practice; the use of vehicles as weather and road condition

sensors; the Vehicle Data Translator that will ingest, process, and generate derived weather and road condition products for road segments; in-vehicle information systems for communicating weather and road hazards; and advanced data quality control techniques for fixed and mobile datasets.

Actions:
Coordinate with the USDOT Federal Highway Administration (FHWA), State DoTs and private sector stakeholders to define specific R&D initiatives required to provide wireless in-vehicle operations with advanced weather and climate information in the following categories: a) diagnosing pavement condition, b) use and quality assurance of vehicles being used as weather probes, c) precipitation detection and nowcasting, d) processing weather data from vehicle sensors, and e) formulation of informational products to communicate weather and road hazards to drivers, road maintenance, traffic management centers, and road safety stakeholders.

Coordinate with the USDOT FHWA, Federal Railroad and Transit Administrations, Federal marine operators, State DoTs and the private sector to define specific research and development initiatives required to provide these sponsors with decision support systems based on advanced weather and climate information to support their operations.

Design, build, and test prototype road weather applications incorporating mobile data. Transfer software systems to the private sector for broad implementation.
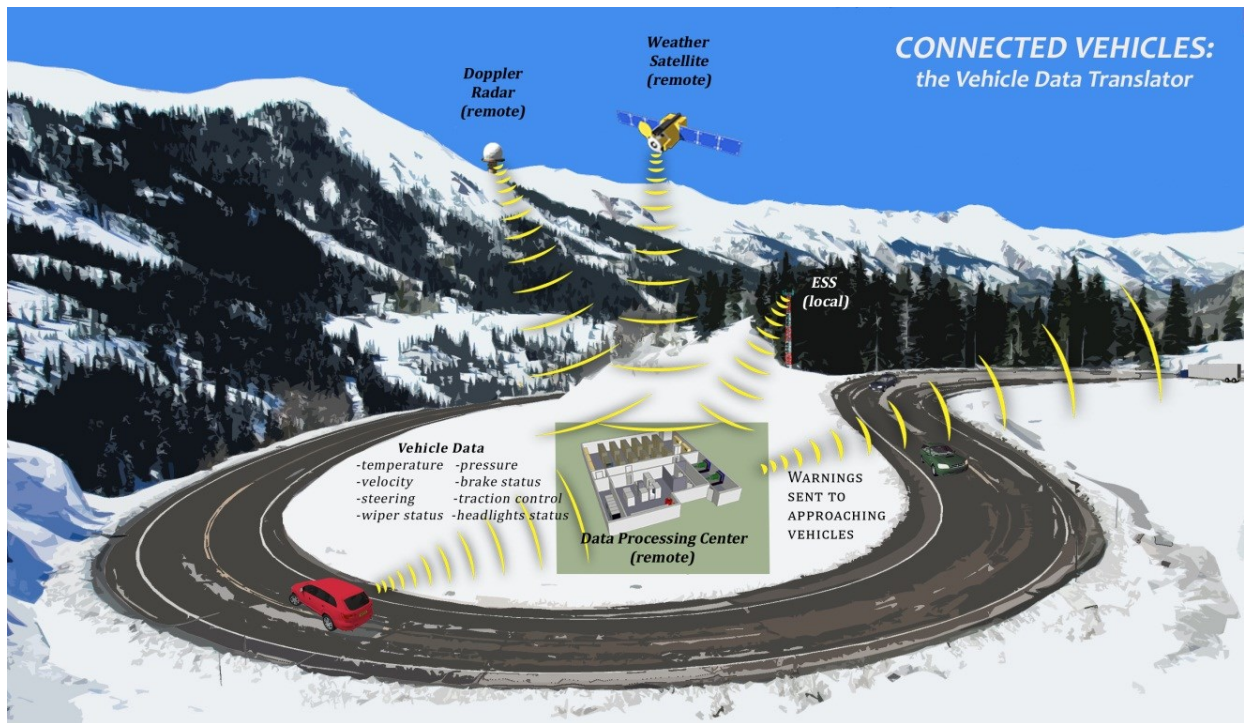

Illustration of the VDT System. Data are first acquired from mobile vehicles and then combined with "traditional" meteorological data sources to create road hazard products. The road hazard information can then be wirelessly transmitted to warn other drivers.

Renewable Energy

Develop new methodologies to more accurately assess and predict variable renewable energy resources (wind and solar radiation) to provide information on resource variability to advance the deployment of renewable energy technology.

Risks associated with energy supply and demand revolve around market dynamics, financial conditions, politics, technology choice, fuels, environmental quality, and weather. The recent policy trend to require a larger fraction of the energy portfolio devoted to renewable energy sources, such as wind and solar, puts additional strain on the energy industry as these sources are less predictable than traditional generation sources. The influence of significant weather events on the energy industry has increased with diminishing reserve margins to meet peak loads. In the Western U.S., weather factors have not only included unusually hot summer and cold winter events, but also low precipitation that reduces hydropower capacity and increases electrical demand for irrigation pumping and groundwater withdrawal. Additionally, utility maintenance and operations could benefit from weather decision support systems at various temporal lead times ranging from minutes to decades, as well as from prediction of extreme events and their likely impact on system and grid management. Improved weather prediction and precise spatial analysis of mesoscale weather events are crucial to both short- and long-term energy management.

Photo of wind turbines at an Xcel Energy wind farm in Northern Colorado

Actions:
NCAR and its research collaborators will actively engage the renewable energy industry and federal agencies to seek opportunities for improving the analysis and prediction of weather variables important to energy supply, particularly wind and solar radiation. Improving the resource assessment/characterization and prediction of wind and solar radiation will require research investments in weather modeling (global to local scales), data assimilation, boundary layer meteorology, cloud and precipitation processes, measurement technology, turbulence, statistical post processing techniques, and land surface characterization and prediction.

NCAR will engage this economic sector by forming partnerships in the research and business community, joining the Utility Variable Generation Integration Group (UVIG), American Wind Energy Association (AWEA), and other relevant alternative energy organizations, expand collaborations with the National Renewable Energy Laboratory (NREL) and the Center for Research and Education in Wind (CREW), North America Wind Energy Academy, serve on committees focused on using climate and weather information in alternative energy operations, present relevant papers at renewable energy conferences, and exhibit NCAR capabilities at relevant stakeholder conferences and trade shows.

NCAR and its research collaborators will focus on weather and climate systems and science that are critical to infrastructure planning and management, prediction of energy demand, management of energy supply, energy pricing and markets, energy system operations and maintenance, regulatory compliance, and economic risk minimization. The energy industry has expressed needs in the following areas which will be NCAR‟s specific foci:

- Improved weather forecast accuracy
- Improved weather nowcasting capabilities (0-3 hour predictions)
- Improved resolution of forecast information and diagnostic data in time and space (e.g., hourly heating and cooling degree day calculations, hourly and shorter term wind and solar predictions)
- A better understanding of the uncertainty that is inherent in the forecasts
- Improved analysis of the resource and its variability over long time scales, including under projected climate change scenarios
- Improved data and analysis of extreme events and their impact on renewable energy production, including providing data for analysis for improving designs
- Assistance for developing countries to utilize their renewable energy resources
- Improved understanding of user capabilities to utilize information for specific applications
- Understanding barriers to using improved information in decision making
- Additional weather observations at targeted strategic locations as determined by quantitative methods
- Quantifying the value of weather information to the utility industry

Wildland Fire Management and Mitigation

Identify opportunities to field test the new WRF-Fire coupled model and CAWFE, which were developed in NCAR (RAL and NESL), in a near-operational environment in collaboration with stakeholders in the land management community, and integrate with decision support systems.

The number and intensity of wildland fires continue to grow taking a huge toll on society. Wildland fire costs the U.S. approximately $10B annually. Climate change and the expansion of developed lands will likely increase the impact of wildland fires. For nearly two decades, NCAR has worked with federal, university, and international partners to develop models such as the Coupled Atmosphere-Wildland Fire Environment (CAWFE) model and more recently, the Weather Research & Forecasting (WRF) model that couples numerical weather prediction with wildland fire models to predict fire behavior and its feedback on the local atmosphere. This effort builds on longstanding NCAR research in areas ranging from atmospheric science, weather prediction, coupled models, data assimilation, land surface modeling, plume dispersion, atmospheric turbulence, system engineering, testing and verification, GIS, and decision support system development. These efforts have significantly improved our understanding of fire behavior and mitigation strategies. Researchers are at the threshold of being able to run near-real-time fire behavior models to support fire control operations. Additional decision support technology could make these models of great use to the fire control community. Continued sponsorship of fire research and development activities will ensure that wildland firefighters have the tools they need to safely perform their duties and advance research associated with coupled modeling systems.
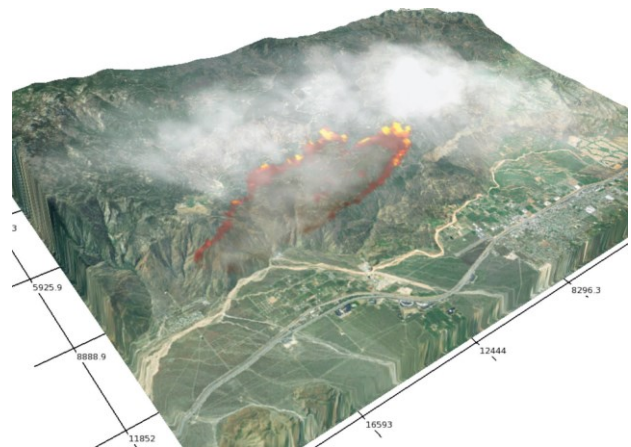
Model simulation of the 2006 Esperanza fire in Cabazon, CA shows the fire line and smoke plume.
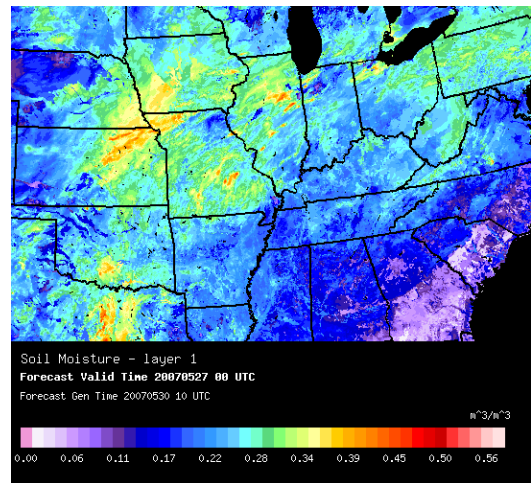
- Coordinate with potential sponsors to identify opportunities to demonstrate the CAWFE and WRF-Fire capabilities to support near real time fire operations.
- Expand testing program to a national and international program level that would be comparable to the existing NCAR Joint Numerical Testbed capabilities and resources.
- Develop decision support capabilities around the WRF-Fire model to meet user needs

Precision Agriculture Decision Support

Using previous work with HRLDAS, DICast® and the Noah Land Surface Model as a baseline, develop decision support systems focused on precision agriculture concepts for various stakeholders (agricultural companies and weather provider companies) in the agricultural sector.

Weather, both directly and indirectly, is the critical factor in the success of a harvest and farmers' livelihoods. Severe weather events, such as hail, high winds, tornados, and flash floods can destroy an entire harvest in a very short period. However, many agricultural decisions simply require more accurate forecasts of the weather and the resultant soil conditions. Precise soil temperature and soil moisture forecasts are critical to the timely application of pesticides and to efficient irrigation practices. With NASA funding, RAL collaborated with industry to develop a prototype agricultural decision support system that optimizes the timing of pesticide application and irrigation to minimize the impact of emerging pests. The project utilized advanced weather and land surface models and a data fusion technology that continuously optimizes the weather and soil predictions. This research has led to improvements in the High-Resolution Land Data Assimilation System (HRLDAS), Dynamic Integrated Forecast System (DICast), and Noah Land Surface Model. A major objective of the research was to evaluate the impact of incorporating NASA MODIS data into the system. This research was instrumental in providing critical feedback to the weather and land surface modeling, and satellite communities and represents a cross disciplinary effort. Continued work in this area will lead to more precise prediction of weather and soil conditions and more efficient and profitable agricultural operations, and will become a component of the WRF-Crop system described in Section 5 above. RAL has an interest in continuing this research with additional sponsorship.

Output from RAL's soil condition prediction system showing soil moisture (kg/m^3) in the top centimeter of soil.

Actions:
Coordinate with potential sponsors to identify needs within the precision agriculture sector that can benefit from decision support systems using advanced weather and climate information. In collaboration with sponsors and development team members, design, build and test prototype agriculture-oriented decision support systems.

Data Analytics and Computational Intelligence for Deterministic and Probabilistic Prediction

Explore new data analytic and computational intelligence methods to improve the overall forecast skill of RAL's DICast system and develop new capabilities to generate probabilistic weather prediction products (e.g., probability density functions). Develop new user-focused techniques for communicating uncertainty.

RAL has been a leader in developing weather prediction systems that blend data from numerical weather prediction models, statistics datasets, real-time observations, and human intelligence to optimize forecasts at user-defined locations. The Dynamic Integrated Forecast System (DICast) is an example of this technology and it is currently being used by several of the nation's largest private sector weather service companies. There is a growing desire in industry to have fine-tuned forecasts for specific user-defined locations as well as over wide gridded areas. This trend is clear in the energy, transportation, agriculture, and location-based service industries. RAL's expertise in meteorology, engineering, computational intelligence, and applied mathematics and statistics, will be utilized to address society's growing need for accurate location-specific and gridded weather information.

Actions:
Coordinate with potential sponsors to identify and prioritize operational needs for deterministic and probabilistic prediction systems and advanced post-processing methods.

Create a standardized database consisting of model output and quality controlled observation values. This database will serve as the foundation for RAL's data analytics algorithm development and will enable researchers to utilize identical input and target data sets for comparative algorithm evaluation. This effort will pave the way for incorporating big data in our analytics.

In collaboration with sponsors and development team members, design, build and test prototype decision support systems that optimize blending of data from various sources to produce both high quality deterministic forecasts as well as to quantify the uncertainty. This effort will require using both computational intelligence methods and forefront methods to calibrate the probabilistic prediction (Kalman filters, analog approaches, Bayesian Model Averaging (BMA), Linear Variance Calibration, quantile regression, etc.).

Perform detailed comparative analyses of various computational intelligence algorithms and evaluate using common input and target data sets. Determine strengths and weaknesses of candidate algorithms. Use those evaluations to guide further algorithmic research and development directions. Determine the optimal number of data streams and relative importance of particular models in optimizing predictions.

Frontiers

Complex Multi-scale Flows and Atmospheric Boundary Layer Research

Perform research to significantly advance our knowledge of complex multiscale flows, particularly in the atmospheric boundary layer, and develop new methods and techniques to more accurately characterize and model the boundary layer to improve the prediction of surface and near- surface weather conditions.

Much of the effort put into improving NWP model forecasts focuses on the upper levels and precipitation prediction; however, most of human activity unfolds at the interface between the atmosphere and land or sea surface. While larger scale, upper level flows often represent the dominant forcing, details of processes that mediate interaction between land or sea and the atmosphere have a profound effect on weather and climate. Many of the applications therefore require highly accurate high-resolution forecasts of wind and temperature variables in the atmospheric boundary layer (ABL). In the past, details of processes in ABLs were often studied in isolation or through a weak coupling with the upper atmosphere. With development of "big data" and exascale computational capabilities it will be possible to combine vast amount of observations with high-resolution numerical simulations resulting in more accurate analyses, better understanding and forecasting of complex, multiscale flows in ABLs.

The ABL is characterized by strong thermodynamic and kinematic turbulent energy exchanges between the atmosphere and the land surface. Thus, the ABL is sensitive to terrain characteristics, surface heating, surface roughness, vegetation, albedo, and soil conditions. Synoptic and mesoscale dynamical processes also impact the ABL including, but not limited to, low-level jets, frontal processes, thermally driven circulations, gravity waves, and critical levels. The details of the diurnal cycle and nocturnal collapse of the boundary layer are not well understood, yet are critical for accurate forecasts of boundary layer variables. Finally, modeling across the so-called *terra incognita* between LES scales and NWP scales is an unsolved problem that requires careful attention to numerical discretization and new turbulence parameterizations. Development of comprehensive multiscale modeling capability is critical to many boundary layer model applications.

Our ability to accurately predict near-surface weather conditions is highly constrained by our lack of knowledge of ABL processes and by their excessively simple treatment in NWP models. A better understanding of the ABL, particularly over complex and/or heterogeneous surfaces, will lead to improved prediction of ABL structure and evolution, and in turn, improved near-surface weather forecasts. Major stakeholder communities that are sensitive to near-surface weather include renewable energy, aviation, air quality, homeland security (e.g., hazardous plume transport), surface transportation, agriculture, construction, water resources (evaporation), and recreation.

In addition to this research leading to improved forecasts of ABL weather, the knowledge gained and new parameterizations developed will have an equally large impact on regional simulations of future climates. Virtually all of the stakeholders, for whom climate downscaling simulations aim to provide information for critical decisions, care most about conditions at or near the surface. Modeling the ABL properly in regional climate models is essential to capitalizing on the large investment in the IPCC model runs used to drive the downscaling work. It is becoming increasingly apparent that ensemble weather prediction on the mesoscale and synoptic scale should include the effects of uncertainties in the parameterizations. The proposed research on ABL processes and parameterization will benefit the further development of such stochastic methods for representing the ABL and its interaction with the land and water surface.

Actions:
Seek opportunities for funding to improve our understanding of complex multiscale flows, particularly in the ABL with an initial focus on turbulence, momentum mixing, the diurnal cycle, and the low-level jet. These phenomena play a critical role in the weather community's ability to predict surface and near-surface wind conditions, which is critical for both the wind energy industry and aviation. NCAR will seek opportunities to participate in field experiments that focus on better understanding complex flow with theory, modeling, and measurements. Large eddy simulation models will also be utilized to evaluate new and improved physics schemes and turbulence parameterizations and their impact on predictability.

Expand the research to include the convective atmospheric boundary layer and its sensitivity to surface characteristics. Focus will be on improving the boundary layer physics schemes (explicit and

parameterized) contained in advanced numerical weather prediction models such as WRF and its LES variation. Perform research to verify the performance of new schemes. Conduct research on modeling across scales that could include assimilation, improved boundary layer parameterizations that are valid across broader scales, and other methodologies to blend high resolution modeling with NWP. The Joint Numerical Testbed Program will be involved in testing the new schemes. Successful improvements will become part of the WRF community modeling system.

Extreme Weather Response

Become a research and development hub for extreme weather decision support systems. Accelerate research and development focused on adaptation of infrastructure to future extreme weather vulnerabilities and communication of hazards to the public.

Since the 1980s, RAL has played a pivotal national role developing weather and climate decision support systems. RAL will continue this community building process by transitioning these knowledge bases to develop systems to improve public, emergency management and first responder situational awareness, capability, and safety.

Actions:
Coordinate with Federal and State agencies, as well as the scientific community, to define specific R&D initiatives required to provide extreme weather decision support systems with advanced weather and climate information for the following communities: a) public, b) emergency management, and c) first responder. For each community, perform research to develop an understanding of their needs, preferences, and uses and communication of advanced weather and climate information. Design, build, and test prototype extreme weather applications. Transfer software systems to the private sector for broad implementation.

Develop new methods to quantify the physical and economic impact of extreme weather events. Quantify the benefits of improved warning process by applying non-market valuation methods to study household's values or improved forecasts of extreme events.

Coordinate with International, Federal, and State agencies, as well as the scientific community, to define specific R&D initiatives regarding adaptation of infrastructure to extreme weather and climate change. Advance understanding of mitigation and preparedness measures needed to withstand anticipated future extreme weather events under differing climate change scenarios. Transfer knowledge to practitioners.

Seasonal Forecasting

Advance the state-of-the-art of seasonal forecasting in order to better serve the needs of industry and society.

Forecasting the seasonal trends in meteorological variables, such as temperature, precipitation, wind, storm frequency, etc. could provide useful information for resource planning for many commercial and societal needs, including the utility, transportation, retail and wholesale, recreation, hydrometeorological, and many other sectors. Seasonal forecasting requires assessing the teleconnection patterns set up by anomalies in the oceanic and land surface forcing patterns. Such anomalies initiate large scale, persistent patterns in the atmospheric response such as the El Nino/Southern Oscillation (ENSO). These patterns in turn produce teleconnection patterns (such as the Pacific North American, Arctic, and North Atlantic Oscillation patterns) that impact the surface climate over continents. Identifying such patterns is the first step to providing forecasts of the most likely seasonal weather patterns that cause anomalies in

meteorological variables, such as temperature, precipitation, winds, and storm frequency. New methods that blend physical understanding with computational intelligence, state-of-the-science statistical methods, and data mining have the potential to advance seasonal prediction capabilities.

Actions:
Understand the needs of the user community for seasonal forecasts and perform R&D to determine how to best meet those needs.

Blend research on dynamical and physical processes with computational intelligence, state-of-the-science statistical methods, and data mining techniques to produce a better understanding of the causes and transition processes from one seasonal regime to another. Use that understanding to produce new forecasting methodologies that blend empirical and dynamical prediction methods.

Develop new decision support tools for seasonal scales around the enhanced understanding and new prediction methods that meet the needs of end users.

7. Goal Area: Testing, Validating and Verifying Advanced Numerical Forecasting Techniques

Overarching Priority

Provide a central collaborative function within NCAR and a distributive network of collaborators for testing and evaluating numerical forecast systems that are important to operational decision makers and the international research community, which will facilitate the ingestion of new research capabilities into operational forecasting centers.

Motivation

A long–standing goal within the numerical prediction community, and particularly within the community of operational users of numerical models, is to have a facility that has expertise in testing and evaluating all types of numerical techniques. This facility would provide unbiased information to operational entities to aid in making decisions regarding, for example, optimal configurations for specific prediction needs, determining requirements for new research, maintaining code repositories for both research and operational users, and providing support for these communities via help desks, workshops and tutorials. Additionally, model and forecast system developers in the research community have required a more efficient method of responding to operational requirements, obtaining access to operational codes, and collaborating on new research work related to the Weather Research and Forecasting (WRF) model and other forecasting systems. The seeds for such a group were planted in RAL in 2004 with the creation of the Joint Numerical Testbed Program (JNTP).   The JNTP was founded on the principle that no development is undertaken by the JNTP except for verification and evaluation tools, and each member of the program has a neutral role in the testing of any numerical technique. This concept has been very successful and has resulted in a strong trust relationship between the JNTP and its sponsors.

A central emphasis of the JNTP is on activities of the Developmental Testbed Center (DTC), which focuses on the WRF model, including community support and testing and evaluation activities; while the DTC is a distributed facility, with staff residing in the JNTP and the Global Systems Division of NOAA's Earth System Research Laboratory (ESRL), the office of the national DTC director and approximately 2/3 of the DTC staff reside in the JNTP. To meet the broad spectrum of community needs, the JNTP includes teams focused on forecast verification, mesoscale modeling, data assimilation, tropical cyclones, and ensemble prediction, as well as an emphasis on statistical methods and analysis of extreme events. Because forecast evaluation is at the heart of many JNTP activities, and because new high resolution forecasts require new approaches for forecast verification, the DTC and the JNTP have concentrated a great deal of effort on providing verification tools for the community, and the development of verification tools and capabilities that can meet the needs of specific users. In addition, the JNTP provides extensive outreach related to verification methods and tools, modeling components, and statistical methods.

The testbed activities in the JNTP are expanding to include applications in renewable energy and climate, as well as applications such as hydrometeorological prediction. In addition, the outreach activities are expanding to include a focus on capacity development, supporting the use of advanced statistical and verification techniques, and state-of-the-art modeling systems. These outreach activities include tutorials and short courses as well as other training activities, and close collaboration with users in the process of developing and implementing new prediction capabilities for weather and climate and applications.

Near-Term Objectives

Forecast evaluation tool development and support

Develop, test, and implement as a community resource a suite of advanced verification tools with an emphasis on the special needs of the research, operational and specific user sectors.

The availability of appropriate model verification and forecast evaluation tools is fundamental to all activities of the JNTP and is critical for model testing activities undertaken by the broader NWP community. Moreover, in evaluating new forecasting capabilities, it has become increasingly important to utilize verification approaches that are user–specific, and that provide information about the quality of forecasts relative to the purposes for which the forecast information is used. In response to JNTP and community needs, the DTC and the JNTP have developed and implemented the state-of-the-art Model Evaluation Tools (MET) software package, which includes traditional and new forecast evaluation methods and is freely available to the operational and research communities. In addition, the JNTP provides user support in the form of tutorials, documentation and helpdesks. The community of MET users includes operational modeling groups, university researchers, and private forecasting organizations.
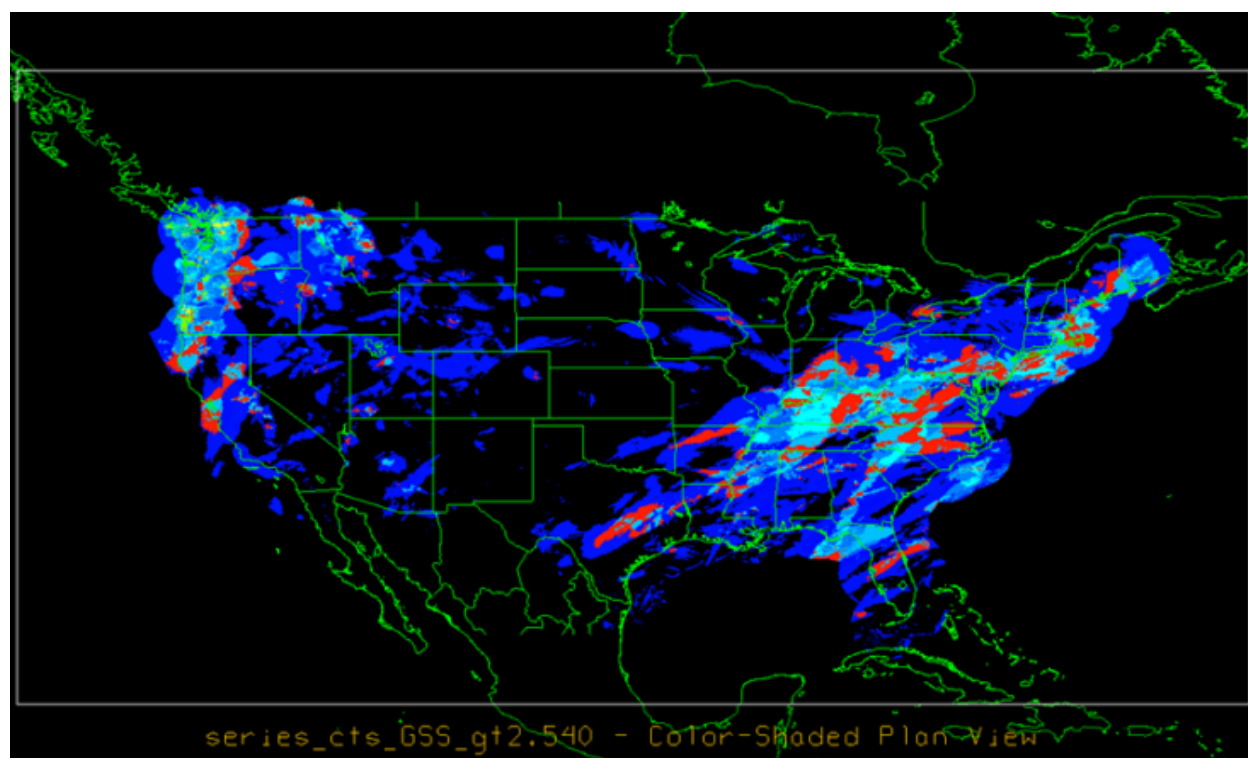
Example of new tool to examine forecast performance as a function of spatial location. Statistic shown is Gilbert Skill Score; warmer colors indicate greater forecasting skill.

Because the needs of users are diverse, and because traditional approaches are often inadequate to meet specific users' needs for forecast quality information, the JNTP also engages in research to develop new, improved forecast verification and evaluation methods, such as spatial verification approaches, and leads community efforts to compare and evaluate the new methodologies. New diagnostic tools are also needed for new application areas, including climate, hydrology, solar energy, land surface models, tropical

cyclones, ensembles, and air quality. New verification method research also focuses on new types of observations, such as new measurements from NASA satellites that can be used to evaluate forecasts of cloud properties (e.g., cloud top and base, cloud horizontal and vertical structure) and attributes of forecasts over oceanic and other data-sparse regions. Exploitation of new observation platforms will enhance our ability to evaluate and improve new types of forecasting systems. The JNTP will continue to focus on development of new forecast evaluation capabilities, with initial focus on renewable energy, hydrologic, and climate forecasts, and anticipated expansion into additional areas such as other user-focused predictions and decision support systems in the future (a frontier area).

Support of community codes

Provide testing and evaluation and software support for NWP systems for general forecast applications including state-of-the-art community modeling systems that include current operational technologies. The software suite included in the community system and testing activities includes mesoscale and global models as well as data assimilation, tropical cyclone, and ensemble system.

This area of focus is a core activity for the JNTP and the DTC. Currently the JNTP collaborates with NCAR's Earth System Laboratory (NESL), the operational and research branches of the National Oceanic and Atmospheric Administration (NOAA) and the Air Force Weather Agency (AFWA) through the DTC to test and evaluate configurations of the WRF model. The JNTP and DTC provide unbiased assessments of operational weather prediction systems as well as new techniques that have shown potential to improve the operational systems. In addition, assessments are associated with data assimilation systems, tropical cyclone prediction systems, and ensemble forecasting systems. These assessments are based on carefully-controlled, extensive tests that utilize both traditional and advanced forecast evaluation techniques.
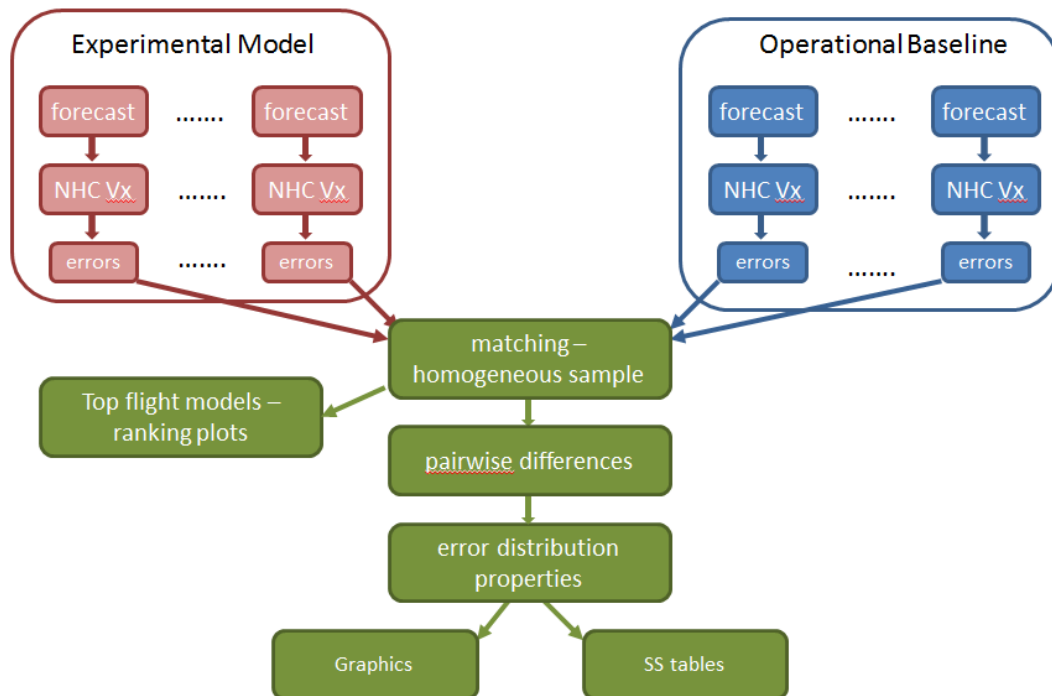
Example of a verification and testing capability for new modeling systems, showing all aspects of the tools and methods. This example is for evaluation of new hurricane prediction systems.

In addition to conducting extensive tests of WRF configurations, the JNTP through its participation in the DTC provides a wide range of potential WRF users and users of data assimilation and tropical prediction systems, including both researchers and developers, with access to the state of the art software that makes up these prediction systems, including code access, documentation and user support. These community code efforts provide a critical framework for the operational and research communities to collaborate in order to accelerate the transition of new technology into operational weather forecasting. In addition, the JNTP provides extensive and in-depth testing and evaluation (including real-time forecast demonstrations) for experimental forecasting systems such as the systems engaged in the Hurricane Forecast Improvement Project. The JNTP is broadening the scope of its testing and evaluation activities to focus on end-to-end forecasting systems, with testing associated with all software components. Expansion toward testing and support of global prediction systems is anticipated in the near future.

Applications of extreme value theory

Develop and apply methods for evaluating weather and climate extremes

High impact weather – causing economic and human impacts – is frequently associated with weather and climate extremes. Analyzing and modeling extreme weather and climate events is a critical activity to allow understanding and improved prediction of these types of events. Statistical methods designed to directly evaluate extreme events ("extreme value analysis") are not commonly applied in meteorological and climate studies; use of these approaches will benefit efforts in a number of activities in RAL, including climate change analysis, severe weather prediction and analysis, and evaluation of tropical cyclone wind and precipitation impacts. Tools to apply extreme value analysis in these kinds of areas have been implemented through NCAR's Weather and Climate Impacts Assessment Science Program (WCIASP) and can be utilized beneficially in a wide range of studies associated with weather, climate, hydrologic, and other types of extremes. Ongoing and future areas of development and application include precipitation and water resource extremes. Additional possible areas of focus include hurricane weather and impacts, and climate change estimation and impacts.

Capacity building for NWP applications and evaluation

Extend capacity building, technology transfer, and education and outreach activities to reach a broader community of NWP developers, providers and users.

An ultimate goal of many activities in the JNTP (and in RAL) is the transfer of knowledge and capabilities to individuals and organizations. For example, the JNTP organizes and supports numerous tutorials and workshops related to the application of the community software systems that are supported through the DTC. In addition, the JNTP supports the transfer of knowledge and implementation of modeling capabilities for international collaborators through training activities related to NWP, forecasting, and verification; and assisting with implementation, tailoring and support of improved NWP systems. Inclusion of a research component is a critical aspect of these activities, which benefits the target organization or facility as well as the wider community. For example, such research may include investigation of modeling capabilities for new phenomena such as dust storms or flooding in particular topographic domains. By nature these activities include contributions across RAL programs, and may involve scientists from NESL as well. Extending the outreach and capacity building activities of the JNTP and RAL will help to bring the overall community to a more advanced level of modeling and model testing, and will broaden and strengthen the impacts of the forecasting systems on society.

Frontiers

Advanced computing methods to facilitate model support, testing and evaluation

Establish new computational infrastructures to enable the NWP community to participate in model testing and evaluation through use of common tools and datasets that will facilitate broader community participation in testbed activities

Advanced computing infrastructures offer many opportunities and benefits for the types of activities – model testing and evaluation – that are supported by the JNTP and the DTC. For example, a web-based (or possible cloud-based) infrastructure for MET and its associated database and display system (METViewer) would enable a "community" NWP testbed for outside users. This facility would include hosting of large datasets and other infrastructure to allow outside users to utilize consistent software tools and datasets for their own testing and would greatly broaden the scope of what could be accomplished through the testbeds. The extensive software engineering capabilities in the JNTP make this a realistic frontier activity to be undertaken in the future, which would have great benefits for the broader NWP community.

Evaluation of models for specific user applications

Expand JNTP activities to test and evaluate the use of coupled and secondary applications with NWP models, including derived products and user impacts. Specific applications may include hydrologic, fire weather, air quality, aviation weather, energy, agricultural, biological and human impact models, and decision support systems.

NWP modeling systems are often used in conjunction with a coupled model to describe the effects of weather on other systems. The resulting system can consist of a tightly coupled model (ocean, land surface) or may involve a one-way coupling (e.g., providing NWP datasets as initial conditions for a sound propagation model). In addition, mesoscale NWP models are often used for particular applications, such as regional climate or aviation-specific parameters. An independent assessment of the combined modeling system and applied forecasts, based on user-relevant evaluation approaches, will allow end-users of the products to meaningfully assess the quality of the information with which they are making decisions. In addition, JNTP will help assess information needs and provide guidance on appropriate observing strategies to enable meaningful system evaluations. Work in these areas will require close partnerships with organizations with expertise in the application area and a developed understanding within the JNTP of the forecast aspects to be evaluated. Due to the breadth of knowledge and capabilities represented by the JNTP, it is well-poised to successfully take on these forecast evaluation challenges.

8. Goal Area: Climate, Weather and Society

Overarching Priority

Promote societal sustainability and resilience to environmental variability by conducting interdisciplinary research on the interactions among society, weather, and climate, and enhance societal gains by bringing social science into new weather and climate research and products.

Motivation

Society is creating and experiencing profound impacts from the recent weather and climate changes across almost all scales. These impacts range from *global* resource availability, migration, political stability, and health, to *regional* agricultural and ecosystem sustainability, to *local* watersheds and communities, to *individual* households and decision-makers. Human society is increasingly vulnerable, not only to changing climate, but also to increasingly erratic, and often extreme, environmental phenomena such as heat waves, hurricanes, floods, atmospheric pollution and droughts. The fundamental goal of RAL's climate, weather, and society research program is to improve the understanding of (1) societal impacts, vulnerabilities and adaptation to weather extremes and climate change, (2) drivers of social and environmental changes and (3) alternatives for building sustainability and improving adaptive capacity. Furthermore, the program aims to create usable scientific information and improve communication of weather and climate risks and uncertainties to diverse population and stakeholders.

RAL leads research on social, economic, and governance structures related to weather, climate, and environmental change at local, regional and global scales. The program emphasizes interdisciplinary research to help society benefit from current and emerging weather and climate prediction capabilities by integrating social science knowledge and methods into the weather/climate research and policy-making communities. Research on sustainability is conducted by developing interdisciplinary frameworks on the key global societal processes (e.g., urbanization, governance, and resource use) that drive changes in carbon, climate and environmental quality across space and time. Research on impacts, vulnerability and adaptation to weather extremes and environmental change is conducted by generating scenarios of projected change, developing frameworks, tools and methods for analyzing current and future vulnerability, performing integrated analyses and building decision-support tools. The involvement of various stakeholders and users with the research effort is central to the approaches to develop actionable science that serves society. RAL seeks not only to foster a research agenda that identifies underlying processes and risk factors of changes in climate and weather, but also to work with governmental-, private- and social-sector stakeholders to identify the scales that are relevant for decision-making and to seek and propose sound solutions -- informed by quantitative, interdisciplinary, multi-scale scientific research -- to the complex socio-ecological problems that are caused- or exacerbated by climate and environmental change.

Near-Term Objectives

In both the climate and weather arenas, RAL scientists work across physical and social science disciplines to bring research at the society-environment-atmosphere interface to bear on critical societal decision-making processes. Specific objectives and actions to achieve this include:

- Improving models, frameworks, methods and tools for understanding impacts and vulnerability and improving sustainability and adaptive capacity though integrated interdisciplinary research efforts that draw on and join diverse science domains such as ecology, sociology, economics, geography, statistics and other social and environmental sciences
- Developing science-based planning approaches incorporating changes in the probability of weather and climate extremes, characterizing observational, model, and vulnerability-assessment uncertainties, and integrating climate change information with planning tools that are responsive to the specific needs of the wide spectrum of decision-makers
- Connecting decision makers to improved weather forecasts and climate information by delivering this data, information and knowledge in ways they understand, value, and can use

Social-Ecological Systems in a Changing Climate: An Interdisciplinary Approach

Enhance the sustainability and social value of managed natural resources through more effective integration of science in policy processes.

Economic, social, cultural and institutional factors play important roles in shaping the relationship of human communities to their environments. These factors are critical determinants of the sustainability of natural resource use, and key drivers of the capacity of a community to manage the impacts of climate variability and to adapt to climate change. In addition, the bio-geophysical characteristics of a natural resource system largely determine its potential for generating both services and hazards, and social-ecological systems tend to co-evolve, with natural characteristics shaping both the human uses of the system, and the institutions governing its use. An interdisciplinary approach is needed to understand the dynamics of such coupled human-natural systems, and to evaluate the potential consequences of further interventions. We will collaborate with scientists from atmospheric, hydrologic, engineering and biological disciplines on specific policy-relevant analyses, while also working to develop improved methodologies for such integrated analysis. Work will focus on identifying how economic, socio-cultural and institutional factors influence human uses of ecosystem services, and the role of these factors in shaping vulnerabilities and responses to climatic variability and change.

Action:

- Contribute to an interdisciplinary analysis of the potential consequences of changing snow processes and land surface conditions in the Colorado Headwaters region for the availability of transbasin water supplies to Colorado's Front Range
- Work to develop and implement a "decision-centric" methodology for assessing the performance of Front Range water-utility management options under changing climate conditions.
- Develop a methodology for evaluating the economic consequences of alternative policies for reducing Georgia's agricultural water withdrawals during droughts in order to protect flows in interstate rivers.
- Organize a multidisciplinary review of the implications of climate variability and change for water resource policy and planning in the Western U.S., and develop guidance for future resource management and policy development.

Communication, Use, and Value of Weather Information

Improve the effectiveness of the weather forecasting and warning system through the study of communication, interpretation, use, and economic analysis to value weather forecast information, including analyzing the impact of uncertainty.

The ultimate goal of the weather forecast and warning system is to create societal value by providing usable information for decision-making. Lack of research at the weather-society interface has been identified as a major gap in NRC reports and other community documents. There is insufficient empirical knowledge about how diverse actors in the forecast system communicate, interpret, and use currently available weather forecast and warning information, much less new or improved information. The social sciences offer comprehensive theories, methods, and applications that can build this critical knowledge.

Actions:

- Economic valuation of the nation's hurricane forecast and warning process
- Increasing the public's understanding, use of, and preferences for storm surge information
- Improving risk assessment and communication of hazardous weather information (e.g., flash floods, hurricanes, severe weather)
- Advancing the understanding of the forecast process and how that process can be codified
- Economics of weather and forecasts impacts on the US and the international economy

Urban Futures

Promote more resilient and sustainable cities by developing city level and policy relevant, integrated models and frameworks that inform and are informed by global-scale interdisciplinary research

Urbanization and urban areas represent critical points of interaction between billions of individuals and environmental change. Urban households, industries, infrastructures and decision makers are key sources of environmental impacts ranging from greenhouse gases and aerosols emissions to changes in the hydrological and carbon cycles. Cities concentrate populations, economic activities and built environments, thus increasing potential impacts from floods, heat waves, air pollution and other hazards. However, this concentration of risk is also making cities crucibles of innovation. Recent large environmental disasters are making many urban authorities aware of their key role in fostering effective and meaningful mitigation and adaptation initiatives to avoid significant asset losses.

Actions:

- Develop city-level and policy relevant, integrated models and frameworks on the interactions between physical and social drivers of climate, weather, carbon and atmospheric impacts, vulnerabilities and capacities to respond in Latin American and Asian cities
- Use an urban regime approach to explore the influence of actors, institutions and infrastructure on the opportunities and limits for urban transitions to emerge
- Carry out urban-scale integrated interdisciplinary studies that inform and are informed by global-scale interdisciplinary research
- Contribute to capacity-building in Latin America and Asia to foster different urban futures through educational, mentoring and outreach activities at the science-policy interface

Weather, Climate and Health

Improve our understanding of the complex interactions among weather and climate processes, ecosystems, and human health.

There is widespread scientific consensus that the world's climate is changing and that there will be a broad range of impacts on health through a variety of factors, including greater heat stress, air pollution, respiratory disease exacerbation, and changes in the geographic distribution of vector-, food- and water-borne disease. A multi-disciplinary, multi-institutional approach is required to address these complex climate-related public health challenges. Currently, there is a lack of appropriately scaled and integrated social-physical models for the development of adaptation and mitigation strategies to reduce negative health outcomes in the face of climate variability and climate change. Our team employs both social and physical scientists to qualitatively and quantitatively address weather- and climate-related health impacts.

Actions:

- Continue to build a program at NCAR in Weather, Climate and Health.
- Conduct field work in funded areas with a focus on reducing negative health impacts.
- Develop and employ economical physically- and statistically-based approaches toward integrated modeling and prediction of climate-sensitive health issues at regional-to-local scales.
- Evaluate population vulnerability to human health impacts of climate variability and change.
- Develop adaptation/mitigation strategies to address current and emerging health issues.

GIS Science Program

Enhance our ability for spatially-explicit interdisciplinary research and knowledge integration.

Understanding societal risks and vulnerabilities to weather hazards and climate change requires integration of georeferenced information from physical and social sciences, including weather and climate data, information about natural and built environments, demographic characteristics, as well as social and behavioral processes. Through interdisciplinary research in GI science and technology, the GIS program fosters interdisciplinary science, spatial data interoperability, and knowledge sharing.

Actions:
- Develop and implement research frameworks, methods, and tools for integration of diverse, multidisciplinary datasets which are both quantitative and qualitative and exist at different spatial and temporal scales. Apply these innovative methods in research on societal vulnerability, weather hazards impacts and climate adaptation, with the main focus on water, human health and disaster risk reduction in urban and coastal systems
- Enhance GIS integration with social science data and modeling efforts (e.g., agent-based modeling, participatory GIS, and social media)
- Improve usability of weather and climate models for decision-making: expand current R&D efforts on web services and web GIS technologies with regard to distribution of WRF and CESM model outputs (e.g., IPCC AR5 data and products) to decision-makers. Continue to implement spatial data interoperability standards.
- Build community and capacity for Atmo-GIS research and knowledge integration at the science-policy interface: increase local-level capacity through GIS-focused education that links GIS and climate science with societal impacts and vulnerability research.
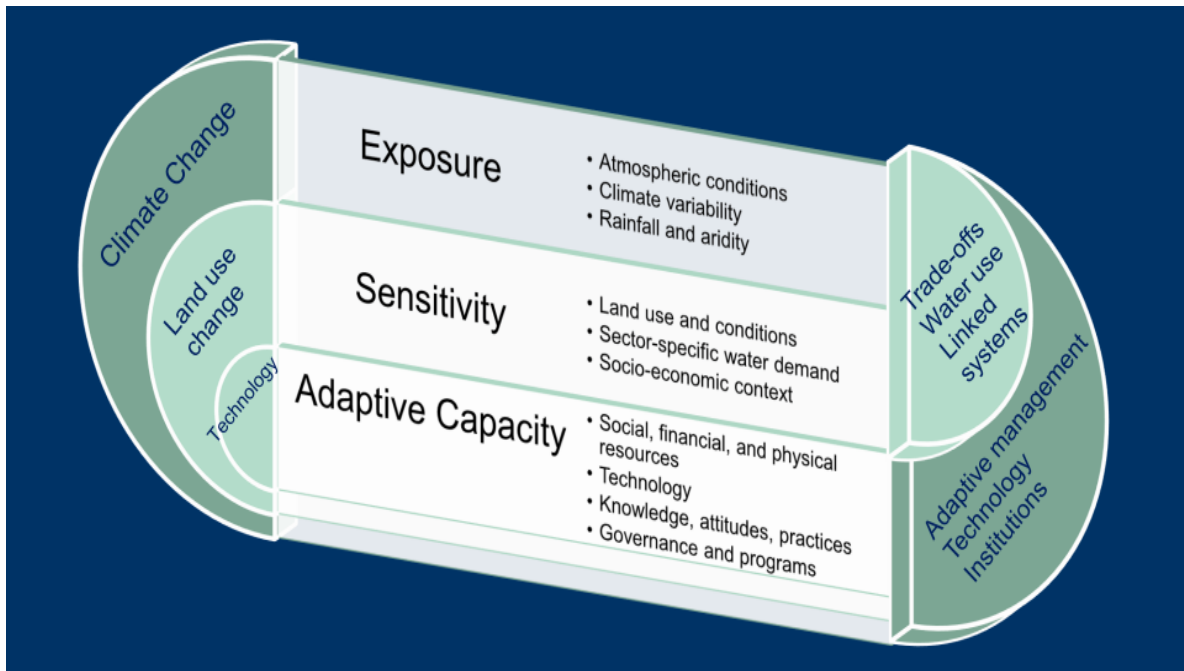
Characterizing drought vulnerability

Regional Climate for Adaptation

Deliver sound climate science to decision-makers at regional and local scales to promote sustainability and reduce human system vulnerabilities to anticipated climate change impacts.

As the reality of human-induced climate change is accepted by policymakers and the public at large, the demand for actionable, regional-scale information and knowledge about observed and projected climate changes and impacts at individual, local, and regional levels is increasing rapidly. Effective decision-making about adaptation will require accurate and usable information about regional-scale climate change and the relationships among climate change and other important environmental and socio-economic stressors, including land use change, invasive species, "conventional" pollution, and market forces.

Actions:

- Usable Climate Science: Investigate, understand, and document the climate science needs of decision-makers in critical end-use domains (e.g., urban planning, water resources, natural resources, and ecological sustainability) within multiple development contexts by leading activities and working groups internationally, in the US and in the NCAR flagship regional & global modeling programs.
- Integrated Vulnerability and Adaptation Research: Develop and apply tools and metrics to measure and quantify the effectiveness of climate adaptive interventions under co-occurring changes to social and bio-geophysical conditions at system boundary thresholds, particularly on specific 'high impact' geographies such as urban, coastal, and high Alpine systems.
- Capacity Building: Develop training workshops, fellowship programs, and scientist exchanges with local and regional partners to foster collaboration, innovation, and multi-directional capacity building. Develop tools, methods and techniques to assist in the translation of climate science information to support localized decision-making.

Frontier

Scalable, Solution-Oriented Research for Climate Change Impacts

Understanding, quantifying and simulating the interactions and impacts of climate and weather drivers on local, regional and global socio-ecological systems.

Society is transforming the Earth's system in unprecedented ways, often with significant variations across space and time. In turn, the impacts of climate change on the human system vary dramatically due to differences in cultural, socioeconomic, institutional and physical processes at the local level. To date, research on the drivers of climate change at local scales has been aimed at characterizing the societal processes and mechanisms that influence energy use and climate change, while research on the impacts of climate change at local scales has focused on characterizing the exposure, vulnerability, and adaptive capacity of communities. The mounting human toll and economic losses from increasing extreme weather events associated with climate change, which particularly affect vulnerable populations and places, justify the need for a research agenda that goes beyond identifying underlying processes and risk factors. Working with government-, private- and social-sector stakeholders, we will identify the scales that are relevant for decision-making, in order seek and propose sound solutions -- informed by quantitative, interdisciplinary, multi-scale scientific research -- to the complex socio-ecological problems that are caused- or exacerbated by climate and environmental change. Significant advances are required in the following areas:

Actions:

- Identify places of greatest societal and environmental need for scalable, solution-oriented research on climate change impacts. Develop criteria for case selection through careful examination of current evidence of climate change, baseline vulnerabilities, and rapid rates of change in such factors as climate and weather events, population dynamics, adequacy of infrastructures and built environments, disease vectors, ecological tipping points, and hydrological cycle. The motivation and selection process of specific case locations will be similar to those that lead to choosing a site for a meteorological field campaign: opportunity to increase scientific knowledge about complex, poorly-understood processes, subsequent detailed process-level analyses, that can be integrated into broader context of weather and climate impacts research, and unique opportunity to collaborate with university partners and decision-makers.
- Conduct in-depth studies in the regions of greatest need with high societal vulnerability, aimed at developing scalable, transferable methodologies that quantitatively and qualitatively link high-resolution socio-economic and behavioral data with geophysical data from global climate and mesoscale weather models. Conduct in-depth research on mechanistic drivers of both greenhouse gas emissions and socio-ecological vulnerabilities at the scale of decision-making.
- Work with communities in the regions of greatest need to develop processes for multi-level, multi-sectoral stakeholder engagement to identify appropriate scales of research and information needs and to understand impacts and interactions among societal drivers of changes in weather and climate, policy and governance, and baseline vulnerabilities.
- Develop strategies to characterize, quantify and communicate uncertainties of socio-economic and ecological drivers, impacts and vulnerabilities at multiple socioecological levels.

Research advances in these areas will require both observations and modeling. In-depth analysis of social and behavioral processes and interactions among all elements of socio-ecological systems and

atmospheric properties will require novel approaches to quantitatively synthesize the required multi-disciplinary, multi-scale datasets. Specific research directions will further foster NCAR's current strengths in interdisciplinary research and knowledge integration at the science-policy interface. New local-level studies will be carefully selected based on our current knowledge of the areas in greatest of need of solution-oriented research, and fully integrated into existing core expertise areas at NCAR focused on predicting and characterizing weather, climate and environmental change at a variety of scales. In summary, we aim to enhance the relevance and uptake of NCAR's extensive climate and weather modeling capabilities by designing a suite of local- and regional-level studies of the climate and weather drivers and impacts on socio-ecological systems that inform and are informed by global-scale interdisciplinary research.

9. Appendices

RAL organizational structure

In the fall of 2004, the Research Applications Laboratory was formed from two previous groups: the Research Applications Program (RAP), and the Developmental Testbed Center (DTC). Given the very aggressive growth history of RAP over the previous 15 years, the senior managers determined it was time to reorganize around a number of central themes with management units of appropriate size to efficiently carry on the activity of the laboratory into the future. In the summer of 2008 the Institute for the Study of Society and Environment (ISSE) was also placed in RAL, though it was dissolved the following year. A number of the ISSE staff, though, elected to remain in RAL and now make up the core of the Climate Science and Applications Program, formed in 2009. The current organization chart is shown in the earlier Section 1, and is amplified for easy reference below to highlight the principal directions of each division.

- The *Aviation Applications Program (AAP)* plans, develops, and transfers advanced weather technologies to support current and future aviation operations nationally and internationally.

- The *Climate Science and Applications Program* (*CSAP)* conducts research on the interactions among society, the atmosphere and the environment to better understand weather- and climate-related risks and to incorporate this improved understanding into decision making and policy.

- The *Hydrometeorological Applications Program (HAP)* works to understand how water vapor, precipitation, and land surface hydrology interact across scales to define the hydrological cycle, including under global change.

- The *Joint Numerical Testbed Program (JNTP)* serves as both a facility and a national distributive network of collaborators for testing, validating, and comparing numerical techniques for analyses and forecasts of atmospheric parameters important to scientists and operational decision makers.

- The *National Security Applications Program (NSAP)* emphasizes research and development in mesoscale prediction, data assimilation, urban-scale meteorology, and plume transport modeling to give operational forecasters, decision makers and emergency planners accurate, timely guidance and support.

- The *Weather Systems and Assessment Program (WSAP)* develops and implements advanced weather decision support systems for new user sectors such as surface transportation, renewable energy, and international aviation applications. It also seeks to communicate, understand, and quantify the economic benefits of weather information for society.

It should be noted that the programs and plans outlined in Chapter 3 through 8 correspond only loosely to the management units indicated above, as many of the projects that are carried out span efforts in several groups, and the research carried out often involves multiple sponsors. Sponsors are thus able to leverage off the support of one another, and RAL is able to build programs of significant size and scope from smaller pieces funded independently.

RAL Advisory Panel

The RAL Advisory Panel consists of members of the academic community along with government and private-sector members of the operational community. They are nationally or internationally recognized as leaders in their respective fields of expertise. The panel members cut across all aspects of the Laboratory's work. They meet once per year to provide advice regarding the status, future directions, and conduct of RAL programs.

2013 members of the RAL Advisory Panel include:

- Dr. Glen Anderson, Engility Corporation, Washington, D.C.
- Mr. Joe Burns, United Airlines Flight Center, Denver, CO
- Ms. Pam Clark, U.S. Army Research Laboratory, Adelphi, MD
- Dr. James Doyle, Naval Research Laboratory, Monterey, CA
- Dr. Maria Carmen Lemos, University of Michigan, Ann Arbor, MI
- Mr. Rod MacKenzie, Harman International, Washington, DC
- Dr. Robert Rauber, University of Illinois – Urbana-Champaign, IL
- Dr. James Reagan, The MITRE Corporation, McLean, VA
- Dr. Scott Sandgathe, University of Washington, Seattle, WA

Additional Advisory Panel members during the period from 2005 to present include:

- Mr. Mark Andrews, Joint Planning and Development Office, Washington, DC
- Dr. Bruce Davis, Department of Homeland Security, Washington, DC
- Dr. Leland Ellis, Department of Homeland Security, Washington, DC
- Dr. Efi Foufoula-Georgiou, University of Minnesota, Minneapolis, MN
- Ms. Jeanne Foust, ESRI, Eau Claire, WI
- Mr. Robert Francis, National Transportation Safety Board (ret.), Washington, DC
- Mr. Art Handman, KMJ Consulting, Gorham, ME
- Dr. Sharon Harlan, Arizona State University, Tempe, AZ
- Dr. Paul Houser, George Mason University, Fairfax, VA
- Dr. Richard Johnson, Colorado State University, Ft. Collins, CO
- Mr. Carl McCullough, FAA (ret.), Aerospace Consultant, Trinity, FL
- Dr. Ron McPherson, American Meteorological Society, Boston, MA
- Ms. Shelley Row, Institute of Transportation Engineers, Washington, DC
- Dr. Agam Sinha, The MITRE Corporation, McLean, VA
- Ms. Sheila Steffenson, ESRI, Vienna, VA
- Ms. Lisa Devon Streit, Deputy Chief Operating Officer Office of the Undersecretary, DOE
- Dr. Don Veal, University of Wyoming (ret.), Particle Measuring Systems
- Mr. Bradley Udall, NOAA/ESRL, and University of Colorado, Boulder, CO

Acronym dictionary

4DVar – Four Dimensional Variation data assimilation technique
AAP – Aviation Applications Program in RAL
ABL – Atmospheric Boundary Layer
ACD – Atmospheric Chemistry Division in ESSL
AFWA – Air Force Weather Agency
ADAPTE – Adaptation to the Health Impacts of Air Pollution and Weather in Latin American Cities
AGL – Above ground level
AID – United States Agency for International Development
AGU – American Geophysical Union
AMPS – Antarctic Mesoscale Prediction System
AOML – Atlantic Oceanographic and Meteorological Laboratory, FL
AOML/HRD – Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division
AMS – American Meteorological Society
APL – Applied Physics Laboratory of John Hopkins University
ATEC – United States Army Test and Evaluation Command
ATM – Air Traffic Management
AWEA – American Wind Energy Association
AWIPS – Advanced Weather Interactive Processing System
BEACHON – Bio-hydro-atmosphere interactions of Energy, Aerosols, Carbon, H_2O, Organics, and Nitrogen
C&V – Ceiling and visibility
CAA – Civil Aviation Administration in Taiwan
CAASD – Center for Advanced Aviation Systems Development, MITRE Corporation
CCMC – Community Coordinated Modeling Center in NASA
CCSM – Community Climate System Model
CDC – Centers for Disease Control and Prevention
CDI – Cyber-Enabled Discovery and Innovation
CGD – Climate and Global Dynamics Division of ESSL
CIESIN –Center for International Earth Science Information Network
CIIFEN – Centro Internacional para la Investigación del Fenómeno de El Niño.
CISL – Computational and Information Systems Laboratory in NCAR
CISM – Center for Integrated Space Weather Modeling in Boston University
CONUS – Continental United States
CoSPA – Consolidated Storm Prediction for Aviation

CRIEPI – Central Research Institute of Electric Power Industry
CSEM – Center for Space Environment Modeling in University of Michigan
CSI – Critical Success Index
CVA – Ceiling and visibility analysis product
CVF – Ceiling and visibility forecast product
CWB – Central Weather Bureau, Taiwan
DANIDA – Ministry of Foreign Affairs of Denmark
DARPA – Defense Applied Research Program Administration
DART – Data Assimilation Research Testbed
DATC – Data Assimilation Testbed Center
DFID – UK Department for International Development
DHS – Department of Homeland Security
DICast – Dynamic Integrated Forecast system
DOE – U.S. Department of Energy
DOD – U. S. Department of Defense
DOI – U. S. Department of the Interior
DOT – U. S. Department of Transportation
DTC – WRF Developmental Testbed Center
DTC – Developmental Test Command
DTRA – Defense Threat Reduction Agency
EOL – Earth Observing Laboratory in NCAR
EPA – U.S. Environmental Protection Agency
ECLAC – Economic Commission of Latin America and the Caribbean
EMC – Environmental Modeling Center
ESM – Earth System Model
ESMF – Earth Systems Modeling Framework
ESRL – Earth Systems Research Laboratory in OAR
ESSL – Earth and Sun Systems Laboratory in NCAR
EuLag - A model; underlying equations are either solved in an EUlerian or a LAGrangian framework
FAA – DOT Federal Aviation Administration
FDDA – Four Dimensional Data Assimilation
FHWA – Federal Highways Administration
FIM – Flow-following finite-volume Icosahedral Model
GA – General Aviation
GFDL – Geophysical Fluid Dynamics Laboratory
GFS – Global Forecast System model
GIS – Geographical Information System
GOES-R – Geostationary Operational Environmental Satellite, Series R
GPS – Global Positioning Satellite
GSD – Global Systems Division of NOAA Earth Systems Research Laboratory in OAR
GSI – Gridded Statistical Interpolation
GTG – Graphical Turbulence Guidance
HAO – High Altitude Observatory
HAP – Hydrometeorological Applications Program

HFIP – Hurricane Forecast Improvement Program
HIWC – High ice water content
HPAC – Hazard Prediction and Assessment Capability
HRLDAS – High-Resolution Land Data Assimilation System
IA – Integrated Assessment
ICE-L – Ice in Cloud Experiment
IDB – Inter-American Development Bank
IMAGe – Institute for Mathematics Applied to Geosciences
IMPROVE II – Improvement of Microphysical Parameterization through Observational Verification
IPCC AR4 – Intergovernmental Panel on Climate Change Fourth Assessment Report
ISET – Institute for Social and Environmental Transition
ISP – Integrated Science Program
ISSE – Institute for the Study of Society and Environment
IT – Information Technologist
JNT – Joint Numerical Testbed
JPL – Jet Propulsion Laboratory
JPDO – Joint Program Development Office for NGATS
LANL – Los Alamos National Laboratory
LES – Large Eddy Simulation
MADIS – Meteorological Assimilation Data Ingest System in NOAA
MDA – Missile Defense Agency
MET – Model Evaluation Tools
MDSS – Maintenance Decision Support System
MIT-LL – Massachusetts Institute of Technology, Lincoln Laboratories
MMM – Mesoscale and Microscale Meteorology Division
MODIS – Moderate Resolution Imaging Spectrometer (NASA satellite sensor)
MOS –Model Output Statistics
NAS – National Airspace System
NCEP – National Center for Environmental Prediction in NOAA
NEMS – NOAA Environmental Modeling System
NESDIS – National Environmental Satellite and Data Information Services
NESL – NCAR Earth Systems Laboratory
NEVS – Network Enabled Verification Service
NEXRAD – Next-Generation Radar
NextGen – Next Generation Air Transportation System
NGATS – Next Generation Air Transport System
NHC – National Hurricane Center
NIH – National Institutes of Health
NIST – National Institute of Science and Technology
NGIC – National Ground Intelligence Center
NNEW – NexGen Network Enabled Weather

NOAA – United States National Oceanic and Atmospheric Administration
Noah – NCEP--Oregon State University –Air Force--Hydrologic Research Lab Land Surface Model
NUOPC – National Unified Operational Prediction Capability
NVIA – NCAR Vulnerability, Impacts, and Adaptation program
NRC – National Research Council
NREL – National Renewable Energy Laboratory
NRL – United States Naval Research Laboratory
NSAP – National Security Applications Program
NTSB – National Transportation Safety Board
NSF – National Science Foundation
NWP – Numerical Weather Prediction
NWS – National Weather Service
OAR - Office of Atmospheric Research in NOAA
OFCM – Office of the Federal Coordinator for Meteorology in NOAA
OGC – Open Geospatial Consortium
PFPA – Pentagon Force Protection Agency
PIREPS – Pilot Reports
Quic-URB - Quick Urban & Industrial Complex Dispersion Modeling System (LANL)
R&D – Research and Development
RAL – Research Applications Laboratory in NCAR
RISA – Regional Integrated Sciences & Assessments in NOAA
RITA – Research and Innovative Technology Agency in DoT
ROSES – Research Opportunities in Space and Earth Sciences (grant program in NASA)
RVR – Runway Visual Range
SEI – Stockholm Environment Institute
SIMMER – System for Integrated Modeling of Metropolitan Extreme Heat Risk
SIP – Societal Impacts Program
STEP – Short-Term Explicit Prediction
STIRPAT – Stochastic Impacts by Regression on Population, Affluence, and Technology
TAMDAR -- Tropospheric Airborne Meteorological Data Report
UAV – Unmanned Aerial Vehicle
UNEP - United Nations Environment Program
USDA – United States Department of Agriculture
USGS – United States Geological Survey
USWRP – United States Weather Research Program in NOAA
WEAP – Water Evaluation and Planning Tool
WRF – Weather and Research Forecast model
WS - Water System Program
WSAP – RAL Weather Systems and Assessment Program
WSDDM – Weather Support for De-icing Decision Making