

## **Projecting Future-Year Pollutant Emissions: Emerging Approaches from the EPA ORD Global Change Air Quality Assessment**

Dan Loughlin, Tim Johnson, Carol Shay and Brooke Hemming  
U.S. Environmental Protection Agency, MD E305-02, Research Triangle Park, NC 27711  
[loughlin.dan@epa.gov](mailto:loughlin.dan@epa.gov)

Britta Bierwagen and Anne Grambsch  
U.S. Environmental Protection Agency, Washington, DC  
[bierwagen.britta@epa.gov](mailto:bierwagen.britta@epa.gov)

William G. Benjey\*  
NOAA Air Resources Laboratory, Atmospheric Sciences Modeling Division, Research Triangle Park,  
NC 27711  
[benjey.william@epa.gov](mailto:benjey.william@epa.gov)

\* On assignment to the National Exposure Research Laboratory, U.S. EPA

### **ABSTRACT**

The U.S. EPA's Office of Research and Development is exploring approaches for assessing the relative impacts of climate and emissions changes on future-year air quality. A challenge related to this effort is the development of emission inventories out to the year 2050. This paper describes a methodology that is under development. The methodology allows consideration of various assumptions regarding population growth and migration, economic growth, technological change, fuel resource constraints, and pollutant emissions policies.

### **INTRODUCTION**

The U.S. Climate Change Science Program (CCSP) coordinates the climate-related scientific research activities of 13 Federal government agencies.[1] The U.S. Environmental Protection Agency (EPA) contributes to the CCSP by working to develop an understanding of the potential environmental impacts of anticipated future global changes, including population growth and migration, economic growth, land use change, technology change, climate change, and government actions and policies. As a central component of EPA's contribution to the CCSP, the EPA Office of Research and Development's Global Change Air Quality Assessment is building upon traditional EPA expertise by examining the connection between these global changes and air quality.

Air pollutants of particular concern in the Assessment are tropospheric ozone and fine particulate matter. These pollutants, which are components of urban smog, contribute to human respiratory problems, damage ecosystems, and reduce visibility, among other impacts. They are formed through atmospheric reactions of precursor emissions. Precursors to ozone include nitrogen oxides (NO<sub>x</sub>) and volatile organic compounds (VOCs). In most areas of the U.S., biogenic VOCs are present in sufficient concentration that NO<sub>x</sub> is the limiting chemical species in ozone formation. The predominant source of

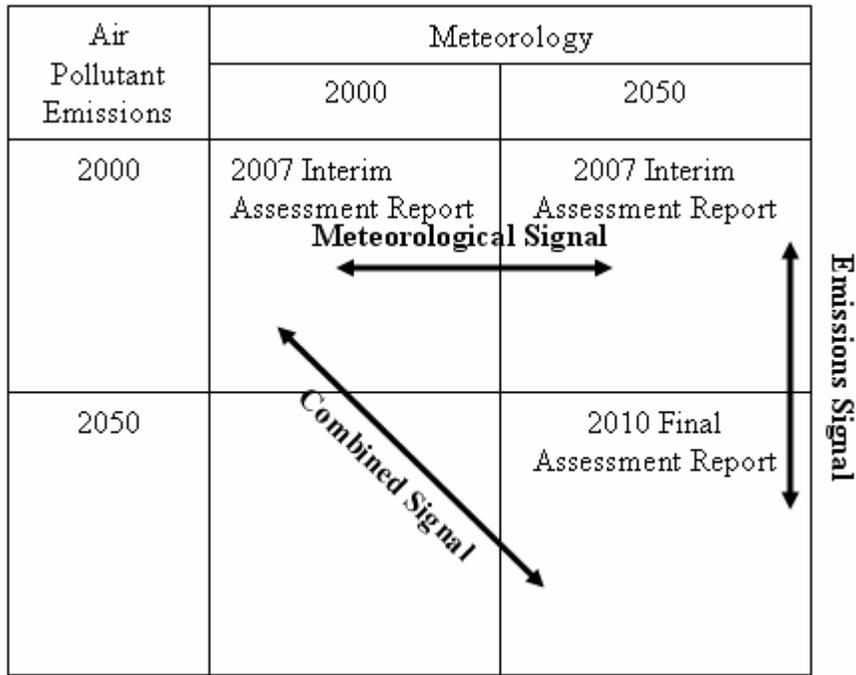
NO<sub>x</sub> emissions is the combustion of fossil fuels. Fine particulate matter can be emitted directly, such as black carbon from incomplete combustion, or can be formed through atmospheric chemical reactions, with sulfur oxides (SO<sub>x</sub>), NO<sub>x</sub>, and ammonia being common precursors.

Human health concerns have led to ambient air quality standards being implemented for ozone and particulates. Many areas of the country have not attained these standards, however, leading to more stringent air quality regulations, including the NO<sub>x</sub> SIP Call [2], Clean Air Interstate Rule (CAIR) [3], Heavy Duty Highway Diesel Rule [4], and Nonroad Diesel Rule [5]. These regulations are designed to bring most urban areas of the U.S. into attainment by 2015.

The ability of these programs to maintain air quality further into the future is less certain. If the U.S. population and economy continue to grow through 2050, a potential result is increased emissions from additional demands for energy and transportation services, among other factors. Further, climate change projections predict generally warmer temperatures, exacerbating air pollution by increasing the photochemical reaction rates that produce ozone and fine particulates. Countering these factors, economic and policy drivers may result in technology change, including energy efficiency improvements and reduced pollutant emissions rates. Characterizing the relative and combined impact of these factors is an important step in anticipating future-year air quality and in identifying whether additional technologies or policy measures will be necessary to protect human health and the environment. This characterization is one of the primary products of the Global Change Air Quality Assessment, with contributing work being carried out both through in-house and external research activities.

The in-house modeling activities of the Global Change Air Quality Assessment are aimed at evaluating the individual and combined impacts of climate and emissions changes on air quality in 2050. EPA is performing this work in two phases. The initial work, to be described in the 2007 Interim Assessment Report, has largely focused on characterizing the impacts of climate change on air quality, holding anthropogenic emissions constant. Air pollutant emissions for 2001 [6] were evaluated for meteorological scenarios representing 2000 and 2050, respectively. The meteorological scenarios were developed using a global and regional meteorological models, with the future meteorological scenario reflecting a trajectory of greenhouse gas emissions consistent with the Intergovernmental Panel on Climate Change (IPCC) A1B emissions scenario.[7] This work is summarized by Cooter et al.[8] The 2010 Final Assessment Report will augment the 2007 analysis by evaluating the 2050 meteorological case with projected emissions for 2050.

The relationship between the modeling runs is illustrated in Figure 1. This experimental design is intended to allow the meteorological and emissions signals on air quality to be evaluated individually and together.

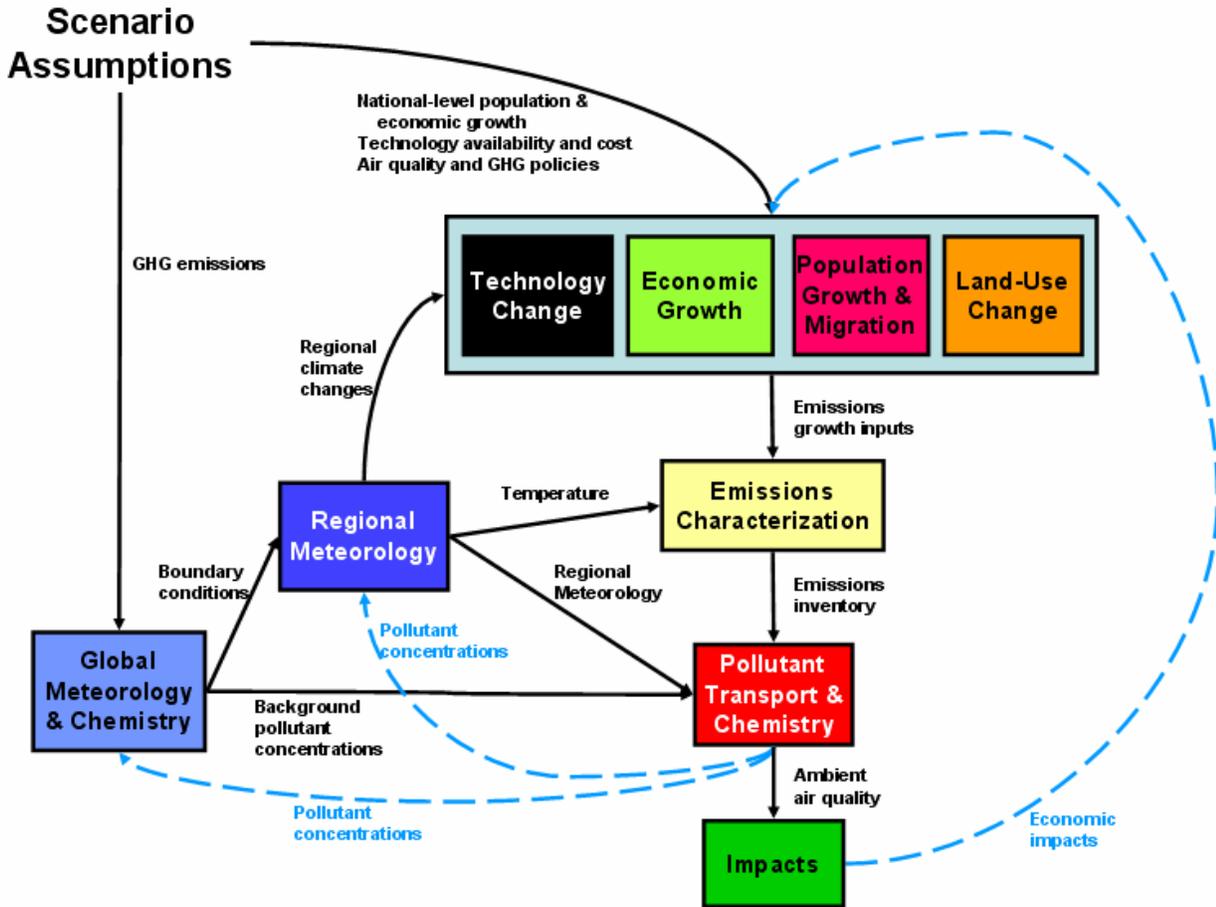


**Figure 1. Experimental design of the Global Change Air Quality Assessment.**

One of the major challenges in carrying out this experimental design is the generation of realistic emission inventories for 2050. The objective of this paper is to provide a general introduction to the in-house work being done to generate estimates of future pollutant emissions for 2050, including new methodologies that are being explored.

### CONCEPTUAL FRAMEWORK

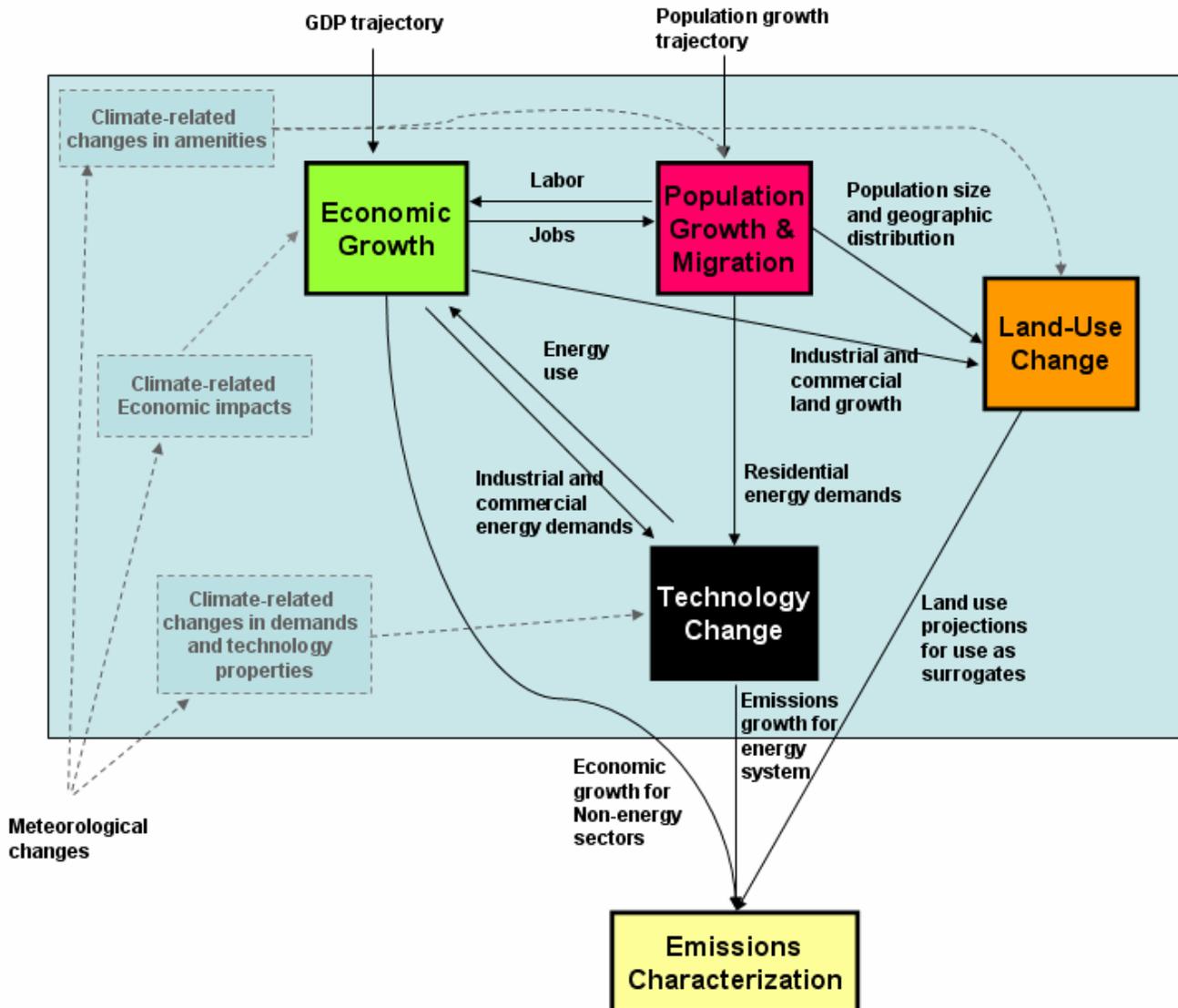
An initial step in creating a 2050 emissions inventory was to develop a conceptual model that outlines the various system components and linkages that influence future-year emissions and air quality. Figure 2 is a graphical depiction of this conceptual model.



**Figure 2. Conceptual framework outlining the influence of global change factors on air quality.**

At this high level, the overall system is driven by various global- and national-scale assumptions. Greenhouse gas emissions are a key input to the global circulation model, which simulates meteorology and atmospheric chemistry. These, in turn, affect regional meteorology, meteorology-sensitive anthropogenic and biogenic emissions, and pollutant transport and chemistry. Assumptions also drive technology change, economic growth, population growth and migration, and land-use change, which are themselves interrelated. These factors affect the quantity and location of pollutant emissions, and thus on air quality. The dotted lines represent feedbacks that may be important. For example, pollutants such as aerosols and black carbon have radiative forcings that can affect regional climate. Similarly, health and environmental impacts may lead to better or worse economic conditions and changes in mortality rates, thereby affecting some of the drivers for emissions growth.

In Figure 3, the box encompassing technology change, economic growth, population growth and migration, and land-use change is examined in more detail.



**Figure 3. Conceptual model detail on the factors affecting future-year emissions growth.**

This figure indicates the relationship between economic growth and population changes. Economic growth is partially a function of the cost of labor, while population migration is affected by the availability of jobs. Both economic growth and population changes drive energy demands and may indirectly influence changes in the technologies. Population growth and migration have an effect on land use, including the transformation of rural, agricultural, and forest land to accommodate housing. These changes, in turn, affect the quantity, nature, and geographic distribution of both biogenic and anthropogenic emissions. Climate change has the potential to impact processes represented within many of these components. For example, climate changes can change the attractiveness of living in various areas, the ability to use land for agriculture and recreation, and demands for energy services such as heating and cooling. Non-climate feedbacks indicated in Figure 2, including the effects on the economy and population resulting from air quality impacts, are not included in Figure 3.

## **REALIZING THE CONCEPTUAL MODEL**

Developing emissions scenarios for the 2010 Assessment Report involves realizing the conceptual model illustrated in Figures 2 and 3 with modeling components and a methodology. The level of resources available dictates that existing expertise, models, and tools be leveraged to the extent possible. For example, within its ongoing regulatory and research air quality modeling applications, EPA uses the Sparse Matrix Operator Kernel Emissions (SMOKE) processing model [9], the MM5 regional-scale meteorological model [10], and the Community Multi-Scale Air Quality (CMAQ) model.[11] Given future-year projections of meteorology and emissions, these models can be applied readily to evaluate a 2050 emissions scenario.

Generating 2050 emission inventories for input into SMOKE is not straightforward, however. EPA typically uses the Integrated Planning Model, or IPM, to model fuel use and emissions from the electricity production sector.[12] IPM has been applied to model past and present emissions, as well as to project emissions to a near-term future year, such as 2007, 2015, or 2020. IPM was not developed with the goal of producing emissions projections to 2050. Similarly, EPA's current methods for generating near-term emissions projections for mobile, residential, commercial, and industrial sources, among others, do not account for many types of changes that may occur over a nearly 50-year time period. These include the introduction of new technologies (e.g., advanced nuclear power, coal gasification with carbon sequestration, plug-in gasoline-electric hybrids, and hydrogen fuel cell vehicles), growth and redistribution of population and industries, expansion of urban and suburban areas, and changes in heating and cooling demands related to climate change. Accounting for these factors requires the development of a new emissions projection methodology.

To this end, an emissions projection methodology is being developed that includes: the ICLUS (Integrated Climate and Land Use Scenario) system [13], a modeling system that links a population growth and migration model with a land use change model; MARKAL (MARKet ALlocation), an energy system model that projects the penetration of technologies and their associated emissions [14]; and an economic model that projects industrial growth and energy demands. The selection of which economic model to use has not been finalized, although the EMPAX economic model, a state-level computational general equilibrium model of the U.S., is one of the candidates and is described here.[15] The ICLUS and EMPAX modeling systems are currently under development. The degree of their inclusion in this methodology will be determined by its development schedule and availability.

These models and their data linkages are shown in Figure 4.

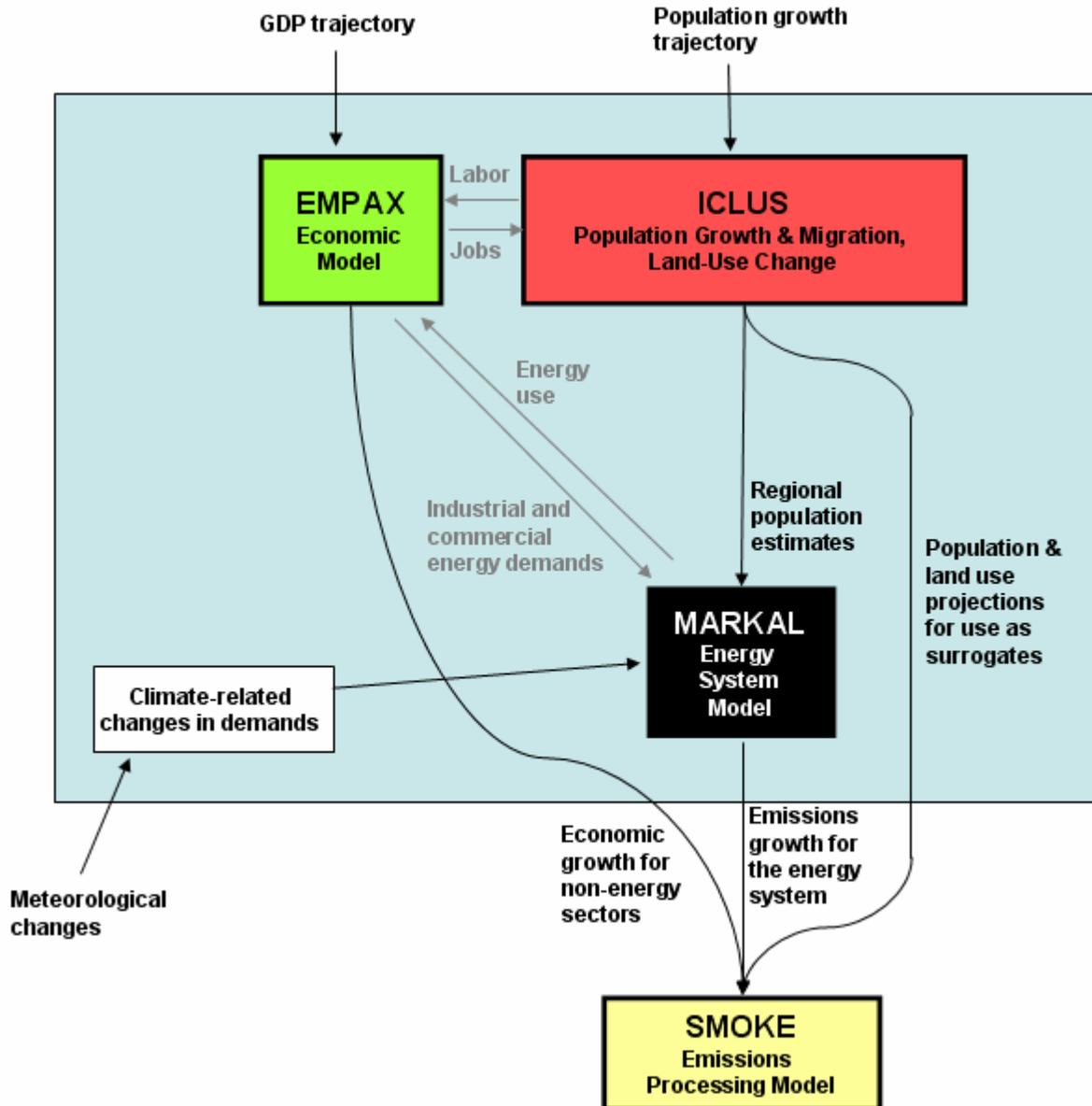


Figure 4. Models and linkages for developing emissions growth factors.

The “Jobs,” “Labor,” “Energy Use,” and “Industrial and Commercial Energy Demands” linkages are currently grayed to indicate that these linkages may or may not be included in the 2010 Assessment Report, depending on available time and resources. The feasibility of including the additional climate-related linkages and feedbacks shown in Figures 2 and 3 is being evaluated.

## **INDIVIDUAL MODELING COMPONENTS**

Each of the modeling components that comprise this methodology are described briefly below.

### Economic Projections: EMPAX

EMPAX is a regional computable general equilibrium model of the U.S. economy. It is designed to estimate the regional and national macroeconomic impacts of environmental regulations and other drivers. The dynamic version of EMPAX-CGE represents seventeen sectors of the U.S. economy in five geographic regions. EMPAX-CGE is currently being expanded to provide state-level outputs. The modeling time horizon extends to 2050, modeled in five-year increments. Among the outputs are future-year domestic product by industry and region. The use of these growth factors as: (i) inputs into the calculation of emission estimates from non-energy system sources, and (ii) drivers for energy demands in technology modeling, will be examined within the 2010 Assessment Report.

### Population Growth and Migration and Land Use Change Projections: ICLUS

The Integrated Climate and Land Use Scenarios (ICLUS) project consists of a population growth and migration model and a land use change model. Population growth is modeled using a cohort-component methodology and migration using a gravity model.[16] The cohort-component model grows population as a function of birth rates, mortality rates, and domestic and international migration. The gravity model is driven by factors such as historical patterns and the attractive influence of amenities associated with urban areas and the unattractiveness associated with overcrowding. County-level population estimates are then input into the SERGoM land-use change model.[17] SERGoM outputs future-year housing density estimates at a 100 meter resolution, accounting for factors such as major roads and road network densities, developable lands, protected areas, water bodies, and proximity and accessibility to urban areas. Housing densities produced by SERGoM can be analyzed to characterize urban, suburban, and rural area boundaries. Within the emissions projection process, future-year county-level population estimates may be combined with climate projections to estimate changes in regional energy demands. Further, land use category projections may be used to generate emissions surrogates that are used within SMOKE to geographically allocate future-year area source emissions.

### Technology Projections: MARKAL

The MARKet ALlocation model is an optimization model that identifies technology and fuel pathways to meet future energy demands at lowest cost, given current and expected technology characteristics, energy resources, and policies limiting pollutant emissions. MARKAL is a bottom-up model, meaning that it represents energy system technologies explicitly, including technologies related to the import or extraction of energy resources (e.g., oil), to their conversion to useful forms (e.g., gasoline), and to their use in meeting energy service demands (e.g., internal combustion automobiles to meet light duty travel demand). Technologies and fuels in each of these categories compete for market share over a modeling time horizon. To evaluate emissions scenarios for the 2010 Assessment Report, the U.S. EPA has developed the U.S. EPA MARKAL-9R database for use with MARKAL. The 9R database represents the U.S. as nine regions, analogous to the U.S. Census Divisions, extends to the year 2050, and includes the electricity production, industrial, commercial, residential, and transportation sectors. MARKAL outputs are parsed to generate emissions growth and control factors at the Source Classification Code (SCC) level. These multiplicative factors are used within the SMOKE emissions processing model to develop future-year emissions inputs into CMAQ.

## Emissions Processing: SMOKE

The Sparse Matrix Operator Kernel Emission model prepares emission data for use in the air quality model. SMOKE was designed to use matrix computations to efficiently compute and combine emissions from all sources. Within this project, SMOKE takes a base-year emissions inventory as input, applies MARKAL-generated growth and control factors to energy-related sources, grows non-energy source emissions using growth factors derived from economic or population projections, then uses ICLUS population and land use projections, as well as other surrogates, to geographically apportion emissions. Future-year emissions are then allocated spatially and temporally and gridded.

## **CURRENT STATUS AND NEXT STEPS**

EPA is continuing the development of various modeling components to be used within this emissions projection methodology. We expect to have these modifications completed and the various model linkages finalized such that a 2050 emissions inventory will be developed during the summer of 2007.

The overall modeling framework will then support a variety of sensitivity analyses. For example, alternative future-year emission inventories may be developed and compared using different assumptions regarding population growth and migration, as well as technology evolution and adoption. Different IPCC SRES scenarios could provide a basis for this comparison. The SRES A1b scenario family currently supplies the baseline assumptions for the larger ORD Global Change Air Quality Assessment. An examination of the impacts of a future closer to the SRES A2 or even B2 storylines would offer insight into how this choice affects conclusions.

The 2010 Assessment will also explore a series of specific energy-technology scenarios, and examine the impact of the related technology pathways on air quality during, for example, the peak summer ozone season for the years surrounding 2050. Such scenarios might include: a high-technology case with hydrogen fuel cell vehicles, plug-in hybrids, carbon capture and sequestration, and advanced nuclear plants; a renewable-intensive case with greatly expanded use of wind and solar power, plus biofuels; a more conventional technology pathway consisting of continued reliance on coal, natural gas, and petroleum; and a range of assumptions regarding the decentralization of electric power generation.

Finally, the 2010 Assessment may examine the range of energy-related criteria pollutant emission trajectories compatible with the SRES A1b scenario CO<sub>2</sub> emissions. The analysis, for instance, could constrain the MARKAL model to meet the SRES A1b CO<sub>2</sub> assumptions, and use Monte Carlo-based methods on key input parameters to produce a distribution of output NO<sub>x</sub>, SO<sub>2</sub>, and PM emission values consistent with the A1b CO<sub>2</sub> emissions profile. The analysis would therefore identify technology pathways that correspond to the typical and extreme values of the criteria pollutant emissions distribution and draw more general conclusions about the connection between technology change, greenhouse gas emissions, and air quality.

## **DISCLAIMER**

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Oceanic and Atmospheric Administration (NOAA) and under agreement number DW13921548. This work constitutes a contribution to the NOAA Air Quality Program. Although it has been reviewed by EPA and NOAA and approved for publication, it does not necessarily reflect the policies or views of these organizations.

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