WHITE PAPER:

INTEGRATION OF AIR QUALITY AND CLIMATE CHANGE – MODELING CONNECTIONS FROM GLOBAL TO REGIONAL SCALES

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List of Acronyms

AMAD	Atmospheric Modeling and Analysis Division
AMIP	Atmospheric Model Intercomparison Project
AOGCM	Atmosphere-Ocean General Circulation Model
AR4	(IPCC) Assessment Report 4
AR5	(IPCC) Assessment Report 5
BC	Black Carbon
BEIS	Biogenic Emissions Inventory System
CAM	Community Atmospheric Model
CAP	Criteria Air Pollutant
CCN	Cloud Condensation Nuclei
CCSM	Community Climate System Model
CDC	Centers for Disease Control
CESM	Community Earth System Model
CIRAQ	Climate Impacts on Regional Air Quality
CLM	Community Land Model
CM	(NOAA GFDL) Coupled Model
CMAQ	Community Multiscale Air Quality (Model)
CORDEX	Coordinated Regional Climate Downscaling Experiment
DOE	Department of Energy
DMS	Dimethyl Sulfide
DOD	Department of Defense
EDGAR	Emissions Database for Global Atmospheric Research
EPA	Environmental Protection Agency
ESMF	Earth System Modeling Framework
FORE-SCE	Forecasting Scenarios of Land Use Change
GEOS-Chem	Goddard Earth Observing System – Chemistry (model)
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	Greenhouse Gas
GISS	Goddard Institute for Space Sciences
GLIMPSE	GEOS-Chem LIDORT Integrated with MARKAL for the Purpose of Scenario Exploration
ITR	Integrated Transdisciplinary Research
IPCC	Intergovernmental Panel on Climate Change
LIDORT	Linearized Discrete Ordinate Radiative Transfer
LSM	Land-Surface Model
LW	Longwave (radiation)
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate Change
MARKAL	Market Allocation (model)
MEGAN	Model of Emissions of Gaseous and Aerosols from Nature
MODIS	Moderate Resolution Imaging Spectroradiometer
NARCCAP	North American Regional Climate Change Assessment Program
NARR	North American Regional Reanalysis
NASA	National Aeronautics and Space Administration

NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCER	National Center for Environmental Research
NEI	National Emissions Inventory
NERL	National Exposure Research Laboratory
NLCD	National Land Cover Database
NNRP	NCEP/NCAR Reanalysis Project
NOAA	National Oceanic and Atmospheric Administration
NRMRL	National Risk Management Research Laboratory
NSF	National Science Foundation
OAP	Office of Atmospheric Programs
OAQPS	Office of Air Quality Planning and Standards
OAR	Office of Air and Radiation
ORD	Office of Research and Development
PBL	Planetary Boundary Layer
PM	Particulate Matter
PoBNS	Programs of Broad National Significance
RCCM	Regional Climate Chemistry Model
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RRTMG	Rapid Radiative Transfer Model for GCMs
SLCF	Short-Lived Climate Forcers
SST	Sea-Surface Temperature
STAR	Science to Achieve Results
SW	Shortwave (radiation)
USDA	United States Department of Agriculture
USGS	United States Geological Survey
VOC	Volatile Organic Compound
WRF	Weather Research and Forecasting (model)

1. Introduction

As part of the EPA Office of Research and Development (ORD), the National Exposure Research Laboratory (NERL) is in the process of developing *Integrated Transdisciplinary Research (ITR)* programs to better address *Problems of Broad, National Significance (PoBNS)*. These programs are intended to provide strategic research directions in high priority topics that would benefit from more integrated collaborative research implementation across ORD's Laboratories and Centers. The nexus between air quality, climate change, and the energy system, with a focus on environmental impacts and the effects of climate change mitigation and adaptation strategies, has been identified as one of these ITR programs. The purpose of this white paper is to establish the roles of AMAD in the emerging research areas of climate change and environmental impacts by identifying key questions and research approaches, which include applications as well as model and methods development to address these questions. A focused research plan for climate and energy will aid AMAD in organizing effective collaborations with other NERL Divisions, other ORD Laboratories and Centers, EPA program and regional offices, and external groups to accomplish the required research.

We begin by identifying the environmental problem, outlining other Federally-funded climate research programs, and setting general goals for AMAD's involvement. Section 2 describes the science and policy drivers for the Agency that can be broadly divided into two categories: *risk assessment and adaptation*, and *risk mitigation*. Section 3 presents AMAD's conceptual approach and plans for collaborations, some of which have already been initiated. AMAD's research approach, presented in Section 4, describes plans for development of modeling tools for assessment of climate change impacts for the United States and for assessment of mitigation strategies. Finally, Section 5 is dedicated to describing expected products.

Environmental Problem

Consumption of fossil fuels contributes to global warming and degrades air quality, both of which profoundly impact human and ecosystem health. Atmospheric levels of carbon dioxide (CO_2) and other greenhouse gases have increased dramatically since the Industrial Revolution, and emissions from fossil fuel combustion have been linked to human disease since the London smog event in 1952. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (Solomon et al., 2007) concluded that the continued rise in greenhouse gases from human activity is the primary cause of the temperature increases observed over the 20th century and that global warming is likely to continue over the next century even with significant mitigation of greenhouse gas emissions. These temperature increases also lead to changes in other climatic conditions such as changes in precipitation intensity and duration. Extreme weather conditions could become more frequent which, in turn, can adversely affect human and ecosystem health. Anthropogenic combustion also represents the largest emissions source of primary particulate matter (PM), as well as oxides of nitrogen and sulfur, which react in the atmosphere to form ozone and secondary PM. These pollutants are known to contribute to respiratory and cardiovascular effects in human populations as well as ecological effects to aquatic (acidification and eutrophication) and terrestrial ecosystems (damage to agricultural and other vegetation).

Climate research at other agencies

The Department of Energy (DOE) funds the development of climate models, develops technologies to reduce emissions from energy systems, and collects data on the Earth's radiation budget. Specifically, the DOE is "particularly interested in developing models that better define interactions between climate change and decadal modes of natural climate variability, simulate climate extremes under a changing climate, and help resolve the uncertainties of the indirect effects of aerosols on climate."

As a science funding agency, the National Science Foundation (NSF) has many activities relevant to climate science. Current topics of greatest interest include "developing models that will produce reliable predictions of 1) climate change at regional and decadal scales; 2) resulting impacts; and 3) potential adaptations of living systems to these impacts. Related research may, for example, include studies of natural decadal climate change, regional aspects of water and nutrient cycling, and methods to test predictions of climate change."

DOE and NSF are the main funders of the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM). This model seeks to comprehensively simulate the complex interplay of physical, chemical, and biological processes of the atmosphere, ocean, and land surface. The first version was released in June 2010. In order to facilitate participation from a broad, inter-disciplinary community of scientists, CESM uses the Earth System Modeling Framework (ESMF), which is designed to support the interconnection of geophysical models. ESMF is funded by NOAA, NASA, NSF, and DoD.

NOAA also plays an important role in climate science. The Geophysical Fluid Dynamics Laboratory is developing an Earth System Model, CM3, the Coupled Atmosphere Ocean Land Ice model version 3. Future plans include "Our vision of global modeling is an integrated ESM [Earth System Model], projecting not only climate variability on seasonal to centennial timescales, but also biogeochemical and ecosystem cycling and biospheric feedbacks on the climate system. This is a comprehensive effort, requiring incorporation of climate dynamics, ecological processes and human activity." On the regional scale, NOAA's Earth System Research Laboratory has developed WRF-Chem, a coupled interactive chemistry-meteorology model. Current efforts are focused on developing WRF-Chem as a regional climate model. In addition to developing models, NOAA also runs the National Climatic Data Center to archive weather data.

NASA's contribution to climate science includes the Goddard Institute for Space Studies (GISS) ModelE, a coupled Atmosphere-Ocean-Land-Ice model. NASA's earth observing satellites are using remote sensing techniques to track the composition of the atmosphere, understand the impact of aerosols on clouds, and quantify the fluxes of greenhouse gases.

The Centers for Disease Control (CDC) is using its prevention expertise to anticipate potential impacts of climate change on human health. Also, the U.S. Department of Agriculture (USDA) is particularly interested in developing climate models that can be linked to crop, forestry and livestock models. Such models will be used to help assess possible risk management strategies and projections of yields at various spatial and temporal scales.

Goals

There is a large established national and international community of scientists who have studied global climate change issues for many years. AMAD, as a relative newcomer in the climate science community, must determine which scientific questions that it is uniquely positioned to help answer and for which it can create a niche in the climate change arena. AMAD's broad goals include:

- To lead scientific investigations of the interactions between climate change and air quality.
- To be recognized internationally for our contributions to better understanding climate science on regional scales.
- To develop partnerships across the Agency to quantify impacts of climate change on human health, water resources, and ecosystem resources.

To achieve these goals AMAD scientists must become expert users of climate models and atmospheric chemistry models at both the global and regional scales to perform scientific investigations as well as assessments. Traditionally AMAD has developed, evaluated, and applied meteorological and atmospheric chemistry models on local to continental scales. The climate change research arena requires an expansion of our toolkit to the global scale. AMAD's primary modeling expertise will remain on the local and regional scales, and AMAD will use global models primarily to downscale results to finer regional scales to address the Agency's concerns from health and ecological perspectives. Thus one of AMAD's focal areas will be the development and comparison of dynamical and statistical downscaling methods from global to regional climate. AMAD will also develop methods to link global and regional atmospheric chemical models and will refine the Community Multiscale Air Quality (CMAQ) model for full hemispheric air quality simulations. AMAD will further develop, test, and refine its integrated meteorological/air quality model to assess the impacts of the short-lived gas and aerosol species on direct radiative forcing, cloud radiative properties, and precipitation. Concurrently, AMAD will develop screening tools to more quickly assess the radiative effects of various greenhouse gas (GHG) and particulate matter (PM) control scenarios that will be used to select focused analyses with more comprehensive modeling tools on the principal scenarios of interest from a climate change perspective. AMAD scientists will perform modeling assessments of the effects of climate change and related adaptation and mitigation actions on regional and local air quality, and water availability and quality.

2. Science and Policy Drivers

The scientific issues of global climate change have been studied for decades. However, in response to the 2007 U.S. Supreme Court decision *Massachusetts vs. EPA* and the recently finalized Endangerment Finding under the Clean Air Act, the EPA must rapidly prepare for rulemaking regarding control of greenhouse gas emissions. Additionally, the EPA Office of Air and Radiation (OAR) recognizes that some "traditional" pollutants regulated under the Clean Air Act also have radiative forcing properties (e.g., the black carbon component of $PM_{2.5}$, ozone) that impact climate. The Agency has a need for integrated policy approaches to both mitigate climate change and manage air quality.

The urgency has also greatly increased to understand the implications of climate change on local and regional scales given the numerous anticipated impacts on environmental protection and regulatory responsibilities of the Agency. For example, research has already demonstrated that future climate conditions will very likely increase air quality risks and decrease the effectiveness of emission control efforts (e.g., Nolte et al., 2008; Weaver et al., 2009). In addition to enhanced photochemical production in a generally warmer environment, greater frequency of stagnation events could exacerbate air quality problems. It is also anticipated that increases in extreme precipitation events could lead to additional water-borne disease outbreaks and degradation of water quality conditions. Anticipated damages to aquatic and terrestrial ecosystems could include impacts such as encroachment by invasive species and biome migration.

The Agency's needs fall into two broad questions from the air quality, climate, and energy ITR plan that will be used to organize and focus the AMAD research activities described in this white paper:

A. Risk Assessment and Adaptation: How will climate change impact air and water quality, water availability, and ecosystems?

AMAD has initiated a series of research investigations that are focused on risk assessment, specifically asking how climate change might impact air quality in the future. The first phase of this study, which considered air quality under current emissions with a future climate, was completed during 2007 (Nolte et al., 2008) and work is underway with a second phase that considers potential future emission scenarios as well. The latter effort will contribute to a second assessment of future scenario (both climate and emissions) impacts on ozone and $PM_{2.5}$. The primary client for this work is EPA OAR's Office of Air Quality Planning and Standards (OAQPS) which uses these assessment results to inform its policy decisions regarding the effectiveness of regulations in light of future climate change and how to design policies that can adapt to increased air quality risks from climate change.

In addition to this ongoing work on air quality impacts from climate change, the Agency has additional risk assessment needs to consider how a changing climate will impact other regulated endpoints, namely water quality and ecosystem resources. Regional climate scenarios similar to those used to assess climate impacts on air quality are needed for these assessments; however, water and ecological assessments have finer spatial scale requirements that further challenge the uncertainty of regional climate scenarios and how future temperatures and precipitation may change. The client for assessment information on these topics is ultimately the EPA Office of Water which includes the Office of Ground Water and Drinking Water and Office of Wetlands, Oceans, and Watersheds.

B. Risk Mitigation: How best to contribute to climate change mitigation through U.S. controls of both long-lived greenhouse gases and short-lived pollutants?

While the central theme of the AMAD climate and air quality research has historically focused on air quality assessments, the introduction of climate change mitigation into the Agency mission creates a critical need for decision-making tools that can be used to recommend optimal U.S. policy choices that mitigate climate change. Given that some traditional criteria pollutants have radiative forcing properties that also affect climate, the optimal policy solutions are likely to be a combination of greenhouse gas emission reductions and controls on black carbon, ozone, and methane (an ozone precursor and greenhouse gas itself). If air quality management options are chosen that both improve air quality and support climate mitigation, an additional benefit is that positive impacts will be realized for climate trends in the nearer term while greenhouse gas mitigation impacts on climate will be evident only after several decades due to their much longer chemical lifetimes (Levy et al., 2008).

To characterize potential climate and air quality impacts from various greenhouse gas and short-lived radiatively active air pollutants, modeling tools are needed that consider global impacts from various emission mitigation scenarios and that can translate these impacts to regional scales. The EPA OAR can use this suite of tools to determine policy options that improve air quality and help mitigate climate change.

3. Conceptual Approach

To address the key scientific and policy drivers identified above, a system of models is needed that can assess the regional-scale impacts of future climate change and quantify the effects of mitigation options. The conceptual approach for such a system of models is shown in Figure 1. The first step is to develop scenarios that describe the trajectory of emission and land use changes for a potential future realization or for a given policy option. This includes GHGs, short-lived climate forcers (SLCF), and criteria air pollutants (CAPs) identified by the Clean Air Act. On the right side of Figure 1, these emission and land use change scenarios are used to drive the complex numerical models of global and regional climate. Atmosphere-Ocean General Circulation Models (AOGCMs) are needed to project the impact of anthropogenic forcing on global climate. AOGCMs that include online chemistry and aerosol processes are preferred because they include the impact of SLCF as well as the well-mixed GHGs. To understand the regional impacts of climate change on finer spatial and temporal scales, “time slices” from the AOGCM simulations (with higher-temporal frequency output for time periods on order of a decade) are downscaled using the Weather Research and Forecasting (WRF) model as a regional climate model. AMAD’s goal is to better resolve the impacts of global change on the United States, particularly changes in average conditions, variability, and extreme events of near-surface temperature and precipitation. To improve AMAD’s understanding of the impacts of SLCF on regional climate, AMAD will use its two-way coupled WRF-CMAQ model to simulate regional climate, chemistry, and aerosol processes in an integrated fashion. In partnership with other scientists within the Agency, the results from AMAD’s regional climate simulations will form the basis for assessments of the impacts of regional climate change on air quality, human health, water resources, and ecosystems. Examples of climate impacts could include changes in storm tracks and frequency that increase the frequency of stagnation events and reduce air quality, early onset of spring that disrupts ecosystems, and extreme precipitation events that lead to drought or flooding and efficient transfer of atmospheric contaminants to land and water.

The system of complex numerical models in Figure 1 requires considerable computational resources which limits the number of scenarios that can be realistically examined. Yet, large uncertainties in future emission projections require consideration of a large number of scenarios. A parallel set of reduced-form models, on the left side of Figure 1, form a suite of screening tools that can be used to rapidly assess the impacts of emission changes on global climate change and regional air quality. These screening tools will be derived using an adjoint version of a global chemical-transport model, GEOS-Chem, and the regional chemical-transport model, CMAQ. These can be used in conjunction with the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC), a tool that approximates the global change in temperature due to a change in GHG emissions using a statistical parameterization based on the AOGCMs used in the IPCC AR4.

To address questions relevant to the assessment of climate change risks, AMAD initially will use a subset of the Representative Concentration Pathway scenarios of the IPCC Fifth Assessment Report (AR5) to drive the system of complex numerical models in Figure 1 that lead from emission scenarios to quantitative assessments. To understand the impacts of climate mitigation policy options for simultaneously addressing climate change and air quality, the screening tools can be used to identify options that reduce radiative forcing while improving air quality, which can be developed into more comprehensive scenarios to drive the global and regional climate models in order to more accurately and credibly quantify the effects of a mitigation action on human health, air quality, water resources, and ecosystems (see Figure 1).

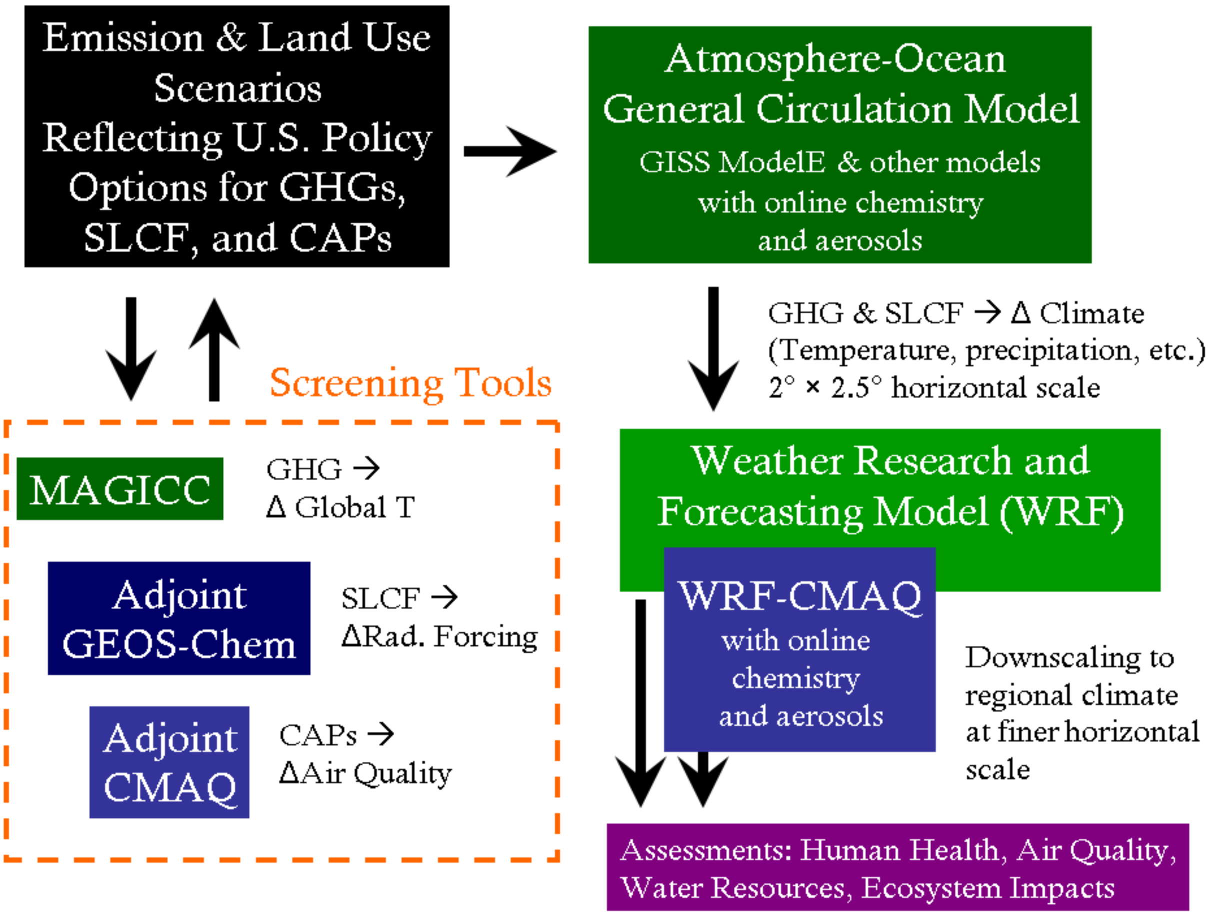

Figure 1: Integrated framework of modeling tools for addressing the key science and policy drivers for AMAD's climate and energy research.

Collaborators

Constructing a comprehensive system of models and modeling applications requires AMAD to broaden its skills and capabilities by collaborating and partnering with other parts of ORD, Federal agencies, and academic researchers. First, AMAD's simulations require the development of future scenarios of emissions and land use change. AMAD is continuing to work with the developers of ORD National Risk Management Research Laboratory's (NRMRL) MARKet ALlocation (MARKAL) energy-economics model to provide consistent scenarios of both GHGs and SLCF for assessing and understanding the changes in emissions due to policy actions. An important area of collaboration is to develop scenarios that consistently capture changes in both emissions and land use in a way that can be included in AMAD's climate modeling. For non-anthropogenic emissions, the Science to Achieve Results (STAR) grants program within the EPA National Center for Environmental Research (NCER) has recently funded several projects to quantify the impacts of climate change on biogenic and geogenic emission sources such as wind-blown dust, soils, the biosphere, wildfires, and lightning. AMAD will stay abreast of these continual developments and integrate these approaches in the future as they become critical to the model assessments and client needs.

Second, to become advanced users of the AOGCMs, AMAD will partner with the developers of these models. There are three U.S. institutions with AOGCMs that participated in the IPCC AR4: the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS), the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL), and the National Center for Atmospheric Research (NCAR). AMAD has established a formal collaboration with GISS. AMAD has made initial contact with scientists at GFDL and NCAR, and AMAD is seeking to solidify collaboration in regional climate research with both groups. It will be important to consider several AOGCMs in order to increase the robustness of the assessment of regional climate change impacts.

Since regional climate modeling is relatively new, AMAD will leverage its existing collaborations with the WRF community to adapt and improve regional climate capabilities. This includes consultation on appropriate physics options, methods for data assimilation, and integrating chemistry and aerosol processes using WRF-CMAQ.

The theoretical and practical development of adjoint models is also relatively new. To extend AMAD's capabilities in these areas, AMAD is collaborating with the developers of the CMAQ adjoint and GEOS-Chem adjoint models with projects jointly funded by EPA and NASA.

Finally, as AMAD develops and refines its regional climate simulations for use in assessments of climate change impacts to water resources and ecosystems, it is critical to form collaborative partnerships with the EPA Laboratories and Centers that will be leading these assessments. It will be important that AMAD's ecosystem research group be involved and work with the Ecological Services Research Program collaborators within the EPA to better understand how the regional scenarios are used and what improvements would be most critical to the assessments. To address impacts of climate change on water quality and quantity, AMAD will partner with the Laboratories and Centers designated as part of the ORD emerging program on Sustainable Waters.

AMAD's growing expertise in regional climate modeling can help improve these assessments. Also, better understanding of the climate metrics most important for critical Agency applications will help AMAD focus its development efforts and improve our modeling tools. However, cultivating and sustaining productive collaborations can be time-consuming. Therefore, AMAD will judiciously pursue collaborative partnerships focusing on research areas that are high-priority to the Agency.

4. Research Approach

4.1 Assessing Global to Regional Climate Impacts

Climate is typically defined as the long-term average (several decades) of meteorological conditions in a given location. Climate can change over longer time scales due to changes in the Earth's radiation budget, known as radiative forcing. These changes can have myriad causes, including physical factors such as variations in the Earth's orbit or the amount of solar radiation emitted by the Sun, as well as changes in the chemical composition of the atmosphere. Certain atmospheric constituents known as GHGs (e.g., water vapor, CO_2, O_3, CH_4, and N_2O) as well as some aerosol species absorb energy radiated from the Earth's surface and radiate a portion of that energy back to the surface, resulting in warming of both the Earth's surface and atmosphere.

All state-of-the-science global climate models (GCMs) are coupled AOGCMs. The ocean components of the models simulate oceanic heat uptake and transport via currents, as well as sea ice melt and formation. Because the ocean is a vast thermal reservoir compared to the relatively thin atmosphere, these dynamic processes are critical to simulating climate change over centuries. For some "time slice" (on the order of a decade) applications, a climatic average representation of the ocean is used with the atmospheric component, allowing the model to be run at higher spatial and/or temporal resolution.

An AOGCM simulation must span a long period of time because conclusions drawn based on too short a simulation may be invalid if the modeling period happens to be anomalous. Because of the complexity of the physical system being simulated and the requirement for long simulation periods, computational resource constraints necessitate that AOGCMs be run at relatively coarse spatial and temporal resolution. The IPCC AR4 AOGCMs had horizontal spatial resolutions ranging from ~1.1° × ~1.1° to 4° × 5° (Randall et al., 2007, Table 8.1). These large spatial scales are insufficient to resolve geographical features, such as mountains and lakes that can have significant impacts on regional climate. In addition, many applications of interest to the Agency are episodic in nature, such as the change in frequency and spatial distribution of extreme events, and a higher temporal resolution is required of climatic fields than is typical of AOGCMs. Therefore fields from AOGCMs will be inadequate to fully understand the regional climate change issues that are of interest to the Agency. In response, AMAD will acquire fields from AOGCMs to drive regional climate simulations to address the Agency's needs and to study the relevant scientific questions.

Obtaining global model fields

The IPCC AR4 (Solomon et al., 2007) included results from 23 different AOGCMs. Based on the results presented in AR4, no single model can be considered to be the best for all aspects of global climate modeling. Though it would be ideal to conduct regional climate modeling studies using an ensemble of models, as was done in the AR4, this is not feasible with resources currently available to AMAD. Accordingly, the question arises as to which AOGCM(s) to choose for regional climate downscaling. The perceived scientific quality of the model and the modeling group's scientific reputation and publication track record are two important factors for selection of a particular AOGCM. Other criteria worth considering are the availability and quality of the model's documentation, the size of the community using the model, and whether training or help is available for prospective users. It is also desirable to establish collaboration with the AOGCM developers, in which they conduct the AOGCM simulations and/or provide training and guidance on how to set up and use the model and interpret model results.

AMAD scientists previously conducted a pilot project, Climate Impact on Regional Air Quality (CIRAQ), in which partners in academia performed the AOGCM simulation of future global climate under one future GHG scenario, and collaborators at the Department of Energy's Pacific Northwest National Laboratory used these AOGCM fields to simulate regional climate over the continental United States. Currently, collaborators at GISS are conducting future climate simulations for the IPCC AR5, and they will provide highly time-resolved fields (i.e., time slices) from those simulations to AMAD for regional climate downscaling. However, ultimately EPA will need the capability to conduct additional global climate simulations under alternative GHG emission scenarios. Accordingly, AMAD plans to develop expertise at *using* AOGCMs, rather than merely being consumers of the data generated by them.

AOGCMs are typically evaluated for mean temperature and precipitation over large spatial areas (e.g., continental-scale) and over long time periods (e.g., decades). In order to determine the validity and to quantify the benefit of downscaling the AOGCM fields with the regional climate model (RCM), one key challenge for AMAD will be to develop evaluation methods for both global and regional climate modeling. Of particular interest for regional climate modeling is the frequency of extreme events such as heat waves and droughts. Careful evaluation of the performance of the AOGCM under current climate will be necessary to evaluate the efficacy of the regional climate downscaling. Of particular importance for regional climate modeling are the AOGCM biases over the United States and the extent to which the AOGCM accurately captures synoptic circulation and teleconnection patterns reflecting changes in atmospheric waves and the jet stream.

Assessing Regional Climate Change

AOGCMs are used to predict gridded future climate conditions with world-wide coverage. To investigate and understand regional effects of climate change (and particularly to capture extreme events), higher temporal and spatial frequency of the gridded fields is required. One broad category of methods to create regional climate fields that are influenced by AOGCM simulations is "downscaling." Downscaling involves using the fields from an AOGCM in combination with additional information about the regional scale (e.g., topography, land use, historical regional climate data) and physical, mathematical, and/or statistical models to extend the AOGCM simulation to finer spatial and temporal granularity. With increased horizontal texture, the downscaled fields are more sensitive than the AOGCMs to local spatial heterogeneities in weather and climate that result from topographical changes, land/water interfaces, vegetation, and population. Downscaled climate fields can then be used to predict the regional impacts of climate change on water quality and availability, agriculture, ecosystems, human health, and air quality resulting from emissions control strategies, and energy demand. Through the CIRAQ project, downscaled meteorological fields were generated by external collaborators for use in the CMAQ modeling system to assess predicted changes in ozone and particulate matter resulting from predicted changes in climate at 2050 (Nolte et al., 2008). Based on the lessons learned from the CIRAQ project and the desire to tailor downscaled fields to better capture extreme events, AMAD will be leading research to assess regional climate change based on downscaled AOGCM fields. The AOGCM fields will be captured at a much finer temporal output increment (e.g., six-hourly) to accommodate regional downscaling methods. AMAD's primary focus will be on extreme events (e.g., heat waves, droughts, flooding, stagnation events) and the frequency of such events, in addition to changes in local mean temperatures and precipitation. For example, increased periods of stagnation during the summer can adversely affect air quality, which may necessitate additional regulation of air pollutants. In addition, changes in drought and/or flooding patterns over time can affect water quality and availability for the general population as well as agriculture. As with all of the research in AMAD, the assessment of regional climate change using downscaling techniques will have components of research and development as well as policy-relevant application.

AMAD will investigate the use of both dynamical and statistical downscaling techniques for regional downscaling of AOGCM simulations. Both dynamical and statistical downscaling are somewhat small but growing research areas. Initial research in AMAD for dynamical and statistical downscaling will follow parallel paths to develop a greater understanding of the published research with each technique thus far, to determine which methodologies (if any) are appropriate to AMAD's research goals, and to extend and/or refine those techniques to downscale AOGCM predictions. The first AOGCM fields that will be used to evaluate downscaling techniques will be from the IPCC AR5 fields from the NASA GISS ModelE. Follow-on work in downscaling will be conducted using fields from the NOAA GFDL Coupled Model (CM3) and the NCAR Community Climate System Model (CCSM) or the Community Earth System Model (CESM) when collaborations with those research groups are formalized and as those AOGCM fields become available. Additional partnerships will be established in the regional climate modeling community, as appropriate, to leverage and improve the most current scientific approaches in regional climate modeling.

Dynamical Downscaling

Regional climate change simulations are critical for impact assessment because AOGCMs are computationally too expensive for long-term high resolution simulations. Regional climate models (RCMs) can be used to investigate environmental issues that are important at regional and local scales. RCMs are high-resolution numerical models that can be used to provide detailed representation of physical processes in response to complex topography, land-sea contrasts, and sharp land-use gradients (Dickinson et al., 1989; Giorgi and Bates, 1989). Unlike AOGCM simulations where the non-linear atmospheric processes are sensitive to perturbations in the initial conditions and it is possible for the models to diverge after only a few days of simulation, the RCM is constrained by the lateral boundary forcing. The RCM's simulated climate represents a synthesis of the global climate information provided at the lateral boundaries and the physical and dynamical processes in the RCM. The ultimate goal is to improve the representation of regional climate by improving physics and/or increasing model resolution. However, error can be introduced at the RCM lateral boundaries due to errors in the AOGCM fields or inconsistencies in the atmospheric circulations suggested by the RCM and the AOGCM. It is difficult to distinguish the errors related to physics and resolution from those arising at the lateral boundaries, but it has been demonstrated that a common problem in using RCMs is that the simulated state tends to deviate from the driving state at large scales (von Storch et al., 2000; Giorgi and Bi, 2000). Thus an active area of research for AMAD will be to try to establish regional climate modeling techniques that will moderately constrain the RCM to the AOGCM's forcing while enabling the RCM to develop the finer-scale physical and dynamical processes.

For AMAD's dynamical downscaling, the WRF model will be used initially. Dynamical downscaling presents several technical challenges to define a credible methodology. The following list includes several of the technical decisions related to WRF model simulations that need to be addressed and justified before moving forward.

- Domain definitions (sizes, spatial extents, etc.)
- Horizontal grid spacing (108-km, 36-km, 12-km, other?)

- Nesting options (if any, e.g., 108-36 km one-way, no feedback; 108-36 km two-way, with feedback)
- Vertical layers (number and specification),
- Model top (100 hPa, 50 hPa, or further into the stratosphere?)
- Physics options
- Four-dimensional data assimilation - Nudging (if, where, how, and how strong)
- Length of spin-up time to achieve physical and dynamical balance
- Initialization of specific fields (e.g., soil moisture and temperature)
- Level of constraint of the AOGCM forcing on the WRF simulation
- How to evaluate downscaled runs to develop downscaling methodology with confidence in future climate scenarios
- How to characterize and quantify the uncertainty in the WRF simulations

As the first step in the development and evaluation of a dynamical downscaling methodology, a series of regional climate simulations will be conducted using present-day global reanalysis fields at a comparable spatial and temporal resolution to the AOGCMs that AMAD will acquire via partnerships. For example, the 2.5° x 2.5° version of the NCEP/DOE Atmospheric Model Intercomparison Project (AMIP) Reanalysis 2 (R-2) data sets will be used in the WRF model as initial and lateral and surface boundary conditions to mimic AOGCM fields. The WRF model will then be run as an RCM (i.e., continuously, without updating the simulation with additional observational knowledge of the atmosphere) to downscale the R-2. The R-2-WRF simulations will be run using multiple physics, nudging, and gridding configurations with the goal of selecting a primary dynamical downscaling configuration. The resultant WRF model simulations will then be compared with the higher resolution (i.e., 32-km) North American Regional Reanalysis (NARR) data set to evaluate the efficacy of the dynamical downscaling techniques. Some creativity must be employed in the evaluation methods such that the focus is on evaluating climate rather than weather. Though it is acknowledged that success with an R-2/WRF dynamical downscaling technique may not be analogous to coupling an unrelated AOGCM with WRF, this approach to evaluating and establishing the validity of the dynamical downscaling techniques is widely accepted in the literature (e.g. Xue et al., 2007; Gustafson and Leung, 2007).

Concurrent with the R-2/WRF evaluations, an initial dynamical downscaling linkage will be established using the NASA GISS ModelE and WRF. A one-year data set is used to examine the initial annual cycle fields, and that data set will be expanded to include multiple consecutive years and future time periods. As NASA GISS develops ModelE fields for the IPCC AR5, those data will be made available at high temporal frequency (i.e., six-hourly) for “time slice intervals” of the AOGCM simulation. Using knowledge gained from the R-2/WRF testing, a base dynamical downscaling technique will be employed to create regional downscaled climate fields.

As part of the efforts with the reanalysis fields and the AOGCM fields, dynamical downscaling work will examine more closely the method and strength of constraining the RCM (i.e., WRF) toward the AOGCM. Specifically, both spectral (Waldron et al., 1996) and analysis nudging (Stauffer and Seaman, 1990) will be tested to determine the suitability of each method to force the RCM to adopt the prescribed large scales over the entire domain. Analysis nudging approximates the fields at each grid point while spectral nudging uses the large-scale waves of the driving field to keep the interior model solution consistent with the driving fields. Interior nudging is a "hot" research topic in the regional climate modeling community with great potential for AMAD to lead the science. Two scientific questions with respect to nudging will help guide our experiments. Rockel et al. (2008) identified one of the higher-order questions: *Should interior nudging be used for AOGCM lateral boundary forcing driven simulations, since real-world observational constraints on the simulations are absent in the AOGCM unlike reanalysis driven simulations?* The second question is derived from in-house expertise on the importance of the implementation of nudging: *What is the relative contribution of the nudging coefficients to the regional climate modeling simulations?* It will be important to balance the benefits of using nudging techniques to improve the RCM simulations with the potential unintended consequence of reducing the variability (and extremes) in the solution. In addition, special attention will be given to the nudging techniques for aerosol-radiation-cloud-chemistry interactions in the integrated regional climate-chemistry modeling system (see Section 4.2.2), which could be very sensitive to small changes in the atmosphere. Evaluation techniques such as spectral power (Castro et al., 2005) and isotropic digital filter (Feser and von Storch, 2005) will be applied to understand if the RCM is improving the regional-scale variability. Lessons learned from these simulations will then be used to help determine the robustness of the sensitivity using longer-term integrations (~ten years). A WRF simulation from the North American Regional Climate Change Assessment Program (NARCCAP) with no nudging may serve as a baseline for comparison of added value of the nudging when using the same physics options. AMAD will also strive to participate and contribute to regional climate modeling intercomparison activities such as NARCCAP and the Coordinated Regional Climate Downscaling Experiment (CORDEX).

A major area of interest for regional climate modeling is the ability of the RCM to simulate physical processes important for climate, including radiation, cloud cover, and surface heat and moisture fluxes. Biases in WRF's representation of these physical processes may have a larger effect on long-term simulated climate than would be evident from integrations conducted for a shorter period or when nudging is used to constrain the RCM to observations. The ability to simulate these physical processes more accurately will be critical for understanding the coupled climate-air quality system.

One initial area of focus in this area will be analyzing certain of the radiation schemes implemented in WRF. Although the radiation schemes in WRF have been adapted from global climate models and are tuned for the total global forcing, they may need to be improved for regional climate modeling purposes. In addition, the treatment of partially cloudy conditions may need to be adjusted within the radiation schemes. A research activity will be conducted to evaluate the most advanced radiation schemes in WRF against satellite-based observations to determine the strengths and target areas of improvement in those schemes.

Another area of interest in defining the dynamical downscaling technique is the selection of the land-surface model (LSM) for the RCM. The existing LSM options in the WRF system are designed for short-term forecasting or retrospective simulation. They are intended to model the effects of vegetation and soil conditions on the atmosphere through parameterizations of surface fluxes including soil evaporation, evapotranspiration, and evaporation from wet canopies. Multilayer soil moisture is a key parameter for many of these processes. Thus, some of these LSMs rely on sophisticated land data assimilation systems to initialize soil moisture using a variety of observations such as solar radiation, precipitation, ground level temperature and humidity, etc. Alternatively, soil moisture can be nudged through an indirect data assimilation scheme according to model biases in ground-level temperature and moisture compared to observation based analyses. In either case, extensive use of observed data is needed to frequently update soil moisture conditions because these LSMs do not include the complete hydrological cycle and therefore are incapable of long-term simulation without observational constraint.

For climate modeling, more comprehensive land models are necessary that are designed for long-term simulation without the need for observation-based data assimilation.   For example, the Community Land Model (CLM) (Bonan et al., 2002), which has been developed as part of the Community Climate System Model (CCSM), has comprehensive treatment of the physical, chemical, and biological processes by which terrestrial ecosystems affect and are affected by climate across a variety of spatial and temporal scales. The CLM includes detailed representations of processes such as interception, throughfall, canopy drip, snow accumulation and ablation, infiltration, surface and sub-surface runoff, soil moisture, and surface moisture fluxes by canopy evaporation, transpiration, and soil evaporation. Thus, the CLM or similar climate land models should be adapted for use in the RCM system. A partnership with modelers at the University of California at Berkeley, who have developed a preliminary version of CLM coupled with WRF, has been informally established to pursue this research activity.

It is anticipated that the dynamical downscaling will have a continuously evolving research component. Several aspects of the dynamical downscaling can be expected to be refined as the climate program grows. For example, there will be opportunities to improve the LSM component in WRF to add capabilities and/or tailor the model for climate modeling (either by improving the coupling with specific AOGCMs or by employing generic methods of scientifically credible linkage with any AOGCM). In addition, nudging methodologies (which are somewhat controversial in the dynamical downscaling community) can be further developed and refined for AMAD's dynamical downscaling with a goal of extending techniques back to the retrospective WRF-CMAQ simulations that are central to the regulatory development efforts in AMAD. Furthermore, developing evaluation techniques and the quantification of uncertainty may become an active area of research.

Statistical Downscaling

Statistical downscaling methods use correlations among observed and modeled meteorological variables to predict regional and/or local patterns and events that are likely to occur based on the broader-scale AOGCM simulations. Typically, these approaches do not use the same detailed information that is used in dynamical downscaling, such as physical equations, orographic data, or extensive land-use information. The advantages of statistical downscaling methods lie in their efficiency and speed, and these methods could be particularly attractive if numerous climate scenarios need to be investigated. Statistical methods are not limited by the resolution achievable by the nested regional dynamical model. Thus, statistical methods could possibly be used to gain a better understanding of fine-scale variability, even down to point locations.

It has been reported in the literature that the performances of dynamical and statistical downscaling are comparable for current climatic conditions. However, it is questionable whether statistical models can perform as well under future conditions (Wilby et al., 2002) because statistical downscaling methods rely on associations among meteorological variables. These relationships do not explain all of the inherent variability in atmospheric phenomena; in fact, the choice of variables to be used as the "predictors" in such approaches is a difficult part of the statistical downscaling process. Also, once a statistical model has been developed for a particular time period (e.g., using current climate), it is unclear whether the relationships it incorporates will remain the same under different climatic conditions (e.g., in future decades). While this issue of stationarity is discussed by Schmith (2008) in some detail, it is rarely addressed in individual applications, leaving some doubt as to how accurate the results of statistical downscaling will be for future time periods.

AMAD began its work in statistical downscaling by investigating the techniques typically used in the literature. Many of these are regression-based, modeling either relationships between modeled and observed variables (e.g. Wilby et al, 2002; Spak et al, 2007) or spatial relationships between fine-scale data and its coarse-scale aggregates (e.g. Hoar and Nychka, 2008). AMAD is in the process of investigating problematic issues associated with statistical downscaling, such as violations of the stationarity assumption, systematic differences (biases) between models, and calibration of statistical estimates of uncertainty. Based on these results, AMAD will determine if it is reasonable to utilize statistical downscaling techniques and will identify the situations in which these can be utilized most efficiently and accurately. Particular areas of application may include (again, depending on the research findings previously mentioned):

- Implementing appropriate statistical downscaling approaches using the AOGCM fields
- Continuing to improve our understanding of how uncertainty affects estimates, and particularly how the uncertainty may change when applied to future-year AOGCM simulations.
- Evaluating the performance of statistical downscaling methods in estimating the frequency, duration, and/or intensity of extreme meteorological events.
- Identifying the relative strengths/weaknesses of the dynamical and statistical approaches to downscaling.
- Determining whether hybrid downscaling approaches may be able to capitalize on the strengths of both methods.

4.2 Modeling tools for mitigation of climate change

4.2.1 Global Climate and Chemistry Modeling

For our assessment work described in Section 4.1, the AOGCMs will be driven with the Representative Concentration Pathways that prescribe changes to national-level GHG and SLCF emissions. A critical question is what further climate change mitigation is possible from U.S. controls on SLCF? In particular, our goal is to determine the relative impact of emission reductions of SLCF compared to GHGs.

Using GISS ModelE, we will perform a series of century-long sensitivity studies varying the emissions of SLCF and GHGs. We will quantify the timing and impact of these emissions to global climate change and from the present to 2100. With this understanding, we will work with our colleagues in NRMRL to develop U.S. emission scenarios that properly account for the technology options and economic interactions between sectors, such as electricity generation, industrial activity, and transportation. The product from this work will be a series of policy-relevant climate mitigation scenarios, a series of global model simulations, and a description of appropriate analysis methods to quantify the impacts of SLCF and GHGs emission reductions.

To fully understand the air quality, water quality, human health, and ecosystem impacts of these climate mitigation efforts, the results of these global modeling simulations can be downscaled as described in Section 4.1. The next section describes further regional modeling development efforts to better understand the impacts of SLCF on regional climate.

4.2.2 Regional Climate Chemistry Modeling

While the primary agents of climate change are the long-lived greenhouse gases (GHG), short-lived gases and aerosol likely play an important role. The IPCC AR4 Report (Solomon et al., 2007) estimated that tropospheric ozone and the direct and indirect effects of aerosols contribute significant portions of the mean global radiative forcing. The AR4 also suggests that there is a large uncertainty associated with these forcings and that their spatial scales are continental to global. The major sources of this uncertainty are related to inaccurate characterization of atmospheric loading of aerosols, their chemical composition, and source attribution, all of which are highly variable both spatially and temporally. Accurate characterization of the spatial heterogeneity in aerosol composition and size distribution is critical for estimating their optical and radiative properties and thus in quantifying their impacts on radiation budgets of the earth-atmosphere system. Large amounts of the atmospheric loading of these constituents are created by anthropogenic emissions of precursors and complex atmospheric photochemistry. Although globally much of the secondary aerosols and ozone results from biogenic emissions of volatile organic compounds (VOCs) such as isoprene and terpenes, the productivity of these "natural" emissions is greatly enhanced by the anthropogenic emissions that create a more oxidizing environment (Kanakidou et al., 2005, Matsunaga et al., 2005, Guenther et al., 2006). There are also potentially important interactions between emissions of photochemically active species such as NO_x and CO with long-lived GHGs such as CH_4. Furthermore, because short-lived species respond more quickly to controls than long-lived GHGs, they may represent the most effective way to alter trends in global warming in the near future (Jacobson, 2002). Thus, current and future emissions of air pollutants that lead to elevated levels of aerosols and ozone must be considered by policy makers for mitigation strategies for both climate change and air quality. Linkage of climate models with atmospheric chemistry models that include detailed treatment of emissions, photochemistry, aerosol microphysics, atmospheric transport, and wet and dry deposition, such as are used for air quality research and impact assessment, are needed to fully understand the interactions between GHGs and short-lived gases and aerosols.

The WRF and CMAQ models have been integrated into a single executable computer program with 2-way meteorological and chemical data exchange. Direct effects of aerosols on shortwave radiation and tropospheric ozone on longwave radiation have already been included while implementation of the indirect effects of aerosols on the microphysical and radiative properties of clouds is underway. Direct effects of aerosols on LW radiation, especially BC which is a strong absorber in both SW and LW parts of the spectrum, is also being developed for implementation in WRF-CMAQ. The 2-way coupled WRF-CMAQ model can be configured for use as a Regional Climate Chemistry Model (RCCM) with a coarse resolution hemispheric grid domain ($\Delta X \sim 50$-100 km) and higher resolution nests over North America ($\Delta X \sim 12$-36 km). The hypothesis is that by coupling a Regional Climate Model (RCM), such as WRF, modified as described in Section 4.1 to be more suitable for climate application, to a comprehensive atmospheric chemistry and transport model (CMAQ), regional climate modeling can be improved because of the inclusion of the radiative forcing of short-lived gases and aerosols and the effects of aerosols on cloud microphysics, radiation properties, and precipitation. Conceptually, by superimposing the regional aerosol radiative effects on the large scale GHG forcing, the coupled WRF-CMAQ system on a hemispheric domain driven by AOGCM time-slices can provide process-level insights into the spatial heterogeneity in radiative forcing, their regional climate effects, and their aggregate influence on the earth's radiation budget. An important component of this demonstration is the verification of the simulated radiative effects for retrospective periods. Once the WRF-CMAQ is established as a credible RCCM by assessing retrospective simulations of a series of nested domains downscaled from global reanalysis data, it can be used to investigate many issues related to the interaction of climate and chemistry.

Questions to be addressed using the WRF-CMAQ RCCM:

- How important is radiative forcing from short-lived gases and aerosols relative to GHG forcing, particularly on the regional scale?
- How important is the characterization of the spatial heterogeneity in radiative forcing of short-lived species and how does this heterogeneity influence regional climate variability?
- What is the sensitivity of regional climate to changes in biogenic and anthropogenic emissions?
- What are the regional climate effects of Asian air pollution in Asia and in North America?
- Can we recognize the climate effects of the dramatic increase of Asian air pollution associated with the economic boom from 1990s to 2000s in our model simulations?
- How will climate change affect biogenic emissions and how will the resulting change in gases and aerosols further affect climate?
- How will future emission change scenarios by region and sector affect near future climate change?

Development needed to use WRF-CMAQ as an RCCM

Further development of the WRF-CMAQ system will be needed to establish its capabilities for hemispheric to mesoscale atmospheric chemistry and transport modeling. The expansion to hemispheric scales will necessitate the expansion of the chemistry represented in the model and also the examination of the suitability of existing chemical schemes for the free troposphere. The domain expansion will also necessitate a closer examination of processes in the marine boundary layer since large portions of the modeled troposphere will be over marine environments. For instance dimethyl sulfide (DMS) is an important marine source of atmospheric sulfate. Efforts are already underway to improve the representation of O_3 gradients in the mid-upper troposphere using a potential vorticity scaling and this will be further tested in the hemispheric applications. On a global basis, O_3 is formed predominantly over the continental regions and is typically lost in marine regions through photolysis. Further reductions in the tropospheric O_3 burden through bromine and iodine emitted from open oceans has also been recently postulated. Another area for further improvement will be the inclusion of emissions from aircraft, lightning, and fugitive dust outbreaks.

The direct effects of aerosols on shortwave radiation and the direct effects of tropospheric ozone on longwave (LW) radiation have been implemented in two of the radiation schemes available in WRF that were designed for climate modeling: the Community Atmosphere Model radiation scheme (CAM) (Collins, et al., 2004) and the Rapid Radiative Transfer Model for GCMs (RRTMG) (Iacono et al., 2008). A new Mie scattering algorithm for a wider range of wavelengths including LW has been developed and implemented in the RRTMG scheme. New mixing state treatments for aerosols containing black carbon and other constituents such as sulfate and organic carbon are also being developed and tested. New model simulations of the 2-way WRF-CMAQ using the latest versions of both models have been evaluated for a summer month in the eastern US and an outbreak of wildfires in California in 2008. Comparisons between runs with and without direct feedbacks show significant impacts on solar radiation, 2-m temperature, PBL height, and ozone and PM2.5 concentrations, especially in areas affected by smoke plumes. For example, the reduced SW radiation caused much cooler surface air temperatures (up to 4-5 K in the smoke plumes), lower PBL heights (up to 400 m), and significantly higher ground level concentrations of ozone and PM2.5 (Mathur et al., 2009).

The 2-way WRF-CMAQ model also includes an experimental implementation of indirect effects where aerosols from CMAQ are activated as cloud condensation nuclei which determine the droplet number concentration for a 2-moment 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.

Climate and Chemistry Downscaling

Many of the same developments needed to configure WRF for use as an RCM (Section 4.1) will be needed to configure the WRF-CMAQ as an RCCM. The main difference between the downscaling described above and the WRF-CMAQ modeling described here is that it will include a hemispheric domain on a polar stereographic grid as an intermediate step between the AOGCM and the regional model. There are advantages to this method for both the meteorological downscaling from the AOGCM and chemical downscaling from the global chemistry model. The meteorology on the hemispheric domain can be made to closely replicate the AOGCM (albeit at higher resolution) through spectral and/or grid nudging, sea surface temperature (SST), sea ice, and snow fields from the AOGCM. In addition, much of the physics in WRF can be harmonized with the AOGCM. For example, we have been using the CAM radiation scheme which is also used in NCAR's Community Climate System Model (CCSM) and recently we have implemented aerosol feedback effects in the new RRTMG radiation scheme which is being used in the the Community Atmospheric Model (CAM5), which is the latest atmospheric component of the Community Earth System Model (CESM1). Also, we plan to use the Community Land Model (CLM), which is a component of the CESM1, as a land surface model in WRF. A general problem with regional downscaling from an AOGCM is that it is often ambiguous whether the differences between the higher resolution regional model and the global model are caused by inconsistencies in physics, dynamics, grid structure, and numerical techniques or the result of greater resolution. Thus, by configuring WRF with compatible physics and using data assimilation and surface forcing from the AOGCM, and confirming similar model results on the hemispheric domain, we can have more confidence that results from the regional nested domains reflect more the benefits of higher resolution and are less artifacts of model inconsistencies.

Evaluation

Much of the evaluation of the WRF-CMAQ when applied as an integrated regional climate chemistry model would be similar to the evaluation steps of a downscaled RCM as described above in Section 4.1. For example, an important step in the evaluation of either system would be retrospective experiments where the regional model is applied to a historic period driven by global reanalysis data and observed datasets for SST and sea ice (Randall et al., 2007). Evaluation by comparison to observations and high resolution observation-based analyses would effectively assess the model's ability to accurately downscale from observation-based global information, as a surrogate for an essentially perfect AOGCM. Sensitivity studies where various feedback effects are turned off or emission sectors are zeroed out could be used to investigate the importance of the short-lived gas and aerosol feedbacks to the regional simulations. The role of the hemispheric domain could also be assessed through comparison to RCM simulations that are downscaled directly from global to regional domains. The next phase in evaluation of any downscaling model system should be to replicate the historic simulations described above using an AOGCM model rather than global reanalysis. These experiments should address the question: Are the downscaling model capabilities sufficiently retained when driven by an AOGCM?

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 Clean Air Act 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.

The synergistic applications of global-scale and regional-scale chemistry-climate models provide unique opportunities to inter-compare the relative merits of the two approaches and to address current uncertainties in climate science. For instance, comparison of simulated radiative forcing from short-lived species for selected regions by the two approaches, with appropriate measurements, would provide valuable guidance on the level of spatial heterogeneity that must be resolved to adequately represent regional climate variability (e.g., effects of resolving aerosol composition and size distributions at finer resolutions). Analyses and inter-comparison of results could also help develop region-specific metrics to assess impacts of climate change on various environmental endpoints (e.g., changes in hurricane intensity in the Atlantic, changes in precipitation in the Pearl River Delta) and air quality-climate interactions (e.g., modulation of arctic snow albedo due to black carbon deposition and its source attribution).

4.2.3 Decision support tools for scenario assessment and comparison

The impacts of climate change accumulate over many decades. Emissions, land use change, and other forcing agents on the climate system cannot be reliably forecast over these time scales. The analyses of the Intergovernmental Panel on Climate Change have instead relied on scenarios, rough sketches of potential futures. From scenarios that lead to mitigated climate change, we can learn more about what emission reduction goals are needed. Scenarios also include assumptions about future changes that can only be partially controlled by policy options, such as availability of natural resources, the pace of technological change, and global population migration. Robust policy options are those that achieve our climate mitigation goals across a wide range of assumptions about the future. A key need is a set of modeling tools that can rapidly screen large numbers of scenarios to uncover robust policy options, isolate determining assumptions, and present trade-offs to decision makers.

Process-based, first-principle models alone are not ideally suited for this task. Such models are comprehensive but computationally expensive. They do, however, strive to accurately capture the complex, non-linear relationship between anthropogenic activities and the environmental harms. Climate models and chemical-transport models are no exception.

However, some first-principle models have been augmented to include on-line sensitivity calculations. Adjoint models allow the user to define a receptor and to calculate the sensitivity of the receptor to each model input. For example, an adjoint chemical transport model can calculate the influence of each emission source in the domain on the aerosol concentration in one non-attainment area. In adjoint models, the receptor is defined by a cost function. This function can be as simple as the concentration in a single location, or it can be arbitrarily complex, such as the contribution to locations and times that exceed a concentration threshold.

Model development

Our current model development activities are focused on two different adjoint models. First, we are focusing on ensuring that the CMAQ Adjoint (Hakami et al., 2007) contains the most up to date, state of the science modules as the current released version of CMAQ. Second, along with our collaborators, we are developing a GEOS-Chem Adjoint (Henze et al., 2009) that includes an adjoint of the radiative transfer model LIDORT (Spurr et al., 2001). GEOS-Chem is a global chemical transport model (http://acmg.seas.harvard.edu/geos/index.html). In addition to calculating the sensitivity of concentrations, this model can also calculate the sensitivity of direct radiative forcing due to emission changes. Currently, this is only implemented for shortwave radiation and black carbon; our development activities will extend this to scattering aerosols, ozone, and longwave radiation.

Model application

Using results from these models, we will develop screening tools to rapidly calculate the impact of a given emission reduction strategy on both air quality (for example, PM concentration in non-attainment areas) as well as global or regional change in radiative forcing. We will work closely with our colleagues in NRMRL to ensure the development of economic emission models that are sufficiently comprehensive to explore the relationships between different policy options. We will also work closely with our colleagues in EPA OAQPS and OAP Climate Change Division to ensure the metrics calculated by these adjoint models are relevant to the environmental indicators that the Agency needs to assess the success of regulatory actions.

It is critical to note that the efforts described here are to complement, not to replace the physically based models. We need continued improvement in the physically based models to ensure that the adjoint is correctly representing the interactions between the processes. The reduced-form model is intended only to be a screening tool for rapid scenario discovery. Change in global radiative forcing is a useful indicator of anthropogenic impact of climate change, but it is not sufficient to understand the regional-scale impacts such as extreme heat events and variable precipitation that causes droughts and flooding. The goal of the adjoint models is to illuminate the coarse differences between scenarios, understand the impacts of key assumptions that drive future outcomes, and discover policy options that are robust across these assumptions. Once a subset of robust policy options is identified, this more computationally tractable subset of scenarios must be assessed using the more complete, physically based models described in the other sections of this white paper including the global chemistry and climate models and the regional WRF-CMAQ system both for downscaling of global climate and for further assessment of regional changes in radiative forcing and air quality.

4.2.4 Emissions and Land Cover

Land Cover

Land cover changes are interrelated with many of the anthropogenic activities affecting emissions to the air, all of which interact as a part of climate change. A combination of enhanced information based on current sources and new land cover and emission modeling projection tools will be required as a part of the development of modeling regional climate change and effects. Land model components of AOGCM systems, such as the Community Land Model (CLM) (Gibbard et al., 2005; Lawrence and Chase, 2007), typically characterize vegetation types according to global land-use data such as the MODIS satellite land cover product (available at approximately 1 km spatial resolution). While 1 km spatial resolution is more than sufficient for the grid resolution of current global models, our regional modeling system (WRF-CMAQ) has benefitted from the greater resolution and accuracy of the National Land Cover Database (NLCD) (Fry et al., 2009) which has 30 m spatial resolution for the U.S. based on Landsat Thematic Mapper imagery. This high resolution allows for much more accurate classification of land use categories and better accounting of subgrid spatial heterogeneity. Outside the U.S., MODIS land cover data (Giri et al., 2005) and a new global landuse database available at 300 meter resolution known as the GlobCover data have recently been made available from the European Space Agency (Arino et al., 2007). However, the classification system of the MODIS land cover data is more compatible with NLCD data. Adaptation of the CLM to use these higher resolution landuse databases, which would require significant code modification in collaboration with the CLM developers at NCAR, would result in consistent modeling of dynamic natural land surface processes, chemical surface fluxes (dry deposition and bidirectional surface fluxes), and biogenic emissions in our WRF-CMAQ RCCM.

Projection of land cover for regional climate modeling will require development and application of modeling tools. There are some promising tools that can be built upon in a collaborative effort. On a global scale, the CLM has the advantage of being actively supported by many contributors for use with global climate models. As a dynamic model, it accounts for the major biophysical processes and feedbacks affecting vegetation and hydrology looking forwards many hundreds of years.

Scenarios of projected regional land cover change must also be compatible with scenarios of anthropogenic emissions as well as vegetation cover change. On a global scale, the IPCC is assessing the differences in land cover use and projections applied by the four different Representative Concentration Pathway (RCP) emission scenario teams for the fifth assessment report (AR5) by means of analysis of the effects of the differences (Hurtt et al., 2009). The USGS Forecasting Scenarios of Land Use Change (FORE-SCE) model (Sohl et al, 2007) presents a promising approach for scenario-based land cover projections to approximately 2050, with stochastic components using NLCD-scale land cover in conjunction with econometric model drivers (for example MARKAL, below). FORE-SCE is usually applied on the basis of hydrologic basins, which is consistent with the needs of ecological programs. The spatial scale of application is variable from NLCD-pixels to potentially national scale. Thus far it has been applied to entire regions such as the U.S. Southeast and high plains (Sohl and Sayler, 2008). Substantial work is required to statistically define the landscape drivers for the balance of the United States, in order to apply FORE-SCE nationally. To take full advantage of both FORE-SCE and CLM for future periods of approximately 50 years or more, it will be necessary to establish a comparison between their land cover projections at specified future times. It is not expected that they will provide the same results, but rather different realizations reflecting their different strengths. Initially, collaboration between USGS, NCAR and EPA will be pursued to result in a mutually-agreed description of a common baseline of assumptions and time periods that can be used for model comparisons. Since FORE-SCE is the shorter term and more anthropogenically-focused model, a next step would be to nudge aspects of CLM toward FORE-SCE land cover at approximately 2050, project further (say 2100) with CLM and compare with CLM results without the nudging.

Emissions

In order to project anthropogenic emissions, either on a global or regional scale, sound global and regional inventories are required. The most complete existing global emission inventories for greenhouse gases and air pollutants are maintained online through the Emission Database for Global Atmospheric Research (EDGAR) system (http://www.mnp.nl/edgar/). The inventories are the result of compiling national inventories focused on the year 2000, including those of the United States and Canada, in addition to new emission estimate contributions from individual investigators. Currently, efforts are underway to make 0.5 x 0.5 degree resolution the common spatial resolution of EDGAR data sets. Enhanced EDGAR data sets are the basic components of the 2000 reference year being used for the IPCC emission inventory, again at a spatial resolution of 0.5 x 0.5 degrees (Lamarque et al., 2009). The base IPCC emission data sets are posted on the internet at ftp://-ipcc.fz-juelich.de/pub/emissions. The IPCC data sets should be spatially resolved enough to form the basis for regional climate modeling at hemispheric or continental scales. For purposes of more detailed regional climate modeling of non-greenhouse gases within North America, more spatially and temporally resolved emission inventories than the global AR5 inventories may be required. It will be necessary to substitute the county-level EPA National Emission Inventory (NEI) for EDGAR data, to address the relatively short-lived criteria pollutants for the United States and Canada for the base periods. This is not to prejudge the AR5 scenarios as "truth", only for inter-study comparison. EPA will require additional scenarios to reflect plausible policy directions and additional science questions.

Prioritized future years and policy-relevant scenarios of interest will be selected in conjunction with EPA clients. The number of scenarios examined will be limited by the computational resources and program time limitations. A prioritized list of future scenarios will be developed by NRMRL in collaboration with AMAD using the GEOS-Chem LIDORT Integrated with MARKAL for the Purpose of Scenario Exploration (GLIMPSE) screening tool (under development). The MARKet Allocation (MARKAL) model (Fishbone and Ablilock, 1981), an optimizing econometric energy use and production model, has been applied regionally by the EPA for carbon dioxide, sulfur dioxide, nitrogen dioxide, and PM10. For comparison with AR5 global emission scenarios, the inputs to MARKAL could be scaled to the hemispheric and continental scale assumptions used in the AR5 scenarios. There will also be regional scale scenarios that will vary within the bounding influences of the AR5 scenarios, or be independent from them. Developments to extend the range of gaseous and particulate emission species and economic sectors addressed by MARKAL are underway, with the lead group being NRMRL. For example, addition of volatile organic compound species, methane, ammonia and carbon monoxide are now planned, as well as increased spatial resolution beyond the nine U.S. census divisions now addressed. Spatially dispersed or "nonpoint" sources require indirect data or "surrogates" to spatially allocate their emissions from geographic reporting units such as counties to model grid cells. This has historically been done using detailed surrogate data such as census and land cover information. For future years, additional work is needed to refine initial work to allocate projected emissions spatially using relatively simplified projected information, such as population and land cover combinations. For anthropogenic emission projections beyond 2050 to 2100, research is needed to determine the best approach. Input data for MARKAL and modeling assumptions are much less reliable after 2050. Alternate viable emission projection methods might range from scaling the IPCC AR5 scenarios to extended MARKAL assumptions from 2050 based on more simplified assumptions, or some combination of approaches. It is also likely that additional approaches may be gleaned from the developing literature in the next two to three years.

Sources of naturally occurring emissions, including biogenic emissions, fluxes from oceans, lightning, wildfires, and anthropogenic biomass burning, are areas requiring additional information, to be gained primarily from EPA grant program results and current research updating CMAQ, with the effects on regional climate and feedbacks evaluated in AMAD. Emissions from these sources are currently roughly estimated in the EDGAR global data sets used by AR5, except for biomass burning, which is being addressed by a composite of different models (Lamarque, 2009). However, additional spatial and temporal information is required for regional scale climate modeling. Inclusion of feedback effects as a part of defining and modeling regional emission scenarios is increasingly important for these sources. Biogenic emissions may be addressed by ongoing development of the NCAR-supported Model for Emissions of Gases and Aerosols in Nature (MEGAN) model (Guenther et al., 2006), rather than the Biogenic Emission Inventory System (BEIS) model currently used in EPA emission modeling (Schwede et al, 2005). MEGAN is being used as a part of global climate modeling and is currently being evaluated by AMAD. There are ongoing discussions with NCAR on reaching consensus on grouping of forest species in the land cover database used by MEGAN. AMAD is evaluating the effect on national and regional climate emissions and feedbacks relative to the older BEIS model results and different climate scenarios.

Fluxes of important chemical substances from the ocean, such as mercury (Hg), dimethyl sulfide (DMS), and ammonia (NH_3) are subject to substantial uncertainty, both in magnitude and sign (Liss and Lovelock, 2007; Sunderland et al., 2009; Johnson and Bell, 2009). This is an area of ongoing research from which AMAD will need to glean measurement information from other researchers and collaborate on modeling the fluxes. Emissions of nitrogen species from lightning are possibly a major contributor to nitrogen species emissions globally (Bond et al., 2002). This is the subject of ongoing collaborative work between AMAD investigators and NASA. Because climate change is likely to affect the amount of convective activity in the atmosphere, lightning events will also vary and generate more or less emissions (Reeve and Toumi, 1999). Modeling of emissions from lightning will need to be coupled with the modeling of storm convection within the regional climate applications of WRF and CMAQ. The modeling of future wildfire and biomass burning emissions is related to the modeling of future lightning events in conjunction with regional climate, and regional land cover scenario conditions (Brown et al., 2004; Ramanathan et al., 2001).

5. Research Plan

The research projects described in Section 4 cover a wide range of approaches to climate related issues including the development and application of a suite of tools that can be used to determine the impacts of U.S. climate mitigation policies. These tools span global and regional scales as well as short-term and century-scale temporal impacts. This section first outlines a roadmap for the development of a Global-to-Local scale climate and chemistry modeling system that will be essential for understanding the regional and local impacts of climate change and the relative importance of GHGs and SLCF. Next, milestones for anticipated products for the next five years are listed.

5.1 Development Plan for Regional Climate Chemistry System

There are four concurrent research projects that are building the components needed for the development of a comprehensive Global-to-Local climate chemistry model system.
These are:

1. Global climate model simulations with online chemistry and aerosols for various emission scenarios including time slices with high time resolution output (6 hourly) for downscaling. Initially, we will use the GISS Model-E in collaboration with NASA GISS with the goal of also working with the NCAR CESM and the GFDL AM3.
2. Downscaling regional climate modeling using WRF. This project is focused on testing and evaluating data assimilation techniques and physics components for optimal regional climate representation.

3. Development of the WRF-CMAQ coupled meteorology-chemistry model. This project includes the development and implementation of direct and indirect aerosol and short lived gas effects on radiation and cloud microphysics.
4. Hemispheric modeling using WRF and 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.

Although, each of these four projects have their own research goals, some of which are related to other environmental issues, they are also necessary steps toward the development of the RCCM system. We envision that these efforts will be integrated in a staged approach such that the methods can be thoroughly evaluated for value added at each step.
The developmental stages are:

1. Regional Downscaling – AOGCM to WRF
   Experiments and evaluation of nudging and physics options.
2. Add hemispheric WRF to downscaling experiments
   Does the hemispheric domain improve regional downscaling results?
3. Use WRF-CMAQ for all grids
   Assess impact of chemistry feedbacks at all scales.

This approach will lead to a multiscale integrated regional climate chemistry model capable of much more highly resolved treatment of emissions, photochemistry, aerosol dynamics, and interactions between short-lived gases and aerosols, and radiation and cloud microphysics, than are possible in the coarse grid AOGCMs. A schematic of the model system is shown Figure 2 with anticipated horizontal grid resolution ranges for each WRF-CMAQ model domain.

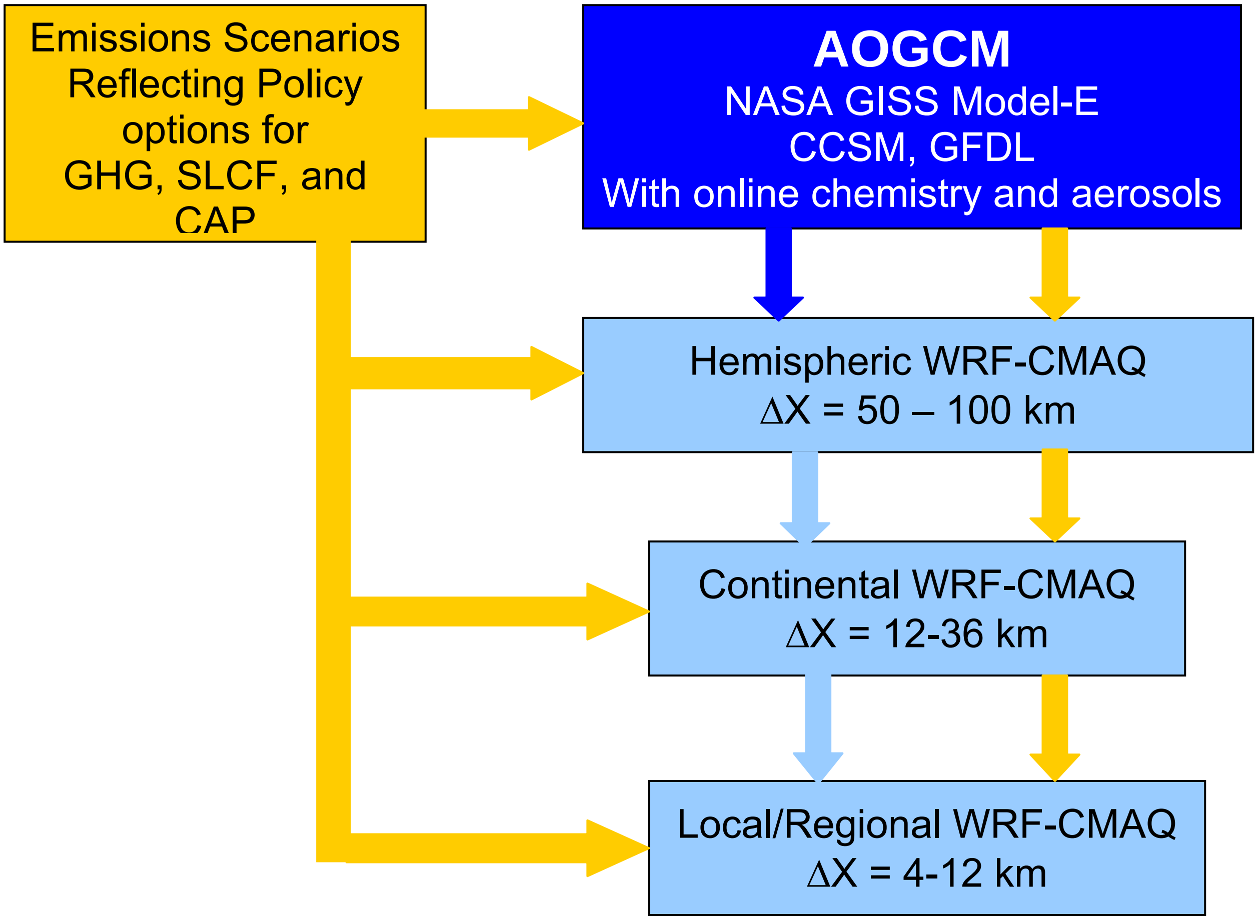

Figure 2: Global-to-Local climate chemistry modeling system. The blue arrows indicate the downscaling of meteorological information while the gold arrows indicate chemical downscaling.

5.2 Anticipated Products

<u>2010</u>

- Develop advanced methods for downscaling global climate simulations to the regional scale

- The 2-way coupled WRF-CMAQ model will be tested with a preliminary indirect aerosol feedback capability

<u>2011</u>

- Downscale AR5 climate simulations to create regional climate simulations that can be used to assess the impacts of regional climate change on human health, air quality, water resources, and ecosystems

- The 2-way coupled WRF-CMAQ model will be publically released

- Installation of GlobCover 300 m land cover data for use with the Community Land Model and for regional climate modeling (CMAQ) on a hemispheric and continental basis. This would require mapping of the land cover classification between that used by NLCD and GlobCover. Classification mapping by 2011.

<u>2012</u>

- Development of GEOS-Chem Adjoint for assessing the impact of emission changes on global radiative forcing due to ozone and aerosols

- Development of decision support tools using adjoint model results for rapidly screening scenarios, understanding key assumptions, and discovering robust policy options for both mitigating climate change and managing air quality

- An analysis of policy-relevant climate mitigation scenarios, focusing on the timing and impact of climate change mitigation due to emission reductions of SLCF compared to GHGs

- The 2-way coupled WRF-CMAQ model will demonstrated for regional climate assessment

- Improved modeling of biogenic and geogenic emission sources including lightning, wildfires, biomass burning, and wind-blown dust emissions within CMAQ - hemispheric and/or regional - with method tested and documented

- Tune and apply the FORE-SCE land cover projection model for the United States, couple with MARKAL as an economic driver, and compare with CLM projections in collaboration with the USGS. FORE-SCE addresses anthropogenic land cover drivers as well as vegetation changes. This would be accomplished for two or three time frames, with the latest being 2050. Multiple climate scenarios could be run using the land cover data set for each time period. Initial methodological comparisons documented.

<u>2013-2014</u>

- Experiments will be conducted using the 2-way coupled WRF-CMAQ model, driven by AOGCM time slice data, using a series of nested grids from hemispheric to mesoscale to assess relative impact of SLCF and GHGs on regional climate

- Installation of GlobCover 300 m land cover data for use with the Community Land Model and for regional climate modeling (CMAQ) on a hemispheric and continental basis - Installation and testing in climate and air quality model components (would need to be done with NCAR involvement)

- Tune and apply the FORE-SCE land cover projection model for the United States, couple with MARKAL as an economic driver, and compare with CLM projections in collaboration with the USGS - harmonized system producing land cover results usable in the regional climate model tested and documented.

- Expand the pollutants, source categories and spatial resolution (to state-level) addressed by MARKAL to include additional criteria and greenhouse substances. NRMRL has begun this effort, and they would do most of work on it.- project completion and testing in phases as sources and pollutants added - some by 2011, the balance of greenhouse pollutants by 2013.

- In collaboration with USGS and NCAR, compare FORE-SCE and CLM land cover projects for agreed time period (e.g. 2050). Document similarities and differences. Use FORE-SCE projected land cover to update projected CLM land cover and then project land cover further in time (2100) using CLM. These results would be analyzed in comparison to CLM land cover not informed by FORE-SCE.

- Procedures for development of new future emission scenarios must be developed and tested. For the period between now and 2050, AMAD will collaborate with USGS to develop MARKAL based scenarios with a set of base scenarios tuned to the new AR5 continental or national projections. MARKAL drivers will be varied to determine how results might vary from the AR5 projections. For the time beyond 2050, different approaches will be developed; possibilities include a model other than MARKAL - an updated MARKAL - or simply percentage variations of the AR5 assumptions. Updating MARKAL to match AR5 will occur by 2013. New approaches for beyond 2050 will be documented by 2014.

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