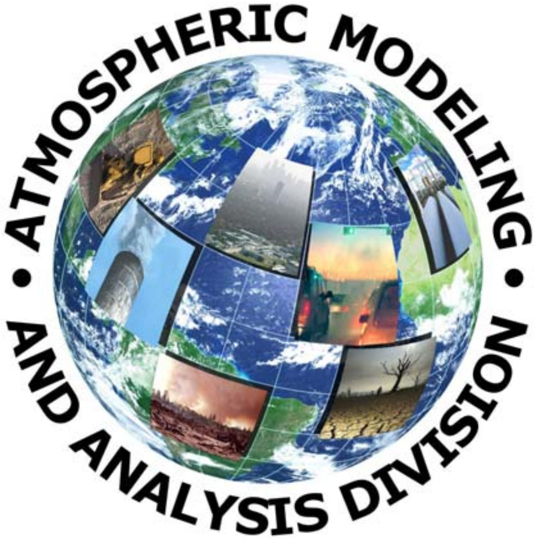
United States Environmental Protection Agency

National Exposure
Research Laboratory



Atmospheric Modeling and Analysis Division

Strategic Research Plan
(2011-2015)

Foreword

The Atmospheric Modeling and Analysis Division (AMAD) has been associated with the Environmental Protection Agency's Office of Research and Development (EPA-ORD) since the founding of the Agency in 1970. Over these forty years, despite changes to the Division's name, the primary mission of AMAD has continuously been the development, application, and evaluation of air quality simulation models for research and regulatory purposes. The Division has grown considerably from a start-up staff in the early years with a focus on local- and urban-scale air quality issues and models, to today's internationally-recognized multi-scale (local to global), multi-pollutant air quality modeling research team. While the Division's mission has not changed, the environmental problems that the Agency and the nation have faced have changed over time, shaping the evolution of the air quality modeling research that AMAD has undertaken. Model applications have generally expanded the time and space scales of the models being developed, as well as the suite of air pollutants treated by the models. The potential impact of climate change on the environment and the need for transdisciplinary research have moved AMAD's research to global and multi-decadal scales, posing tremendous modeling challenges in the decade ahead. As we enter this second decade of the 21st century, this research strategy lays out a bold roadmap for the Division.

The Division's research is not conducted in isolation. On the contrary, we greatly benefit from interactions and collaborations with peers across the nation and the globe. While there are too many such productive relationships to mention here (many are cited within the report), it is worth noting a few up front. Interactions with other federal agencies conducting air pollution research, including the National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and the Department of Energy, have lead to productive working relationships among scientific staff and research collaborations in the air pollution modeling field. Collaborations with the international community have broadened the research perspectives of AMAD and enlarged the scope of modeling applications. Formal collaborations have been established with national environmental agencies in Canada (Environment Canada), the United Kingdom (Environment Agency and Department of Environment, Food and Rural Affairs), and others. Other international scientific collaborations are proceeding with the Air Quality Model Evaluation International Initiative (including over 20 modeling groups across North America and Europe) and the European Union's Cooperation in Science and Technology action groups. Also, AMAD scientists participate in many cooperative research projects with the university community. One deserves special mention here. We have worked with the University of North Carolina at Chapel Hill over the last decade through its Institute for the Environment to establish a Community Modeling and Analysis System (CMAS) Center. This CMAS collaboration provides outreach, support, and training for the models developed by the Division, enabling us to successfully transition research into applications. For example, AMAD's Community Multiscale Air Quality (CMAQ) Model has thousands of users around the world.

This Research Strategy consists of outline summaries of the Division's core research in atmospheric model development and evaluation, as well as three major application areas in which air quality models are used for human exposure, ecosystems exposure, and climate change-air quality assessments. The Appendices contain White Papers on these application areas, providing additional details on our research directions. I welcome your comments on this Research Strategy as we move to the implementation phase. Please do not hesitate to provide feedback on our plans.

S.T. Rao, Ph.D.
Director, Atmospheric Modeling and Analysis Division
(rao.st@epa.gov)

AMAD Strategic Research Plan (2011-2015)

1. INTRODUCTION

The Atmospheric Modeling and Analysis Division (AMAD) of the National Exposure Research Laboratory (NERL), U.S. Environmental Protection Agency (EPA), held its strategic research planning retreat during June 8-10, 2010 in Research Triangle Park, NC. The objectives of the retreat were to develop a five-year research strategy (2011-2015) for AMAD, to obtain concurrence from NERL management on AMAD's research directions, and to lay the foundation for cross-NERL collaborations in air quality modeling applications. This document summarizes the strategic directions for AMAD's major research theme areas as discussed at the Retreat, providing a framework for more detailed annual task planning over the next five years. This planning Retreat continued building on the positive feedback received from the Division Peer Review (Jan. 2009), BOSC Air Program Review (June 2009), NERL Management Meeting (Feb. 2010), joint planning retreat with OAR/OAQPS/AQAD (March 2010), direct input from NERL management (March 2010), and AMAD Branch and Science Council discussions (April-May 2010). The Appendices to this report contain three White Papers discussing additional details of the strategic planning for three of AMAD's research application areas: the linkage of air quality with human exposures, with ecosystems exposures, and with global climate change. AMAD received comments on these papers from an external review panel (March 2010).

1.1 AMAD Mission and Vision

AMAD's mission entails the development and evaluation of atmospheric models on all spatial and temporal scales for assessing changes in air quality and pollutant exposures. AMAD's research links atmospheric models to other NERL, EPA, and community models, and applies its modeling systems to address issues in the science of human and ecosystem exposures and health. The long-term vision stemming from AMAD's mission includes the:

- Development of an integrated modeling system that is capable of simulating global-to-continental-to-regional-to-local scale phenomena of the atmosphere, hydrosphere, and biosphere on relevant temporal scales of interest to exposure assessments
- Design of core model components linked on an application-specific basis to help answer science and policy questions related to human and ecosystem exposure to environmental stressors
- Objective assessment and communication of uncertainties in modeling results.

The first of these elements of the vision may take a decade or longer to develop. The work planned over the next five years will include necessary development and evaluation steps on the path forward to achieve this long-term objective. The second and third elements of the vision embody on-going processes within AMAD's modeling research program that are driven by the needs of particular modeling applications by the program offices, state/local agencies, and scientific community. Figure 1-1 illustrates the highly integrated nature and desired connections of the research conducted by AMAD.

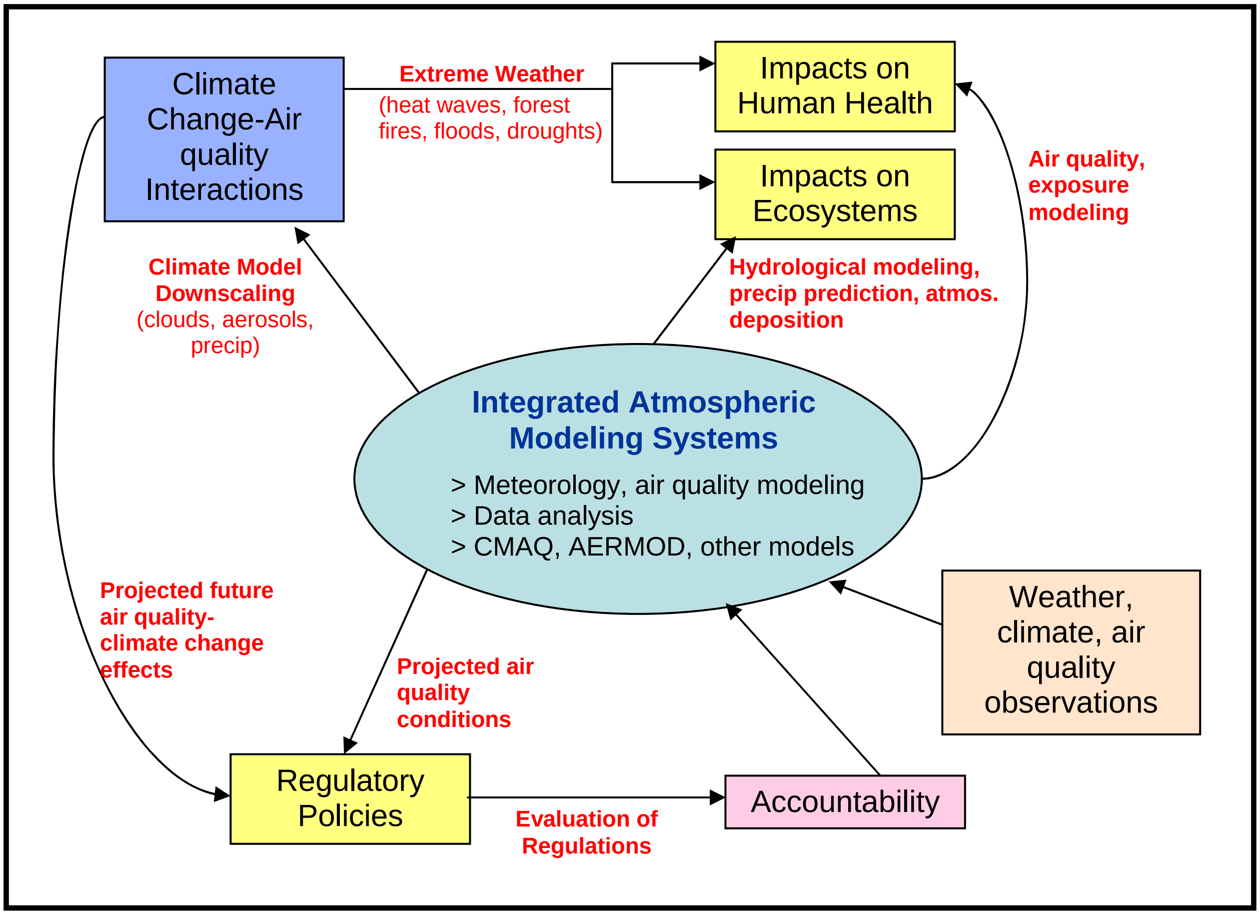


Figure 1-1. AMAD's integrated modeling system to advance transdisciplinary research

1.2 AMAD Values

The values embodied by an organization are important for understanding and best utilizing the organization's strengths. AMAD provides outstanding support to the environmental mission of EPA including building practical and useful state-of-science modeling tools that have an impact on the outcomes of the problems confronting the Agency. AMAD makes its modeling tools broadly available to the scientific and regulatory community and proactively identifies and fills unmet stakeholder needs. Effective teamwork, including a common sense of purpose and leveraging diverse expertise among Division members, is another important value of AMAD. The Division is dedicated to quality work ensuring scientific credibility, and communicating significant results in the published literature to advance the atmospheric modeling field. We are also committed to effective collaboration with the broader scientific community, enhancing the science in AMAD's models and building a broad community of practice in air quality modeling, thereby extending AMAD's models to new application areas. AMAD values balancing the ability to meet EPA needs while maintaining a strong R&D core program on model development and evaluation.

1.3 AMAD Expertise and Strengths

Using a team approach, AMAD scientists integrate diverse disciplines in building comprehensive modeling systems through an effective balance of research and development. Its atmospheric model development and evaluation program pulls together expertise in meteorology, chemistry, physics, engineering, mathematics, numerical modeling, computational science, statistics, and data analysis. AMAD scientists effectively communicate their scientific results by publishing their research in the scholarly literature, presenting papers at professional conferences, and providing web-based access to models and related information. An additional strength is in building collaborations within and outside of EPA to leverage and enhance in-house modeling research.

2. AMAD RESEARCH PLANNING PROCESSES

Research is planned in AMAD in the context of the overall EPA and Office of Research and Development (ORD) strategic plans and tactical priorities. EPA's strategic plan[1] for 2006-2011 and its draft strategic plan[2] for 2011-2015 provide Agency-level guidance and priorities for goals and milestones expected to be accomplished throughout EPA. ORD's strategic plan[3] provides further guidance on refining EPA's broad goals into a research framework composed of core research and problem-driven (applications-oriented) research in the areas of human health-oriented and ecosystems-oriented environmental protection. In addition, the NERL exposure framework[4] provides key scientific guidance that filters EPA's and ORD's priorities in the exposure context.

2.1 Research Drivers

The current draft EPA strategic plan identifies five goals to which the EPA Administrator is committed. These goals include: 1) taking action on climate change and improving air quality, 2) protecting America's waters, 3) cleaning up our communities, 4) ensuring the safety of chemicals and preventing pollution, and 5) enforcing environmental laws. AMAD's research falls mostly within the first of these EPA goals, addressing the modeling needs of urban/regional/continental/global air quality and climate issues. The science and modeling tools produced by AMAD are also relevant to some of the other goals, such as water quality and chemical risks, through incorporation of relevant atmospheric inputs to water quality and human exposure models and assessments. The ORD Assistant Administrator has also expressed his endorsement of these goals, and further supports the following priorities as ORD translates these into research programs and projects: 1) support for EPA's program and regional offices, 2) implement integrated transdisciplinary research (ITR) within ORD, 3) innovate toward sustainable solutions, and 4) communicate effectively. ORD's leaders are currently discussing how to transform the Office's strategic research planning and implementation processes into an ITR framework. AMAD's research program strongly supports the Program offices, especially

---

[1] http://www.epa.gov/ocfo/plan/plan.htm
[2] http://www.epa.gov/ocfo/plan/2011/draft_strategic_plan_june_16_2010.pdf
[3] http://www.epa.gov/OSP/strtplan/documents/final.htm
[4] http://www.epa.gov/nerl/features/exposure_framework.html

the Office of Air and Radiation (OAR). In a March 2010 planning retreat with OAR staff, the following priorities for research were communicated to AMAD: 1) support for regulatory (rule-making) actions, 2) support for new National Ambient Air Quality Standards (NAAQS) and their implementation, 3) assessing intercontinental transport of pollution, 4) assessing the effects of climate change on future air quality, 5) assessing NAAQS impacts on ecosystems, 6) assessing critical loads, and 7) promoting exposure assessments. As outlined in the sections below, AMAD research is responsive to all of these priorities.

All of the above high-level research drivers help shape the directions of this AMAD strategic plan. At the local level, NERL research priorities focus on advancing exposure science for human health and ecosystem services assessments. AMAD's added priority principles include:

- Identifying/quantifying uncertainties at process and model levels
- Improving modeling science and model evaluation procedures to produce tools to address the above NERL and EPA priorities
- Continuing periodic external peer reviews for the models
- Maintaining excellence in research and development
- Providing leadership opportunities at all levels in the Division.

All of these internal EPA research drivers are considered, along with external inputs such as feedback from periodic Division and CMAQ model peer reviews, and CMAS annual conferences, in developing the research agenda for AMAD. From the Division perspective, Figure 2-1 illustrates the research planning process used to develop strategic research plans and their tactical implementation (Tasks).

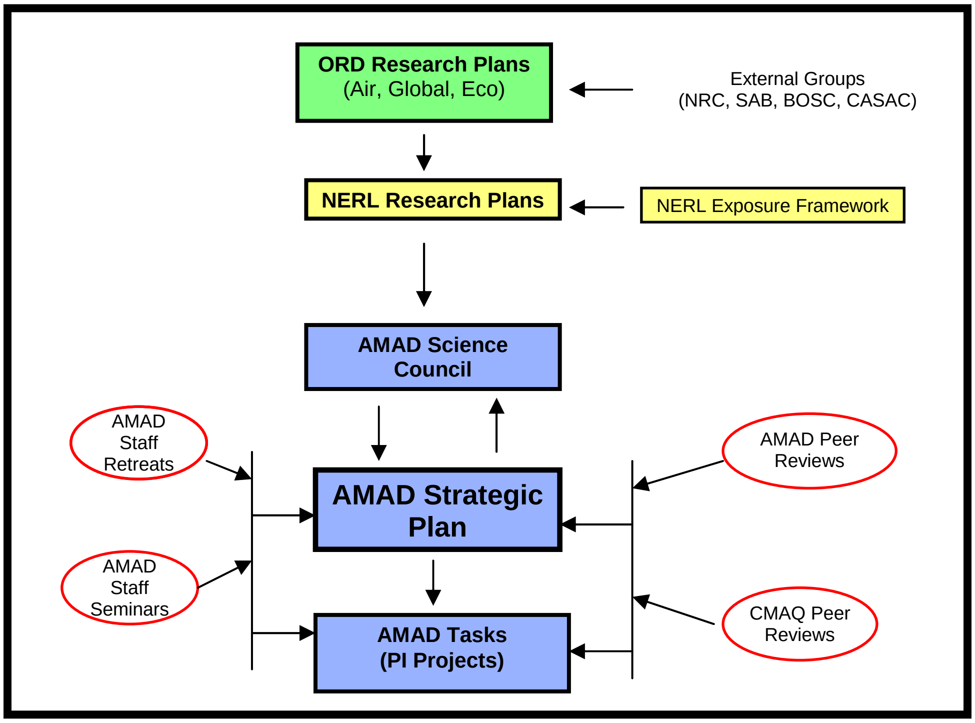


Figure 2-1. AMAD research planning process.

2.2 AMAD Research Prioritization Criteria

The research drivers described above help shape AMAD's research directions. However, there are many more potential programs, projects, and tasks indicated by these directions than AMAD can accommodate within the available resources. Therefore, some objective criteria are needed to help prioritize among various discretionary choices of research projects and tasks. The table below provides AMAD's prioritization criteria for selection of research at the project or program level, as well as the task level of model development and evaluation. These criteria are used by the AMAD Science Council during the annual task development cycle, as well as during strategic planning exercises. Some EPA and ORD research directives are non-discretionary based upon upper-level management decisions, in which case these Division-level criteria are superseded by these decisions.

Table 2-1. AMAD Research Prioritization Criteria

Project/Program Level Criteria	**Model Development and Evaluation Task Criteria**
1) Is an important issue to EPA (Problem of Broad National Significance) 2) Leverages AMAD's expertise 3) Advances exposure science 4) Advances the science in CMAQ (i.e., reduces uncertainty) 5) Advances integrated transdisciplinary research on EPA priorities 6) Provides a sound scientific basis for Agency policies	1) Model/process improvements reduce uncertainty in model-sensitive parameters of significance to decision makers 2) Model/process improvements correct errors/biases or reduce uncertainties based on results of model evaluations, in processes/parameters of significance to decision makers 3) Model/process improvements maintain the modeling platform at the state-of-science, based on peer review comments 4) Advances the science through external collaborations in model development 5) Advances the science through external collaborations in model evaluation 6) Provides significant efficiencies in model utility for community of model users 7) Can accomplish in a timely and affordable manner

2.3 Logic Model for Strategic Planning

The following sections of this document outline research plans in each of AMAD's major theme areas. First, core research on model development and evaluation is described. Next, the major model applications areas are described, including the linkage of air quality modeling to human exposures and health, the linkage of air quality modeling to ecosystem exposures and health, and the interactions between air quality and global climate change. We use the construct of the "logic model" (see Figure 2-2) in our strategic planning for each area. In research planning we start on the right side of the figure to understand all desired outcomes of the research and its applications and move to the left to determine the products and activities that help influence these outcomes. For retrospective assessment of the impact of the research, the logic model is followed from left to right.

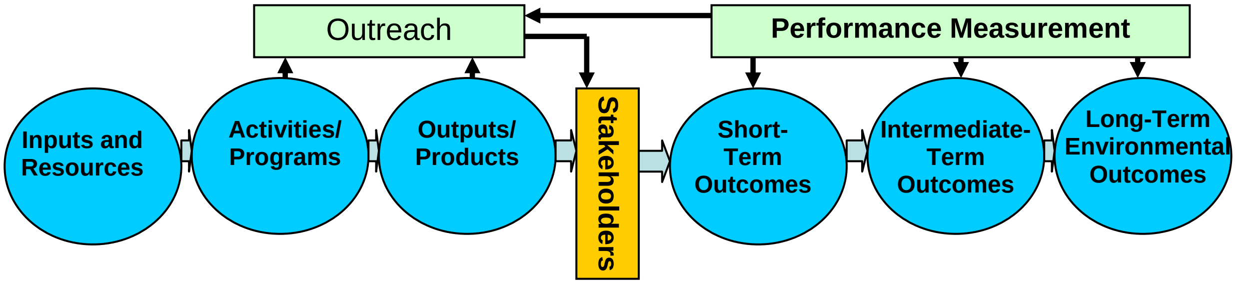


Figure 2-2. Logic model for research planning.

3. AMAD CORE RESEARCH STRATEGIC PLANNING

AMAD's core research focuses on the development, evaluation, and refinement of comprehensive atmospheric modeling systems to support the design and assessment of regulatory actions directed towards abatement of air pollution. The development and refinement of these modeling systems has and continues to be guided by application needs of the system as well as continuous evaluation of the modeling system against available measurements characterizing the dynamical and chemical state of the atmosphere. The evolution of AMAD's core research on model development and evaluation recognizes that the modeling systems must address the increasing complexity arising from new applications that treat multi-pollutant interactions, with the need to facilitate the design of effective abatement strategies that focus on simultaneously controlling multiple criteria pollutants as well address the emerging application needs described in Section 4.

3.1 Logic Model Analysis: Model Development and Evaluation

As indicated above, the long-term outcome of Agency actions is the protection of human health and the environment from the adverse effects of air pollution. The EPA develops NAAQS, in accordance with the Clean Air Act, to protect human health and the environment. The development of optimal emission control strategies to satisfy the NAAQS, which are both environmentally protective and cost effective, requires the use of air quality simulation models that can reliably predict the impact of alternate emission control strategies on ambient levels of criteria pollutants such as ozone and particulate matter. AMAD's complementary model development and evaluation research continuously supports the implementation of these air regulations by developing and providing to the stakeholders and clients with comprehensive atmospheric modeling systems. Through detailed treatment of physical and chemical processes affecting the fate of atmospheric pollutants, these modeling systems provide scientifically sound tools to understand the relationships between sources of air pollution and ambient concentrations over spatial scales ranging from urban to continental, and temporal scales ranging from hourly to annual. This is accomplished through an integrated transdisciplinary approach involving physical, chemical, numerical, and computational modeling to develop a "numerical laboratory" wherein atmospheric physico-chemical interactions can be understood and effectively simulated to guide development of air pollution abatement strategies. Through synthesis of laboratory and field measurements in parameterizations included in the model, and diagnostic testing against measurements over wider spatial and temporal scales, the models provide a framework to test and refine hypotheses and process formulations based on limited and controlled data, thereby improving our understanding of key processes regulating the atmospheric transport and fate of pollutants.

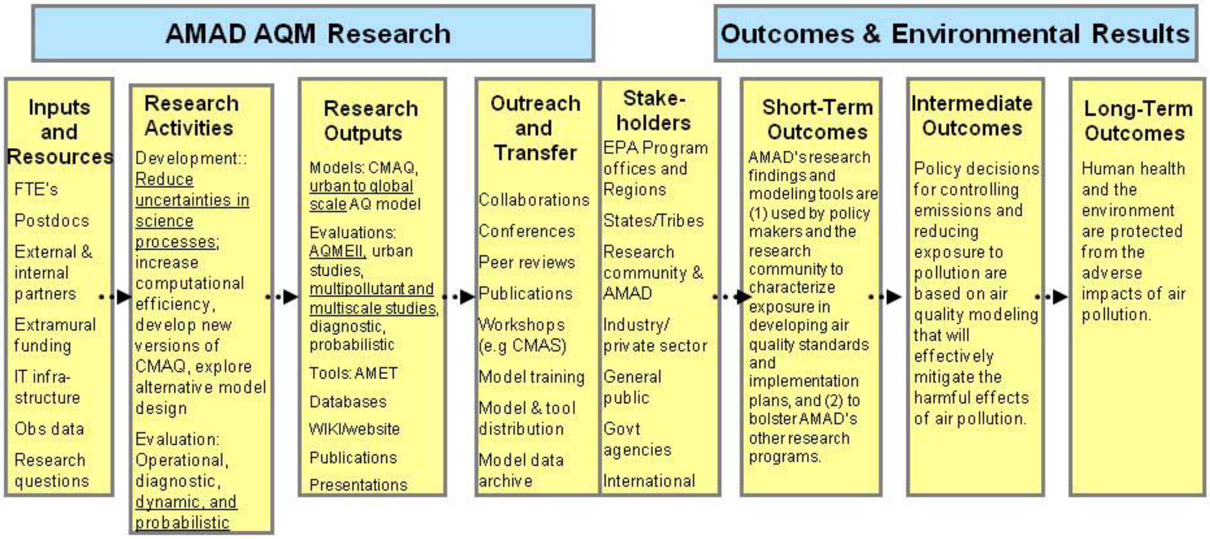


Figure 3-1. Logic model for core air quality modeling research on development and evaluation.

3.2 Long-term vision

The long-term vision of AMAD's model development and evaluation program is to maintain the Agency's leadership role in air quality modeling through the use of a transdisciplinary approach involving physical, chemical, engineering, numerical, computational and statistical sciences to support the continuous evolution of comprehensive air pollution models to support emerging regulatory and research applications. To successfully bring about the short, intermediate, and long-term outcomes discussed above, our modeling system will

- be a fully-integrated (meteorology/chemistry/land surface) chemical transport model capable of representing interactions in the atmosphere on urban-to-global scales, and
- be used for traditional multi-pollutant NAAQS-related problems, as well as for addressing air quality impacts on human health, ecosystems, and global climate.

Additionally, the modeling system will characterize prediction uncertainty, and successive model versions will quantitatively demonstrate a substantial improvement in the prediction accuracy for metrics relevant to decision making compared to their predecessors.

3.3 Major Research Areas/Science Questions

Over the past 10 years, AMAD's core research has focused primarily on developing and improving the Community Multiscale Air Quality (CMAQ) modeling system and its associated meteorological and emissions modeling systems. This system has been and continues to be extensively used by EPA and the states for air quality management analysis (e.g., State Implementation Plans and rulemaking: Clean Air Interstate Rule, Clean Air Mercury Rule, Renewable Fuels Standards Act-2), thereby providing critical regulatory support to assure protection of public health and the environment. Additionally, the modeling system has an active and broad international user community that has contributed to and benefitted from the release of updated versions of the modeling system. Consequently, some aspects of AMAD's core development and evaluation research in the short-term (next 5 years) will focus on maintaining the utility and ensuring the credibility of the CMAQ modeling system for upcoming regulatory support applications by the program and regional offices.

While significant strides have been made in developing capabilities in the CMAQ modeling system to facilitate urban to continental scale air quality assessments, emerging needs associated with more stringent NAAQS and applications to link air quality with human and ecosystem health assessments place additional demands on the modeling system. For example, the recent tightening (and anticipated further revisions) of the O_3 NAAQS to lower threshold values places additional requirements on the ability of atmospheric chemistry transport models to accurately represent the entire spectrum of ambient concentrations including values near the natural background. In addition, the promulgation of coarse PM standards would require the models to exhibit fidelity in representing the emissions from additional sources such as wind-blown dust as well as in representing interactions between crustal ions and gases. Recent advances in measurement technology now provide richer observational information (surface, aloft, and space-borne as well as specialized field studies) on the chemical and dynamical state of the atmosphere and provide opportunities to conduct methodological assessments to identify the areas of poorest predictive capability in the system and thus provide guidance on short- and intermediate-term model development and improvement directions. The short-term research goals that need to be accomplished include:

- Develop and advance a variety of model evaluation methodologies (operational, diagnostic, probabilistic, dynamic) to identify highest-priority model errors impacting current and emerging applications
- Improve the model components (chemistry/transport model as well as input emissions and meteorology) that will mitigate those errors
- Develop and incorporate the latest scientific advances (parameterizations, numerical algorithms, computational methods) to facilitate scientifically rigorous applications of the modeling system.

Emerging applications related to air-quality-climate interactions and developing transdisciplinary linkages that facilitate air quality-human health and air quality-ecosystem assessments dictate the development of new capabilities in existing atmospheric modeling systems. While the focus of current model applications is surface-level air quality analysis, simulations over annual cycles and continental scales require the accurate representation of exchange processes between the boundary layer and free-troposphere. Efficient transport in the free-troposphere, the role of inter-continental transport in modulating background pollution, and the need to characterize policy-relevant background pollution levels, in turn dictate the need to examine regional air quality in context of the global troposphere. On the other end of the spectrum, emerging Agency problems focusing on improving air quality-human exposure linkage, as well as regulatory needs associated with issues such as fine PM urban non-attainment, will require development and application of the air quality model at significantly finer resolutions to capture variability in ambient concentrations of a number of pollutants and resultant human exposure.

To address the needs of emerging assessments for air quality-climate interactions, AMAD recently embarked on the development of a coupled atmospheric dynamics-chemistry model based on coupling the Weather Research and Forecasting (WRF) meteorological model and the CMAQ chemistry-transport model. In this coupled model, the direct and indirect radiative effects of absorbing and scattering aerosols in the troposphere, estimated from the spatially and temporally varying simulated aerosol distribution, can be fed-back to the WRF radiation calculations, resulting in a “2-way” coupling between the atmospheric dynamical and chemical modeling components. Improvements in the representation of both the chemical composition and size distributions of simulated aerosols are needed to accurately characterize their optical and radiative effects and will be an area of further research emphasis.

Consequently, AMAD’s core research will focus on (1) characterizing the needs of these emerging applications through systematic analysis of model and measured data and (2) developing new and/or enhanced process representations to account for and to improve the representation of interactions of atmospheric processes occurring at the various spatial and temporal scales. The major science questions guiding the formulation of AMAD’s core research include:

- What are the primary sources of model bias in the ambient levels and deposition amounts of various pollutants?
    - What are the spatial and temporal (intra-day,diurnal, seasonal, inter-annual) characteristics of the bias in individual constituents and how do they impact the inferences drawn from the model?
    - Do biases across various constituents originate from similar sources?
    - How can emerging observational data sets (e.g., high-time resolution speciated PM, specialized campaigns, remote sensing) be effectively used to characterize systematic biases in model components and provide guidance for improvements in formulation of model components or specification of key model parameters?
- What enhancements in model processes and/or linkages with other modeling systems will be needed to extend the capabilities of regional models such as CMAQ to consistently represent atmospheric pollution from urban to hemispheric scales?

    - What are the appropriate spatial and temporal scales at which ambient levels and deposition amounts need to be characterized to improve estimates of human and ecosystem exposure?
    - What non-linear interactions between gas-, aqueous-, and particle-phase pollutants need to be represented in modeling systems to accurately assess the co-benefits of multi-pollutant emission control strategies?
- What linkages need to be developed between atmospheric chemical-transport and dynamical calculations (a) to improve the spatial and temporal characterization of simulated air pollutants, and (b) to adequately represent the effects of air pollution loading on radiation and simulated dynamical features?
- How can the uncertainties in model predictions be effectively characterized and communicated to enhance the confidence in model-based regulatory decisions/guidance?
- What enhancements in the computational and numerical structure of the model and individual algorithms need to be pursued to achieve the optimal balance between computational efficiency and scientific complexity that enables scientifically robust, yet efficient, application of the modeling system?

3.4 Major Milestones and Products

Figure 3-2 summarizes the timelines associated with various components of the core development and evaluation research, as driven by the model application needs. Several major milestones will be met in the next five years to move the AMAD core research activities on model development and evaluation towards the long-term vision and to address the science issues discussed earlier:

- *Model Releases*: Updated versions of the CMAQ modeling system have been made publicly available at periodic intervals; typically major model releases have occurred every 1-3 years. This release cycle represents a combination of (i) a logical end-point in the model development and assessment cycle to address a particular application need , (ii) addressing a major scientific advancement in representation of a specific process in the model, and (iii) updating model components to enhance the utility of the system for its worldwide user community. Anticipated model releases over the next 5 years include:
    - FY 2011 release of CMAQv5.0 with numerous updates to the representation of gas-phase chemistry and PM speciation
    - FY 2011 release of two-way coupled WRF-CMAQ modeling system
    - FY 2014 release of the CMAQ modeling system including enhancements for urban applications, enhancements for free-tropospheric and longer-lived species chemistry to extend applicability to hemispheric scales, and structural updates to improve modularity and extensibility of the system

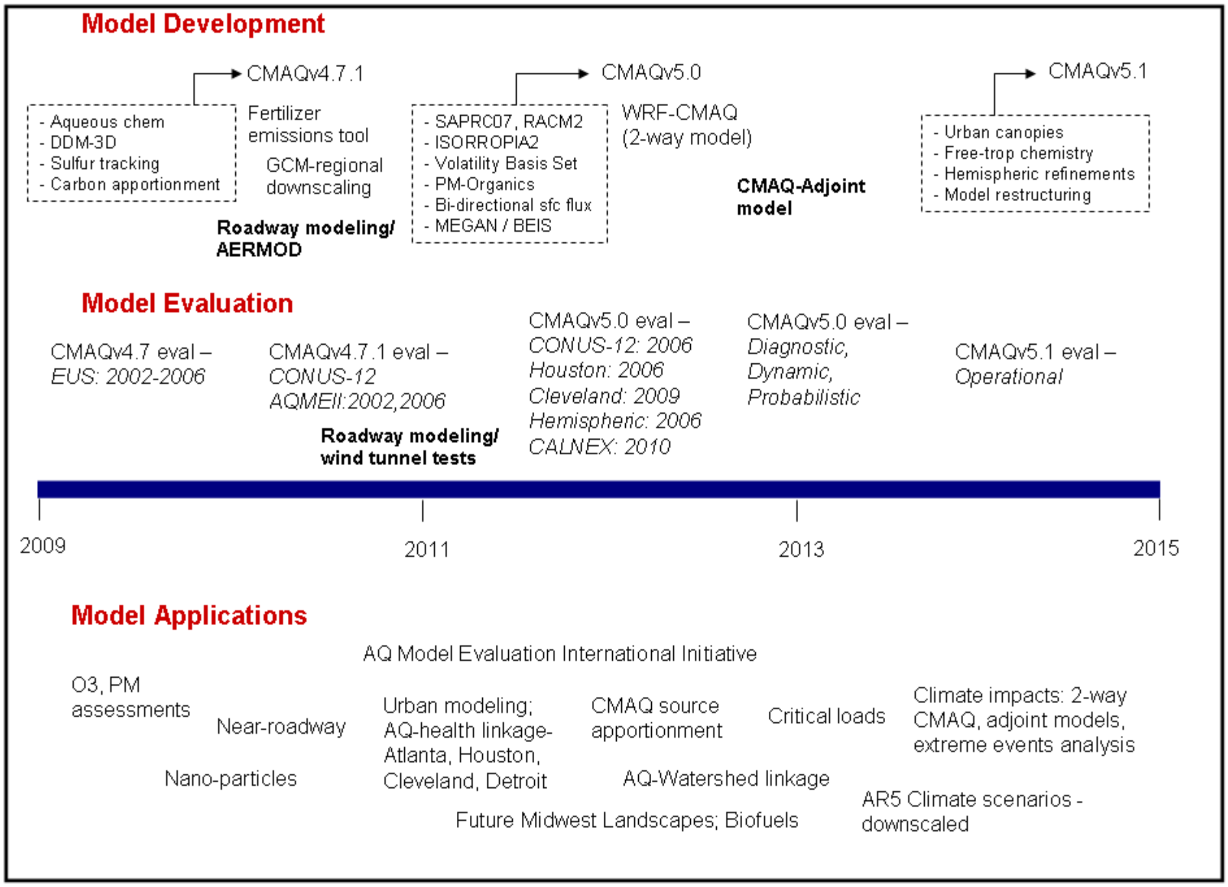


Figure 3-2. Milestone timeline for core model research

- Enhancements to the modeling system for improved predictions of
  - $PM_{2.5}$ in non-attainment areas
  - Organic aerosol mass
  - Coarse PM mass and composition
  - Particle number
- Development, testing, and application of techniques to characterize uncertainty in CMAQ model predictions.
- Development, testing and evaluation of the representation of direct and indirect effects of aerosol loading on radiation and simulated dynamical features in the coupled WRF-CMAQ modeling system
- Development and testing of linkages between land-surface, dynamical, chemical, and emissions components of the two-way WRF-CMAQ modeling system to facilitate the examination of the dependencies and feed-backs between these components and assist with assessments of air quality-climate interactions.

- Extension of the CMAQ modeling system to hemispheric scales to provide a conceptual framework to examine process interactions from urban to intercontinental scales.

3.5 Resources and Challenges

The continued development, analysis, and enhancement of the CMAQ modeling system requires a transdisciplinary skill mix to advance the physical, chemical, engineering, numerical, and computational modeling aspects of the system, as well as to advance analysis techniques that can assist in drawing scientifically-robust inferences on the workings of the atmosphere and air pollution source-receptor relationships. Capabilities of the modeling system need to be continuously expanded to extend its applicability to address the increasingly complex issues related to the design of multi-pollutant control strategies aimed at not only reducing the harmful effects of air pollution on humans and ecosystems, but also to mitigate climate change. These issues, in conjunction with the need for examination of more stringent NAAQS, now necessitate the examination of U.S. air quality issues within the context of global air pollution, and require extensions that enable the consistent examination of air quality from urban to hemispheric scales. Incorporation of additional scientific detail in the modeling system must be pursued in conjunction with exploration of computational efficiency to enable the practical use of the modeling system to address Agency issues in a timely manner. The development, testing, and evaluation of the proposed modeling extensions would greatly benefit from a significant increase in the computational resources currently available within the Agency. As a community-based modeling system, CMAQ has benefitted from a wide spectrum of application and evaluation efforts over diverse geographic domains across the globe by a broad user community, thereby improving the scientific robustness of the modeling system. Further evolution of the modeling system will benefit from this continued user involvement. Resources and avenues to sustain and promote this involvement as well as to facilitate the incorporation of model development contributions from the external community will be needed. In addition, leveraging existing and developing new collaborations with external partners involved with atmospheric modeling and measurements at DOE, NASA, NOAA and academia will be important for expanding the capabilities of the CMAQ modeling system and for conducting rigorous evaluations to both establish the credibility of the modeling system and to provide objective guidance for areas of further model development.

4.0 AMAD APPLICATIONS RESEARCH STRATEGIC PLANNING

AMAD’s models are applied in a diverse array of applications for past and current assessments as well as predictions from “what-if” type analyses. In this section we focus on three major model applications areas that are expected to be emphasized over the next several years. These areas include the applications of air quality models with regard to human exposure, ecosystems exposure, and climate change issues. In addition to the summaries provided here, the Appendix contains extended White Papers on each of these applications areas with additional research planning details.

4.1 Air Quality – Human Exposures and Health

Multiple factors affecting human exposure to atmospheric pollution (e.g., large spatial variations near roads and major industrial sources, infiltration of pollution into homes, human exposure to pollutant mixtures) require approaches that scale from regional to local environments, and to the individuals experiencing the exposure. Hence, this research provides analytical and physical modeling tools and approaches that provide the spatial and temporal detail of concentration and exposure surfaces needed to understand the relationships among pollutants emitted, the resulting air quality, and exposure of humans to these pollutants (Figure 4-1). Such tools and approaches can be used to understand critical exposure issues, determine risk mitigation strategies and evaluate the effectiveness of control strategies with respect to health outcomes.

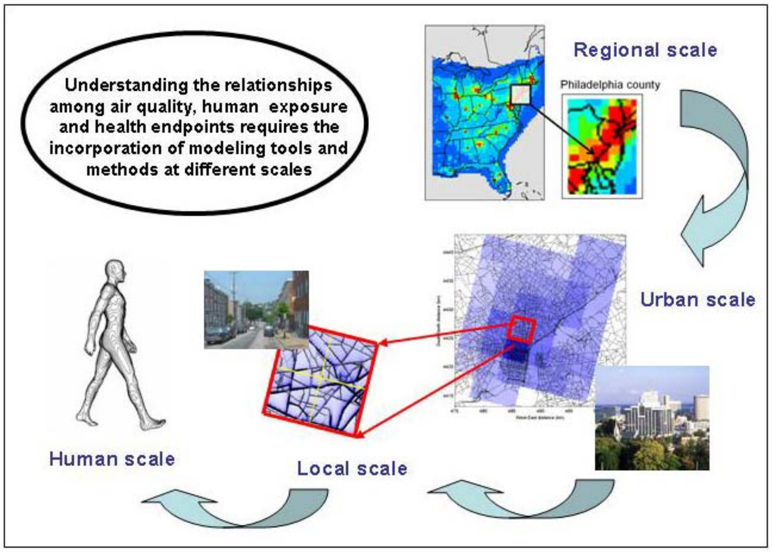
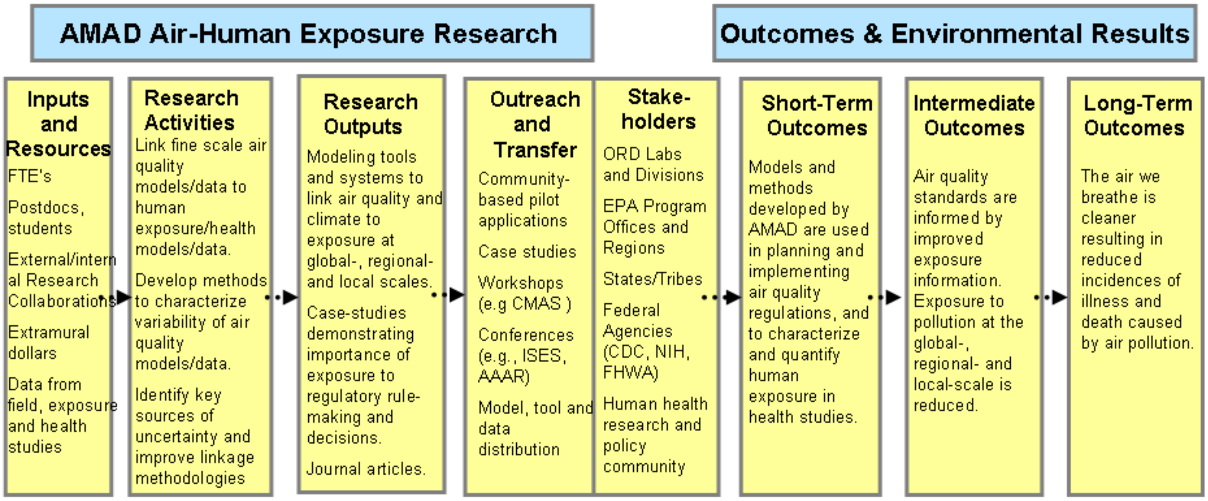


Figure 4-1. Scales reflecting regional to local environment

4.1.1 Logic Model Analysis – Air Quality-Human Exposure

The long-term environmental outcome of this research (shown in the far right column of Figure 4-2) is to reduce the incidences of illness and death caused by air pollution through reductions in anthropogenic emissions. The need for regulatory actions to protect human health is determined through human exposure and health studies that link air quality to health outcomes such as respiratory-related illness, cardio-vascular disease and mortality. These health studies, especially time series studies, require an accurate assessment of the temporal and spatial variations in ambient concentrations. The impact of exposure misclassification or exposure prediction errors on the outcome of air pollution epidemiology studies varies depending on the particular study design. In general, at finer spatial inter- or intra-urban scales (e.g., near roadways), there is a greater likelihood that exposure prediction errors will play an important role in the outcome of epidemiologic studies that use time series. This is particularly relevant for those pollutants that exhibit strong gradients or are heterogeneous across space.



Inputs and Resources
FTE's
Postdocs, students
External/internal Research Collaborations
Extramural dollars
Data from field, exposure and health studies

Research Activities
Link fine scale air quality models/data to human exposure/health models/data.
Develop methods to characterize variability of air quality models/data.
Identify key sources of uncertainty and improve linkage methodologies

Research Outputs
Modeling tools and systems to link air quality and climate to exposure at global-, regional- and local scales.
Case-studies demonstrating importance of exposure to regulatory rule-making and decisions.
Journal articles.

Outreach and Transfer
Community-based pilot applications
Case studies
Workshops (e.g CMAS)
Conferences (e.g., ISES, AAAR)
Model, tool and data distribution

Stake-holders
ORD Labs and Divisions
EPA Program Offices and Regions
States/Tribes
Federal Agencies (CDC, NIH, FHWA)
Human health research and policy community

Short-Term Outcomes
Models and methods developed by AMAD are used in planning and implementing air quality regulations, and to characterize and quantify human exposure in health studies.

Intermediate Outcomes
Air quality standards are informed by improved exposure information. Exposure to pollution at the global-, regional- and local-scale is reduced.

Long-Term Outcomes
The air we breathe is cleaner resulting in reduced incidences of illness and death caused by air pollution.

Figure 4-2. Logic model for Air Quality Human Exposure Research

In the absence of personal exposure measurements, epidemiology studies have traditionally relied upon alternate surrogates of personal exposures, such as area-wide ambient air pollution levels based on readily available outdoor concentrations (Figure 4-3a). Such studies assume that concentrations at these monitoring sites, or average concentrations over a few monitoring sites, are representative of the complex spatial and temporal patterns of air quality within a large urban area. However, there is increasing evidence that the current monitoring network is not capturing the sharp gradients in exposure due to high concentrations near, for example, major roadways. In addition, ambient monitoring data are often non-existent or very sparse for many pollutants (e.g., toxic pollutants). Hence, models can be used to fill in the temporal and spatial data gaps to improve the characterization of air quality for use in human exposure and health studies. Three-dimensional deterministic air quality models, such as the CMAQ model, can estimate concentrations for multiple pollutants across a uniform spatial and temporal scale (Figure 4-3b). Dispersion models, such as AERMOD, can be used to estimate exposure to pollutants near sources and at urban-and local-scales (Figure 4-3c). These models can be used alone or in conjunction with other data, such as ambient measurements, micro-environmental information (e.g., road networks), and exposure metrics (e.g., human behavior patterns, home infiltration rates).

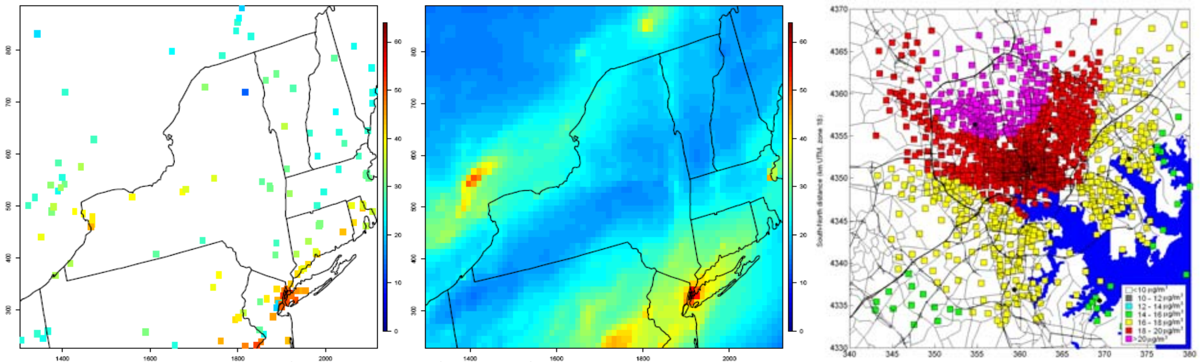


Figure 4-3. Examples of spatial surfaces of daily averaged $PM_{2.5}$ concentrations generated using; a) observations, b) CMAQ model, and c) AERMOD.

Models can also be used to help integrate exposure into air quality management practices, including standard setting and implementation, risk mitigation and assessing the impact of regulatory actions. Models can define the relationships between sources, ambient air concentrations and exposures, making them valuable tools for predicting future outcomes and planning and assessing various risk mitigation strategies.

Thus, research performed under the Air Quality-Human Exposure program will: (1) Advance models to incorporate scale-specific capabilities to improve exposure characterization for use in health studies and regulatory actions; (2) Develop and improve linkages among source, exposure and air quality models; and (3) Demonstrate the value of integrated models and approaches by applying them in human exposure and health studies, and air quality management analyses that are critical to the Agency's mission.

4.1.2 Long-term Vision – Air Quality-Human Exposure

The major research and policy drivers identified above provide the motivation for the following long-term (5-10 years) vision for the AQ-Health Exposure program:

AQ Human Exposure Program
Long-term Vision

State-of-science air quality modeling tools and methods are available that characterize and link air pollution from sources to exposure at the relevant temporal and spatial scales for the population and pollutants of interest for use in human exposure/health studies and regulatory activities.

To achieve this vision, the following goals have been identified:

Major Goals

- Produce integrated models and methods that characterize pollutant concentrations and exposure of multiple pollutants at the relevant scale for use in exposure and health studies and regulatory actions;
- Produce models and methods to link source, air quality and human exposure models and data, and;
- Provide best estimates of concentrations/exposures and the uncertainty in these estimates.

4.1.3 Science Questions

Several science issues were identified in this program that relate to the characterization of air pollution. For example, characterization of air quality is often incomplete due to our limited capability to model micro-environments and the spatial and temporal variability that may be relevant at the scales important for human exposure and health studies. The application of air quality model output in exposure and health studies presents new demands on quantifying uncertainty because such studies must discern a relatively small signal of change embedded in a highly confounded set of outcomes. The need to address exposure to multiple pollutants at various scales challenges the program to develop innovative methods to estimate input data (e.g., meteorology, emissions) and other parameters, such as exposure metrics. Given these and other considerations, the following science questions have been formulated:

- How do we effectively and systematically characterize air quality and exposure for applications at multiple scales and for multiple pollutants?
    - What spatial and temporal resolution is needed to support various applications ranging from health studies to regulatory activities (e.g., acute vs. chronic health studies, National Ambient Air Quality Standards)?
    - How do we improve and refine estimates to achieve the accuracy needed to support health studies and regulatory activities? How does accuracy of the estimate impact the outcome (e.g., health effect measure, regulatory decision)?

- Can we improve linkages between air quality and exposure models?
    - How do we link air quality models (e.g., CMAQ, AERMOD) and other information to better estimate regional- and local-scale pollution?
    - What are the critical drivers for characterizing exposure beyond ambient concentration (e.g., indoor infiltration rates, commuting in vehicles)? How do we incorporate these drivers into air quality models to efficiently provide viable estimates that can address multiple problems?

- How do we quantify the variance and uncertainty inherent in model estimates at various scales for multiple pollutants?
    - What is driving the various components of spatial and temporal variance? How do these common features vary (e.g., by source, composition, size)? How do chemical features change at different spatial and temporal scales, or in different environments (e.g., urban, near-road, regional transport)?
    - How do we characterize sub-grid variability? Can we efficiently apply this characterization to improve exposure estimates at finer scales?
    - How do we quantify uncertainty? How can estimates of uncertainty be used in applications?

4.1.4 Major Research Areas

The major research areas needed to address the science questions and achieve the products and milestones listed above are organized into the following major activities:

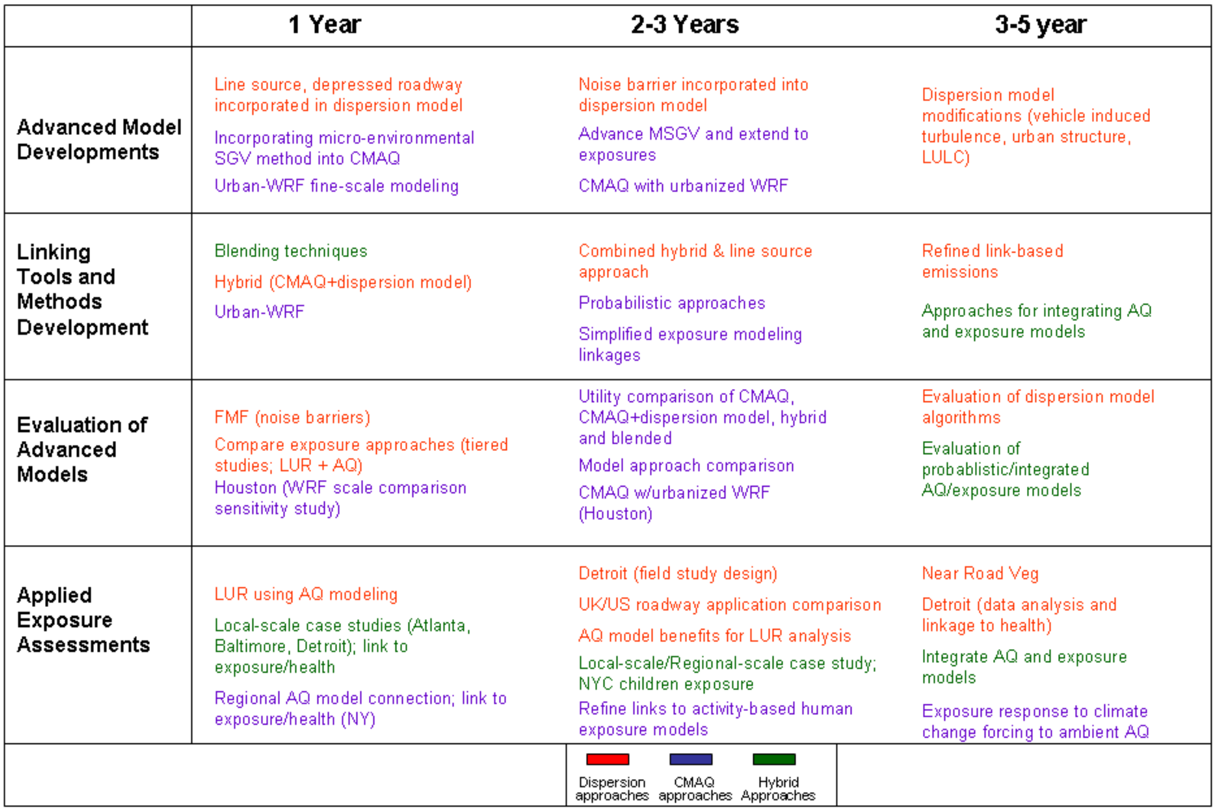
- Advance dispersion and CMAQ models to incorporate urban-and local-scale capabilities for use in characterizing exposure in exposure/health studies and regulatory actions.
    - Develop algorithms to model fine-scale features (e.g., roadway barriers, near-field turbulence)
    - Estimate fine-scale/sub-grid variability
    - Evaluate algorithms/model improvements
  - Develop and improve linkages among source, exposure and air quality models.
    - Develop techniques to combine available data and link air quality and exposure models
    - Incorporate major drivers of exposure, such as critical pollution sources such as roadways, infiltration of pollution into homes and commuting patterns into air quality models
    - Develop innovative and less resource intensive methodologies for model inputs (emissions/meteorology, exposure model)
    - Quantify uncertainty to inform/improve models
- Demonstrate value of improved models/approaches in human exposure/health studies and regulatory actions.
    - Conduct case-studies that demonstrate linkages across risk paradigm (source-to-exposure)
    - Conduct case-studies that demonstrate use of exposure in health studies and specific regulatory actions
    - Test approaches at multiple scales
    - Demonstrate application to multi-source/multi-pollutant scenarios

4.1.5 Major Products

Major products resulting from this research program relate to improving approaches needed for more refined exposure estimates, linking across models, and applying developed tools to demonstrate their value. More specifically:

- Modeling tools/methods that characterize air pollution at multiple scales
  - Approaches to characterize concentration variability at various scales to refine exposure estimates and quantify uncertainty
  - Advanced fine-scale modeling approaches to improve concentration/exposure estimates.
  - Evaluations that examine the importance of refined air quality and exposure characterization in assessing human exposure/health.
- Modeling tools and systems that link air quality to exposure
  - Innovative, less resource intensive methodologies to link air quality and exposure models and transition approaches to operational use.
  - Integrated air quality and exposure modeling for operational use (in collaboration with HEASD).
- Case-studies demonstrating importance of exposure
  - Pilot projects demonstrating the use of air quality model estimates of concentration as a primary input into exposure and epidemiology studies
  - Application and evaluation of models for use in exposure/health studies and regulatory activities at multiple scales.

- Use and evaluation of models/methods that link air quality to exposure in determining emission strategies to reduce human exposures
    - Exposure assessments that use results of demonstration projects in designing and implementing regulations.



	1 Year	2-3 Years	3-5 year
Advanced Model Developments	Line source, depressed roadway incorporated in dispersion model Incorporating micro-environmental SGV method into CMAQ Urban-WRF fine-scale modeling	Noise barrier incorporated into dispersion model Advance MSGV and extend to exposures CMAQ with urbanized WRF	Dispersion model modifications (vehicle induced turbulence, urban structure, LULC)
Linking Tools and Methods Development	Blending techniques Hybrid (CMAQ+dispersion model) Urban-WRF	Combined hybrid & line source approach Probabilistic approaches Simplified exposure modeling linkages	Refined link-based emissions Approaches for integrating AQ and exposure models
Evaluation of Advanced Models	FMF (noise barriers) Compare exposure approaches (tiered studies; LUR + AQ) Houston (WRF scale comparison sensitivity study)	Utility comparison of CMAQ, CMAQ+dispersion model, hybrid and blended Model approach comparison CMAQ w/urbanized WRF (Houston)	Evaluation of dispersion model algorithms Evaluation of probablistic/integrated AQ/exposure models
Applied Exposure Assessments	LUR using AQ modeling Local-scale case studies (Atlanta, Baltimore, Detroit); link to exposure/health Regional AQ model connection; link to exposure/health (NY)	Detroit (field study design) UK/US roadway application comparison AQ model benefits for LUR analysis Local-scale/Regional-scale case study; NYC children exposure Refine links to activity-based human exposure models	Near Road Veg Detroit (data analysis and linkage to health) Integrate AQ and exposure models Exposure response to climate change forcing to ambient AQ
		🟥 Dispersion approaches 🟦 CMAQ approaches 🟩 Hybrid Approaches	

Figure 4-4. Timeline of Major Research Milestones/Products

4.1.6 Resources/Challenges

While there is some ongoing work to include the use of exposure metrics beyond ambient concentrations in the implementation of regulatory decisions, such use is limited. Integrating exposure into regulatory management activities will require a shift in the highly codified regulatory paradigm. Similarly, the regulatory community is familiar with using absolute values for determining compliance, but using modeled predictions bounded with estimates of uncertainty is a difficult concept to implement in the current regulatory structure. Activities such as pilot projects and communication strategies will demonstrate the feasibility of these new approaches. Additionally, the AQ-Human Exposure Program is a relatively new program with limited resources. Meeting the objectives laid out in this strategy will require a heavy reliance on leveraging ongoing efforts, partnerships, and external resources such as contracts and post-doc positions.

The skill mix needed to support this effort is cross-disciplinary, and includes expertise in emissions, meteorology, chemistry, physics, exposure science, epidemiology and risk assessment.   Skills that will be acquired through internal capability include dispersion and grid-based modeling and fluid dynamics. Requirements that will be met through external resources include emissions modeling, exposure and epidemiology modeling, statistics, GIS analysis and risk assessment.

4.2 Air Quality – Ecosystem Exposures and Health

4.2.1 Logic Model Analysis – AQ-Eco Exposure

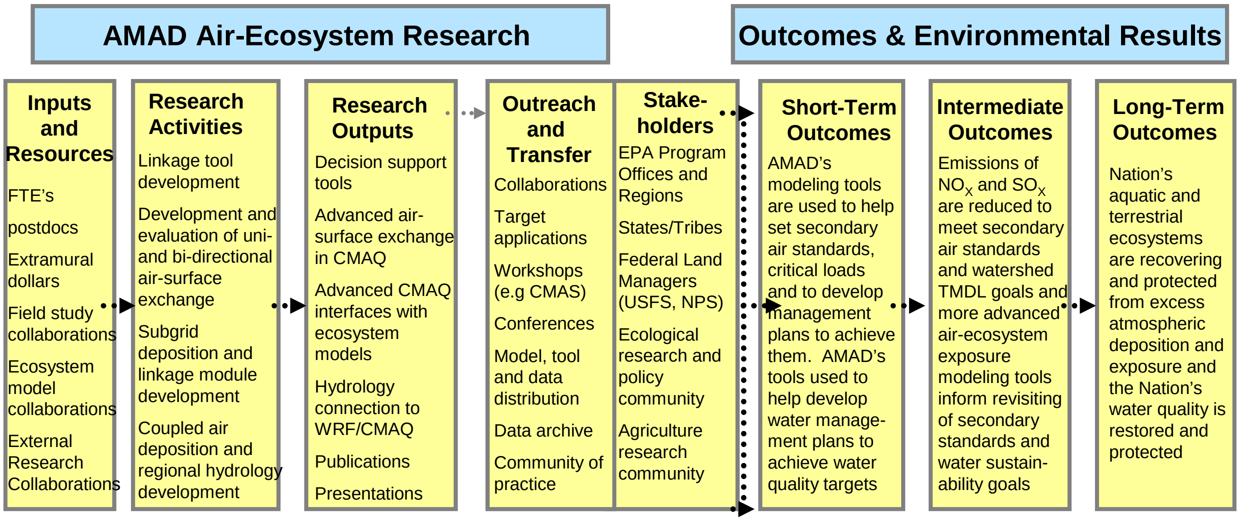


Figure 4-5. Logic model for Air Quality Ecosystem Exposure Research

As shown on the far right of Figure 4-5, the desired long-term outcomes of Agency actions regarding ecosystem health are for the Nation's aquatic and terrestrial ecosystems to be recovering and protected from stressors from the atmosphere, such as acidification and excess nitrogen, and the Nation's water quality is restored and protected. Drivers for achieving these long-term outcomes stem from regulations in the Clean Air Act (CAA) and the Clean Water Act (CWA).

The CAA secondary standards are used to protect welfare, including but not limited to soils, water, wildlife, vegetation, visibility, weather, personal comfort and well-being. In the near-term, the development and revision of secondary standards are focused on ozone damage from exposure to air concentrations, and adverse effects of acidification and nutrient enrichment from exposure to atmospheric deposition. The near-term priority for addressing adverse effects from deposition is to develop a combined secondary standard for SO_X and NO_X emissions to address acidification since the total deposition of sulfur (S) plus nitrogen (N) is acidifying. After acidification, the next priority is to develop secondary standards addressing nitrogen nutrient enrichment of aquatic, estuarine and terrestrial ecosystems. Because the CAA stipulated that the NAAQS were for ambient air concentrations, not deposition, the air quality models serve a critical function to connect air quality and deposition. The CMAQ model is used to develop an

Atmospheric Deposition Transformation Function for the NO_X-SO_X secondary standard development. Also, the management concept of critical loads (CL) supports the development of secondary standards. Air quality models provide a complete budget of total air deposition inputs with full spatial coverage to critical load models and watershed models to relate ecological indicators of harm to deposition levels. The CMAQ air deposition inputs are central to establishing CL's and then to determine CL exceedances under current and future deposition conditions in response to management options and in the context of climate change.

Under the CWA states are required to develop Total Maximum Daily Load (TMDL) management strategies for streams and rivers that are impaired. States are also required to restore estuaries that are impaired. A significant source of impairment, especially for estuaries, is atmospheric deposition of nitrogen to watersheds as well as the water bodies of interest. CMAQ is necessary to provide complete air deposition inputs to watershed and estuary assessments.

Short-term outcomes are targeted to the setting of new NO_X-SO_X combined secondary standards, development of management strategies to achieve them, development of CL assessments, and development of management plans to restore estuarine services, achieve water quality targets and meet TMDL goals. Intermediate outcomes are targeted to revisiting and extending secondary standards to address nutrient enrichment, further extending CL assessments to serve secondary standard setting, and achieving TMDL and water sustainability goals.

4.2.2 Long-term Vision – AQ-Eco Exposure

The above drivers to achieve Agency outcomes provide the context for the long-term (5-10 year) vision for AQ-Eco Exposure research. The long-term vision of what needs to be accomplished to help bring about short-term, intermediate, and long-term outcomes from above is:

- Produce exposure estimates of deposition at the spatial and temporal scales responsible for the receptor response

- Link deposition exposure models to receptor response models in an integrated, transdisciplinary, one-biosphere manner for current and future climate conditions

The research goals that need to be accomplished to realize the vision are:

- Produce state-of-the science air-surface exchange parameterizations and develop added confidence in modeling that exchange

- Develop an effective, multidisciplinary linkage between CMAQ, a model with universal or generalized parameterizations with output data subject to input/parameterization error, and calibrated ecosystem/watershed models having minimized random errors based on monitored data ("paradigm gap" between the models)

- Address temporal and spatial scale mismatches between CMAQ and ecosystem models

- Continue to develop and advance tools and approaches to better link air and water/terrestrial models

- Be leaders in developing transdisciplinary approaches

- Be able to assess climate impacts on ecosystems

4.2.3 Science Questions

Key issues need to be addressed to achieve the research goals. These issues indicate the areas where current capabilities to support the objectives are not sufficient and can be improved. These issues have been identified through consultation with the stakeholders/clients and through synthesis of recent research results stemming from collaborations with ecosystem modelers. The issues include bias in the deposition predictions of CMAQ, the small size of ecosystem areas of concern relative to CMAQ grid dimensions, missing processes in CMAQ, and the paradigm gap between CMAQ and calibrated ecosystem models that thwarts effective linkage between the model types. Climate change and land-use change are emerging issues that also need to be dealt with. Science questions that are associated with each major issue are posed to help formulate components of the research. The science questions are:

- What are the sources of deposition bias and how can they be resolved?

- How can spatial and temporal scale mismatches be addressed or resolved?

- What processes are missing or not sufficiently state-of-the-science and what is needed to incorporate or improve them to be state-of-the-science?

- What are the sources of the paradigm gap between the CMAQ air quality model, a universal, generalized parameterization model, and calibrated ecosystem/watershed models? What approaches will bridge the paradigm gap?

- How will climate and land-use change impact biogeochemical cycling and ecosystem health?

4.2.4 Major Research Areas

There are eight major research areas that comprise the components of the research program needed to answer the science questions posed above. They are organized into four major activities: model development, tool development, model evaluation, and research applications. These activities are fundamentally inter-connected in the research planning process as shown in Figure 4-6 which illustrates the research planning paradigm of iterative model advancement used in AMAD.

Model Development

- Advance CMAQ air-surface exchange algorithms
    - Incorporate bi-directional exchange of NH_3, Hg and pesticides into CMAQ

    - Develop CMAQ adjoint model for inverse modeling of net NH_3 fluxes in bi-directional exchange version of CMAQ

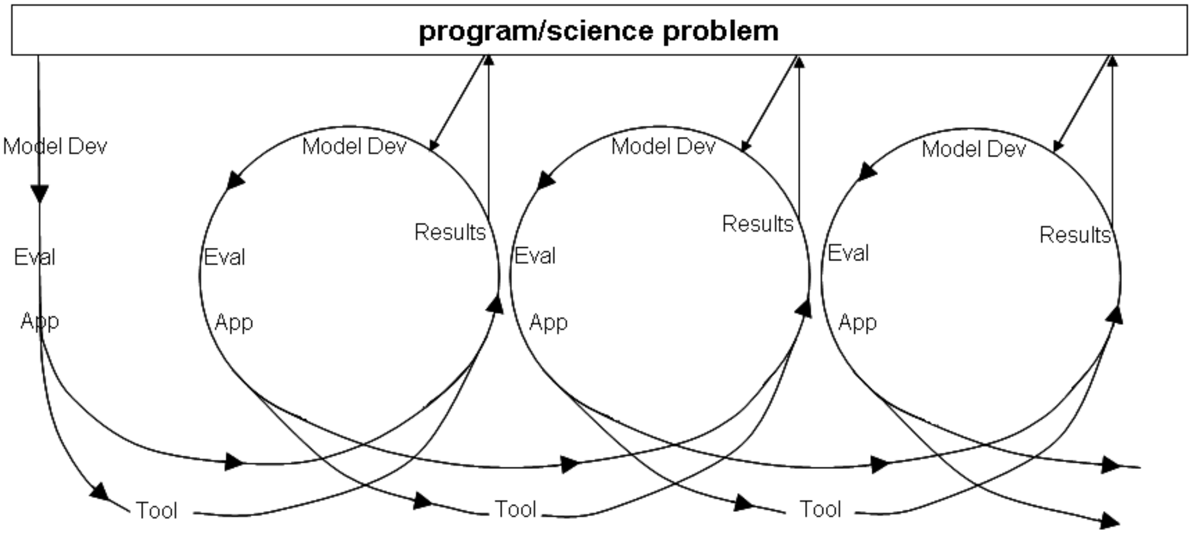


Figure 4-6. Research Planning Approach to Developing Models, Tools and Applications

- Address missing or inaccurate process descriptions
    - Incorporate lightning NO_X production
    - Incorporate cloud impaction deposition to high elevation terrain in CMAQ
    - Incorporate the emissions, transport and deposition of base cations in CMAQ
    - Develop approach to include dissolved organic nitrogen (DON) in system
- Harmonize air-ecosystem linkage and land surface characterizations
    - Convert land use to the National Land Cover Database (NLCD) for WRF and CMAQ
    - Harmonize sub-NLCD land cover class designations across system and address special characteristics of deposition to wetlands and urban surfaces
- Link or incorporate hydrology models into the WRF/CMAQ land-surface modeling system
    - Develop the connection between meteorological model water budgets and surface water hydrology as an extension of the WRF/CMAQ system
    - Develop ability to model changes in precipitation patterns, water budgets, and water availability stemming from climate change
    - Improve predictions of precipitation fields

Tool Development

- Develop fertilizer ammonia application rates (temporal and spatial) to support bi-directional CMAQ and the calculation of terrestrial nitrogen budget scenarios
    - Account for the lateral movement of fertilizer N applied to fields to consistently connect the ammonia application to watershed stream loading
- Address within-grid variability of deposition, especially for complex terrain

    - Extend subgrid land use diversity (mosaic approach) beyond NLCD classes to address deposition to specific sensitive species
    - Characterize terrain effects on concentrations
    - Characterize within-grid emissions variability

Model Evaluation

- Evaluate and reduce deposition prediction biases
    - Evaluate bi-directional and uni-directional surface exchange algorithms
    - Evaluate to explore for and help identify/characterize missing pathways (e.g.)
        - Move beyond lightning NO_X and cloud impaction deposition
        - Dissolved organic nitrogen (DON)
    - Conduct inverse modeling of NH_3 with CMAQ adjoint version for emissions characterization and algorithm uncertainty reduction
    - Improve predictions of precipitation fields, especially in complex terrain

Research Applications

- Conduct targeted research applications
    - Ecosystem Services Research Studies for national atlas and place-based research
    - Critical load/TMDL/Secondary Standards Studies
    - Water quality/water quantity studies

4.2.5 Major Milestones and Products

Major products needed to be produced in the next 5 years to move the AMAD AQ-Eco Exposure research program towards the long-term vision and goals and address the science issues are:

- Incorporation of recognized state-of-the-science air-surface exchange algorithms in CMAQ, particularly bi-directional exchange, with supporting field study/model evaluation work and characterization of uncertainties.

- Incorporation of missing deposition processes to reduce uncertainty in deposition estimates from CMAQ

- Development and implementation of a strategy that bridges the paradigm gap between CMAQ and calibrated ecosystem/watershed models. The strategy includes:
    - Extension of the WRF meteorological land-surface modeling to connect to modeling of hydrology and watershed processes to create an internally-consistent water balance data set for linkage with ecosystem models
    - Connection of hydrology to climate-related dynamic downscaled meteorology to support assessments of the effect of changing climate and land use on ecosystems
    - Extension of integrated air-water transdisciplinary capability within the CMAQ system to move closer to a one-biosphere concept/capability

- Development of long-term, multi-year deposition datasets, especially for emission transition periods

- Development and evaluation of approaches to provide sub-grid deposition values and provide characterization of sub-grid variability to address uncertainty in deposition

- Development of tools to enhance stakeholder communication, support scenario analysis and support advancement of transdisciplinary exchange

Figure 4-7 illustrates a timeline with the anticipated major milestones and products from this research application area.

		1 Year	**2-3 Years**	**3-5 years**
Model Development (CMAQ)	**Air Surface Exchange**	Bidirectional NH_3, Hg	Bidirectional CMAQ Adjoint Updates to uni-directional modules	CMAQ-Pesticide Deposition to Urban Sfc
	Processes	Lightning NO_X	Cloud deposition	Preliminary DON
	Land Use	Harmonize to NLCD	Harmonize biogenic classes	Wetlands and Urban
	Hydrology		Met-Hydrology linkage	Improved hydro-budget Improved precipitation
Tool Development	**N Budgets**	FEST-C (APM)	FEST-C + watershed N	FEST-C + climate N_2O
	Subgrid	Mosaic (deposition)	Subgrid exposure	Advanced subgrid exposure
	Linkage	PRISM adjustement WDT (non-contiguous)	WDT w/ subgrid deposition	Advanced PRISM adjust.
Evaluation	**NH_3, Hg Air Surface Ex.**	NH_3 bi-di – grass	NH_3 bi-di-forest/ NH_3 Adjoint inverse Bi-di Hg eval (w/ OAQPS)	Mobile flux platform
	Deposition	NO_Y dep./ Lightning NO_X	N & S dep./ Explore western bias	New CASTnet &mobile flux
	Hydrology		Linked hydrology	Precipitation & hydrology
Research Applications	**Ecosystem Services**	FML base National Atlas base	FML futures x2 Albemarle-Pamlico bi-di base	Land use & urban change Climate change on N
	Crit. Loads TMDLs	Bi-directional base Ches.Bay N TMDL budgets	Bi-directional futures Subgrid variation studies	CBP-USDA (pesticides) Climate change on dep.
	Water Quantity & Quality	Precip linkage studies	Air-water linkage studies	Climate & water quantity

Figure 4-7. Timeline of Major Research Milestones/Products

4.2.6 Resources/Challenges

The skill mix needed is transdisciplinary. The mix requires collaboration with many scientists within AMAD and collaboration with many scientists external to AMAD. While the AMAD skill mix is broad and covers most areas, a key gap is in the area of meteorological-hydrological modeling to realize the linkage between the meteorology and hydrology. This is a key challenge to be addressed within AMAD. An additional challenge is to foster collaboration with field measurement scientists to design and collect adequate data to parameterize and evaluate the air-surface exchange capabilities of CMAQ. Collaboration with aquatic, terrestrial and landscape ecological modelers is also necessary and resources exist within NERL to support this.

Developing collaborations with external partners, particularly those with ecosystem modeling skills will be particularly important to expanding the transdisciplinary nature of the CMAQ system and its connections with ecosystem models. These partners are both internal and external to EPA and include scientists at USGS, NOAA, USDA, USFS, NPS and NASA as well as in academia.

4.3 Air Quality – Climate Change Interactions

“Taking Action on Climate Change” and “Improving Air Quality” are the top two of 7 Priorities for EPA’s future outlined recently by EPA Administrator Lisa P. Jackson. “Action” includes research to assess vulnerability of environmental systems to climate change, adaptation of environmental systems to a changing climate, and mitigation strategies to limit climate change. Thus, the Agency needs regional climate change assessment tools to quantify the effects of future climate change and greenhouse gas (GHG) emission reductions on human health and the environment including air quality, water quality, water availability, heat stress, and ecosystem impacts, as well as vulnerability of environmental systems to climate extremes and variability. The Agency needs comprehensive modeling tools that include direct and indirect radiative forcing of air pollutants (e.g. aerosols, ozone) to develop short-term climate change mitigation strategies and to assess climate impacts of air quality management options.

Global climate change has become one of the most important and contentious environmental issues of our time. Thus, there are many large and well-funded research efforts that have made significant progress in the science and modeling of climate change over the past decade as recently demonstrated by the 2007 Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC). Global climate models (GCMs) are becoming increasingly complex as they are coupled to ocean models and carbon and nitrogen cycle models. They are also going beyond radiative forcing by long-lived chemical species such as CO_2, N_2O, and CH_4 to consider the effects of short-lived climate forcers (SLCF) such as ozone and aerosols. Although GCMs are increasing their spatial resolution, they still typically have grid cells of 1^ox1^o or larger. These coarse grids are insufficient to resolve many geographical features, such as mountain ranges, lakes, complex coastlines, and land use heterogeneity that can have significant impacts on regional climate. In addition, air pollutant emissions that contribute to high concentrations of SLCF tend to be highly concentrated in urban and industrial areas that are not well resolved at GCM grid sizes. High-resolution regional climate chemistry models can be used with fidelity to resolve geography and land cover that will enable us to project future climate change and the interaction of climate change and air quality at the regional scales that are of particular interest to the Agency.

The long-term vision for AMAD’s climate research is to provide the Agency with modeling tools and scientific analyses to understand the impacts of choices to mitigate climate change and improve air quality, as well as to understand how to adapt environmental protection to a changing climate. This effort will involve developing integrated climate-chemistry models that are precursors to comprehensive earth-system modeling. Since AMAD is a global leader in air quality model development, evaluation, and analysis, AMAD’s particular niche in the climate research community will be in modeling global to mesoscale air quality and climate interactions.

4.3.1 Logic Model Analysis – AQ-Climate

The logic model for air quality and climate interaction research is shown in Figure 4-8. The logic model shows how the various research activities will be transferred to EPA stakeholders/clients and the research community leading to short-term outcomes that are designed to respond to the challenges facing environmental protection in an era of changing climate. In the intermediate and long-term timeframes we plan to have developed modeling tools that will be used for emission control strategies that simultaneously mitigate air pollution impacts and SLCF resulting in cleaner air and reduced climate warming.

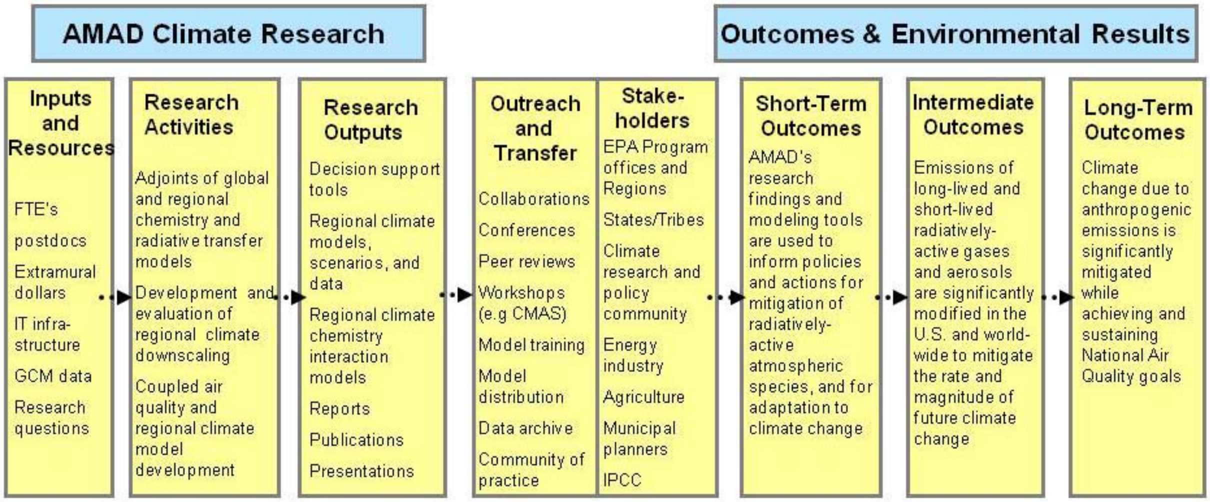


Figure 4-8. Logic model for AQ-Climate research

4.3.2 Science and Policy Drivers

In the 2007 U.S. Supreme Court case, *Massachusetts vs. Environmental Protection Agency*, twelve states and several cities brought suit against the EPA to force the Agency to regulate carbon dioxide and other greenhouse gases as pollutants. The case was decided 5-4 in favor of Massachusetts and the other states leading to the Endangerment and Cause Findings under the Clean Air Act, stating that the EPA must prepare for rulemaking for control of greenhouse gas emissions. Additionally, EPA/OAR recognizes that some "traditional" pollutants regulated under the CAA also have radiative forcing properties (e.g., black carbon and other aerosol species, ozone) that impact climate. Thus, the Agency has a need for integrated policy approaches to both mitigate climate change and manage air quality.

Given the new legal and regulatory mandates for action on climate change, a key EPA question in the area of risk assessment and adaptation is: how will climate change impact air and water quality, water availability, and ecosystems? A key question in the area of risk mitigation is: how can the EPA best contribute to climate change mitigation through U.S. controls of both long-lived greenhouse gases and short-lived pollutants affecting the radiative forcing? AMAD will have a central role in answering these questions through our expertise in regional scale meteorological and air quality modeling and by leveraging the EPA's leading role in emission inventories and projections. AMAD has already established collaborations with the climate change research community to access the upcoming AR5 GCM projections for downscaling to regional scale over the continental U.S. at high resolution for environmental impact assessments, exposure characterization, and adaptation. Since the latest GCMs include SLCF and their direct and indirect radiative feedback effects, AMAD will collaborate with GCM modelers to test future emission scenarios for climate and air quality consequences (e.g controlling black carbon) using EPA emission projection scenarios. AMAD is developing modeling tools for integrated regional air quality and climate assessment based on a two-way coupled meteorology and atmospheric chemistry modeling system with direct and indirect feedback composed of the WRF and CMAQ models. This research includes development of hemispheric WRF-CMAQ modeling to understand impacts of inter-continental transport on U.S. air quality management strategies under present-day and future climate conditions. AMAD is also collaborating to develop screening tools for rapid exploration of climate-mitigating emissions scenarios.

4.3.3 Major Research Areas

The AMAD Air Quality-Climate research program includes two parallel approaches, one of which is designed to yield useful rapid outcomes to help the Agency develop policies on emission control strategies for climate and air quality co-benefits. The other approach involves building modeling tools and capabilities for cutting edge research in air quality-climate change interactions on the regional scale. The rapid approach, known as GLIMPSE, involves development of screening tools for emission scenarios for desirable air quality and climate outcomes based on simulations with a combination of models and model-derived tools including an adjoint of a global atmospheric chemistry model (GEOS-Chem), a radiative transfer model (LIDORT), an emission projection model (MARKAL), and an adjoint of a regional atmospheric chemistry model (CMAQ). A reduced-form model will be constructed from radiative forcing sensitivities to changes in various types of emissions based on a combination of the GEOS-Chem adjoint and the LIDORT model. GLIMPSE will be able to quickly calculate the net radiative forcing distributed over the globe for a large number of MARKAL-based future emission scenarios. From this emission scenario screening exercise, a few particularly interesting scenarios will be selected for use with the full GCM-Chemistry models for more robust assessment of the future climate and air quality consequences.

On a parallel track AMAD will develop and evaluate a regional climate chemistry model (RCCM) system to simultaneously simulate both the air quality and climate forcing implications of emission control strategies. The RCCM is the culmination of three research tasks that will ultimately converge: regional climate downscaling, 2-way WRF-CMAQ model, and hemispheric WRF-CMAQ (see Figure 4-9 for an approximate timeline).

Regional Climate Downscaling

AMAD scientists are developing techniques for regional climate dynamic downscaling using the WRF model to assess the effects of future climate change scenarios on air quality, water quality and availability, heat stress, and health and ecosystem exposures. While, in principle, regional climate downscaling is simply running a mesoscale meteorological model for future periods on the order of 10-years using GCM output for initial and boundary conditions, in practice, there are many issues to consider. Mesoscale meteorology models, such as WRF, are designed to be run for short periods (about 5 days or less) from initial conditions that are already highly resolved and incorporate vast amounts of observed data through data assimilation systems. These models are ill-suited for what amounts to pure forecasting for extended time periods of years or decades. Thus, research into the adequacy of physics components, particularly radiation schemes, cloud models, and land surface models, is required to adapt WRF to regional climate applications. These physics components will likely need to be modified for more accurate accounting of energy and moisture budgets over long timescales. Research into optimal application of four dimensional data assimilation (FDDA) techniques for downscaling is also needed. FDDA techniques, such as analysis nudging or spectral nudging, and new techniques may be adapted to maintain large-scale consistency with the GCM simulation while allowing the regional model the freedom to respond to smaller-scale forcing.

Climate Extremes and Variability

Changes in mean climatic conditions such as temperature and precipitation will have significant impacts on extreme conditions even without alteration of variability. However, it is likely that variability is also changing in a variety of complex ways meaning that the magnitude, frequency, and duration of extreme events will all change. Climate extremes, such as extreme heat and cold events, intense precipitation and drought, storms and coastal flooding have large societal impacts affecting air and water resources, and human and ecosystem health. For example, future heat waves are likely to be more deadly because of higher heat indices from the combined effects of higher temperature and higher humidity (warmer air can hold more water). Increasing precipitation amounts and intensities will increase stress on water treatment facilities leading to more frequent overflow discharge. Higher temperatures will increase surface evaporation which will likely make drought conditions frequent and severe. Thus, an important goal of our climate modeling research is to add skill in predicting changes in spatial and temporal frequencies of extreme events at regional scales. This research will include technique development for analysis of extremes and variability both to evaluate our regional climate modeling skill and to assess the full range of environmental and societal impacts.

Development of RCCM

AMAD is developing and evaluating a regional climate chemistry model based on the 2-way coupled WRF-CMAQ model with direct and indirect feedback to assess mitigation strategies of SLCF and air pollutants. The direct effects of aerosols on shortwave radiation and the direct effects of tropospheric ozone on longwave (LW) radiation have been implemented in the CAM and RRTMG radiation schemes. Particular attention is needed on developing and testing mixing state treatments for aerosols containing black carbon and other constituents such as sulfate and organic carbon. AMAD is also implementing indirect effects where aerosols from CMAQ are activated as cloud condensation nuclei which determine the droplet number concentration for the cloud microphysics model. The resulting effective droplet radius is used in the radiation model to compute cloud optical properties. The indirect effects are being tested by evaluation of cloud radiative forcing compared to satellite measurements.

As a development and evaluation study, the 2-way coupled WRF-CMAQ modeling system will be used to simulate the effects of changing anthropogenic emissions over the past two decades on spatial and temporal variability in tropospheric aerosol loading and resultant radiative forcing over the continental United States. Measurements of ambient aerosols and radiation will be analyzed before and after the implementation of the Title IV CAA controls (SO_2), from early

1990s to the present, to discern trends in radiative forcing (brightening) resulting from reductions in sulfate aerosol. The 2-way coupled WRF-CMAQ model should be able to replicate the observed trends in aerosol concentrations and radiative forcing over this period. Thus, this will be a critical test of the integrity of the model's chemistry and transport, aerosol chemistry and dynamics, and direct and indirect radiation feedback effects.

Hemispheric WRF-CMAQ

Hemispheric applications of WRF and WRF-CMAQ will provide a bridge between the global models and the regional and local scale models, thereby improving downscaling fidelity by use of nested grids within a consistent modeling framework. The hemispheric modeling domain is particularly advantageous for air quality modeling, where there is considerable uncertainty at the lateral boundaries of the regional model. Using a hemispheric domain, the effects of intercontinental transport can be simulated and used in a consistent manner as the nested domains focus on the United States at increased resolutions.

As shown in Figure 4-9, once the downscaling techniques, the 2-way WRF-CMAQ model, and the hemispheric configuration have been sufficiently developed and evaluated, they will be combined into a multiscale RCCM system that will be driven by future GCM projections with cascading grid refinement to regional and local scales. Thus, detailed emission projection scenarios for the U.S. that reflect air quality regulations and various options for climate change mitigation can be used to study the inter-related impacts on future air quality and regional climate conditions.

5. FUTURE INFLUENCES AND RESEARCH DIRECTIONS

EPA's Office of Research and Development is currently formulating a strategy to transform the research planning and execution process to one that reflects the concept of integrated trans-disciplinary research (ITR). As the name implies, this concept better integrates the many research programs, including existing multi-year plans, into a smaller number of more coordinated, better-integrated programs across ORD. The full implications of the ITR transformation on the ORD laboratories and offices are not yet known. AMAD is in an excellent position to move to an ITR framework, as its current research portfolio involves air quality model development, evaluation, and applications that integrate across disciplines, pollutant regimes, and links with models of exposure and with other media.

AMAD's core model development and evaluation research will strive to remain highly relevant to emerging programs in ORD's new environment as well as to traditional stakeholders in EPA's Program Offices and state/local agencies. Also, AMAD's application areas related to linking its models to human and ecosystem exposure models and assessments directly supports NERL's mission and its exposure framework. These activities are also likely to remain highly relevant for the foreseeable future. For the last few years, AMAD has been actively involved in research initiatives in the global climate research area, bringing in significant new resources to the Division. We have scoped out an ambitious strategic research agenda in this area, reflecting the Administrator's top priority. However, the climate research area, while currently growing within EPA, presents perhaps the greatest uncertainty as to future funding and support, as AMAD has not yet received a confirmed base level of significant resources. This overall research area

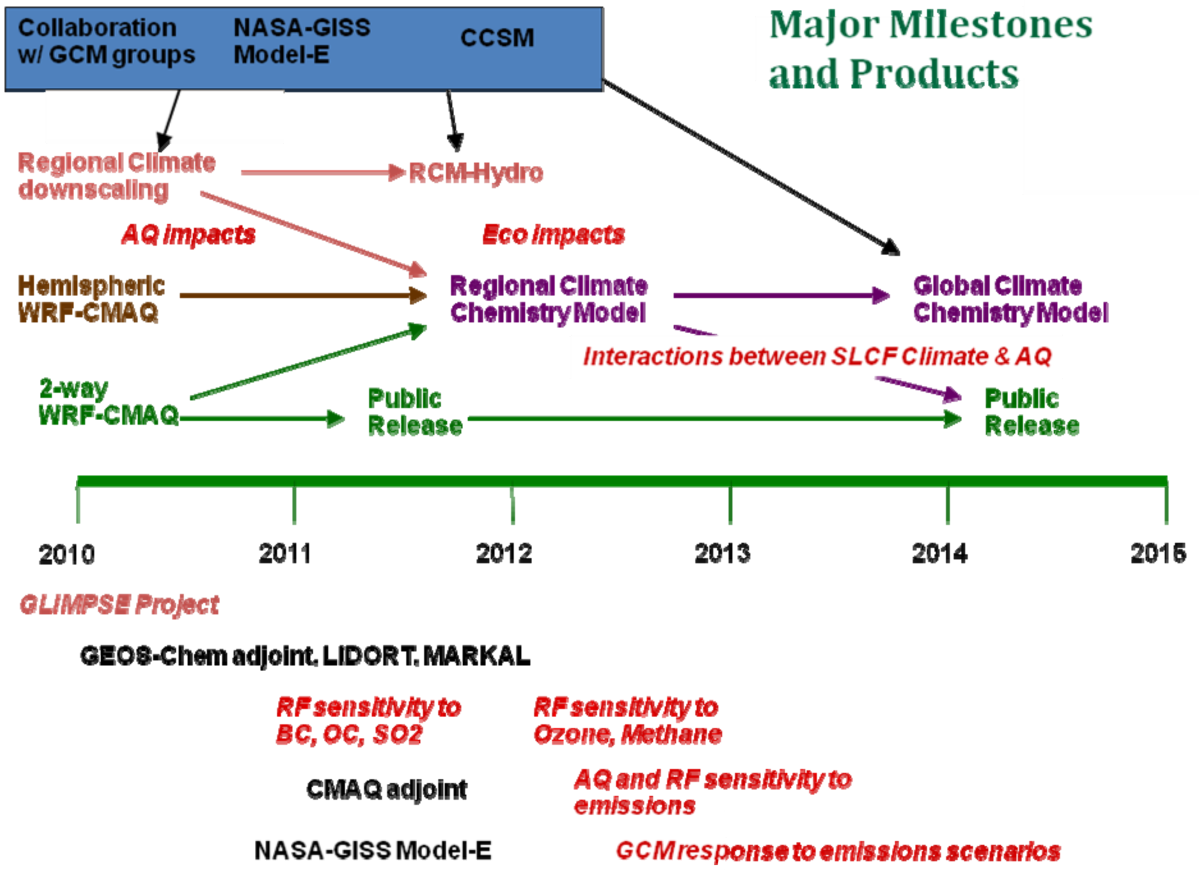


Figure 4-9. Timeline for AMAD AQ-climate research

remains highly visible and much-debated within the U.S. EPA's nanomaterials research program also presents potential new opportunities for AMAD model development and application. Modest resources have been devoted to "nano" pilot projects thus far, and this research effort is beginning to grow within AMAD.

Planning for the Division's future also involves taking stock of its current workforce and planning for future hiring. In recent years, the Division has established a vibrant student and post-doctoral fellow program, involving student contractors, EPA term-position post-docs, as well as post-docs obtained through the National Research Council and the Oak Ridge Institute for Science and Education. At present, AMAD has on-board 13 graduate students and post-docs, constituting over 20% of the Division scientific staff. That number is likely to grow in the next few years. In addition, several permanent federal positions are likely to open up in the five-year time horizon as senior staff retires from federal service. A recent analysis of priority needs in terms of workforce planning identified several disciplines and expertise areas that would be needed as vacancies occur. They include:

- **Atmospheric numerical modeler** – background in both physical and numerical aspects of modeling and computer code development

- **Aerosol modeler –** with specialization in aerosol optics and microphysics; radiative impacts of aerosols
- **Cloud modeler –** background in cloud microphysics and cloud/aerosol interactions
- **Hydrological modeler –** linkage of meteorological processes to land-surface and hydrological modeling; application to regional climate modeling
- **Turbulence and diffusion modeler/reactive plume modeler –** background in modeling at roadway/neighborhood/urban scales for local-scale human and ecosystem exposure assessments
- **Geospatial and satellite data analyst –** application of meteorological, chemical, and aerosol data from satellites for model inputs and evaluation
- **Emissions modeler/atmospheric chemist –** background in developing chemically-speciated source emissions for air quality models; atmospheric chemical kinetic mechanisms
- **Model evaluator –** expertise in data analysis; knowledgeable in regional modeling; atmospheric physical and chemical processes

AMAD's strategic planning process has provided this five-year roadmap to its research programs. This roadmap includes fundamental core modeling research on development and evaluation, responsive to the needs of the applications of EPA's regulatory and research offices. Also described are three major model application areas likely to be emphasized over this timeframe. AMAD's planned research is highly integrated and leveraged across its research programs. Division staff already work in trans-disciplinary teams to accomplish the work. This strategic plan provides the guidance necessary for creating annual tactical task/project planning to accomplish specific goals related to Division strategic objectives.

6. List of Acronyms

AAAR	American Association for Aerosol Research
AERMOD	AMS-EPA Regulatory Model for Dispersion
AMAD	Atmospheric Modeling and Analysis Division
APM	Annual Performance Measure
AQ	Air Quality
AQAD	Air Quality Assessment Division
AQMEII	Air Quality Model Evaluation International Initiative
AR5	Assessment Report #5
BEIS	Biogenic Emissions Inventory System
BOSC	Board Of Scientific Counselors
CAA	Clean Air Act
CALNEX	California Nexus (2010 field experiment)
CAM	Community Atmosphere Model
CASTnet	Clean Air Status and Trends Network
CBP	Chesapeake Bay Program
CCSM	Community Climate System Model
CDC	Centers for Disease Control
CL	Critical Loads
CMAQ	Community Multiscale Air Quality (model)
CMAS	Community Modeling and Analysis System
CONUS	Continental United States
CWA	Clean Water Act
DDM-3D	Decoupled Direct Method in 3 Dimensions
DOE	Department of Energy
DON	Dissolved Organic Nitrogen
EPA	Environmental Protection Agency
EUS	Eastern United States
FDDA	Four-Dimensional Data Assimilation
FEST-C	Fertilizer Emissions Scenario Tool for CMAQ
FHWA	Federal Highway Administration
FMF	Fluid Modeling Facility
FML	Future Midwest Landscapes
FTE	Full-Time Employee
GCM	Global Climate Model
GEOS-Chem	Goddard Earth Observing System-Chemistry (model)
GHG	Greenhouse gases
GIS	Geographical Information Systems
GISS	Goddard Institute for Space Studies
GLIMPSE	GEOS-Chem LIDORT Integrated with MARKAL for the Purpose of Scenario Exploration

HEASD	Human Exposure and Atmospheric Sciences Division
IPCC	Intergovernmental Panel on Climate Change
ISES	International Society of Exposure Science
ISORROPIA2*	Aerosol Thermodynamic Model - version 2
IT	Information Technology
ITR	Integrated Transdisciplinary Research
LIDORT	Linearized Discrete Ordinate Radiative Transfer (model)
LULC	Land-Use Land-Cover
LUR	Land-Use Regression
MARKAL	Market Allocation (emissions model)
MEGAN	Model of Emissions of Gases and Aerosols from Nature
MSGV	Micro-environmental Sub-Grid Variability
NAAQS	National Ambient Air Quality Standards
NASA	National Aeronautics and Space Administration
NERL	National Exposure Research Laboratory
NIH	National Institutes of Health
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NRC	National Research Council
OAQPS	Office of Air Quality Planning and Standards
OAR	Office of Air and Radiation
ORD	Office of Research and Development
PRISM	Parameter-elevation Regressions on Independent Slopes Model
R&D	Research and Development
RACM2	Regional Atmospheric Chemistry Mechanism - version 2
RCCM	Regional Climate Chemistry Model
RF	Radiative Forcing
RRTMG	Rapid Radiative Transfer Model for Global
SAB	Science Advisory Board
SAPRC07	Statewide Air Pollution Research Center (chemical mechanism) - version 07
SGV	Sub-Grid Variability
SLCF	Short-Lived Climate Forcers
TMDL	Total Maximum Daily Load
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Survy
WDT	Watershed Deposition Tool
WRF	Weather Research and Forecasting (model)

* *ISORROPIA is technically not an acronym; it is Greek for "equilibrium"*

APPENDIX

Model Application White Papers:

Integration of Regional- and Local-Scale Air Quality Modeling Research with EPA/ORD's Human Exposure and Health Research Program

Improving Air Quality – Ecosystem Modeling Connections to EPA/ORD's Ecosystem Research Program

Integration of Air Quality and Climate Change – Modeling Connections from Global to Regional Scales