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Projecting state-level air pollutant emissions using an integrated assessment model: GCAM-USA

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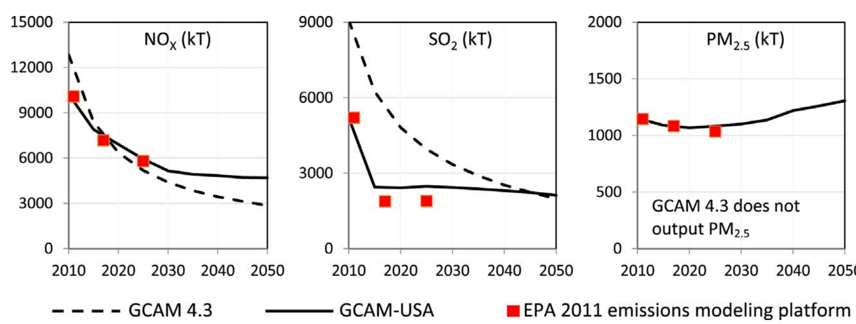
HIGHLIGHTS

- GCAM-USA is modified to reflect U.S. air pollution regulations.
- Sectoral, national, and state emission projections are evaluated with quality metric.
- GCAM-USA agrees better with EPA inventories for NO_X and SO_2 than GCAM.
- The quality metric provides insights into national- and state-level performance.

GRAPHICAL ABSTRACT



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ABSTRACT

Integrated Assessment Models (IAMs) characterize the interactions among human and earth systems. IAMs typically have been applied to investigate future energy, land use, and emission pathways at global to continental scales. Recent directions in IAM development include enhanced technological detail, greater spatial and temporal resolution, and the inclusion of air pollutant emissions. These developments expand the potential applications of IAMs to include support for air quality management and for coordinated environmental, climate, and energy planning. Furthermore, these IAMs could help decision makers more fully understand tradeoffs and synergies among policy goals, identify important cross-sector interactions, and, via scenarios, consider uncertainties in factors such as population and economic growth, technology development, human behavior, and climate change. A version of the Global Change Assessment Model with U.S. state-level resolution (GCAM-USA) is presented that incorporates U.S.-specific emission factors, pollutant controls, and air quality and energy regulations. Resulting air pollutant emission outputs are compared to U.S. Environmental Protection Agency 2011 and projected inventories. A Quality Metric is used to quantify GCAM-USA performance for several pollutants at the sectoral and state levels. This information provides insights into the types of applications for which GCAM-USA is currently well suited and highlights where additional refinement may be warranted. While this analysis is specific to the U.S., the results indicate more generally the importance of enhanced spatial resolution and of considering national and sub-national regulatory constraints within IAMs.

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1. Introduction

The primary goal of air quality management is to protect human health by reducing air pollutant concentrations to safe levels and maintaining those levels into the future. Air quality managers have a variety of regulatory and policy levers at their disposal, including emission standards for new and existing sources, requirements that emissions from new sources be offset by reductions from existing sources, emission cap-and-trade programs, taxes on emissions, renewable portfolio standards for electricity production, energy efficiency standards, and educational efforts that promote energy conservation.

Air pollutant emissions modeling is an important tool in evaluating the short- and long-term effectiveness of candidate management strategies. Within the U.S., criteria air pollutant emissions for key sectors typically are projected into the future using detailed sector-specific models. The Integrated Planning Model (IPM) [1] is often used to estimate future electric sector emissions, while the Motor Vehicle Emissions Simulator (MOVES) model [2] and the NONROAD model [3] are used to estimate present and future on-road and non-road mobile emissions, respectively. For the residential, commercial, and industrial sectors, emissions are projected using multiplicative growth and control factors developed using a variety of methods. A management strategy is evaluated by comparing its emission reductions relative to a baseline projection. The projected emissions also can be further processed with the Sparse Matrix Operator Kernel Emissions (SMOKE) system [4] to create the gridded inputs to an air quality model, such as the Community Multiscale Air Quality (CMAQ) model [5].

While this approach represents the standard practice for evaluating air quality management strategies, it has several drawbacks. For example, the models underlying the emission projections are computationally and data intensive, limiting the number of projections that can be considered. Air quality managers thus are constrained in their ability to explore alternative assumptions about the factors that drive emissions, such as population and economic growth, technology development, climate change, and land-use change. Furthermore, treating sectors independently may neglect important cross-sector interactions. For example, using a sector-by-sector approach it is difficult to examine how induced changes to the price of electricity could lead to fuel switching and emissions implications in other sectors.

Integrated multi-sector models can complement sectoral models to help inform the decision-making process. Many such applications have involved energy system optimization models, such as the MARKet ALlocation (MARKAL) model [6]. MARKAL represents an energy system from energy supply through its use, thus incorporating mining, refining, electricity production, and energy use within the residential, commercial, industrial, and transportation sectors. A focus is on energy since energy-related fuels and technologies within these sectors constitute 90% or more of U.S. anthropogenic emissions of nitrogen oxides (NO_X), sulfur dioxide (SO_2), and carbon dioxide (CO_2), as well as more than 60% of anthropogenic fine particulate matter (PM) [7]. Furthermore, by considering the entire energy system, MARKAL and similar models can endogenously account for cross-sector interactions. The U.S. Environmental Protection Agency (EPA) has applied MARKAL for a variety of applications related to air quality management [8–13]. Also, a state-level variant, NE-MARKAL, has been used for similar applications within New England [14], and single-state versions have been developed for several other states [15,16]. Other modeling frameworks have been applied for similar purposes. For example, the MESSAGE and GAINS models have been used together to estimate future air pollutant emissions in Europe [17]. Optimization-based models such as these make some sacrifices for the sake of efficiency. For example, many are based upon linear programming, and thus require simplifications such as linearization of nonlinear relationships and limited or no consideration of feedbacks.

Integrated assessment models (IAMs) are global models that characterize human and earth systems and the interactions among their components. Within most IAMs, interactions can be nonlinear and many allow characterization of feedbacks. IAMs have been used for a wide range of applications, including projections of future emissions, land use, and water supply and demand [18–21], assessment of the climate impacts of emission scenarios [22], and evaluation of climate change mitigation strategies [23–25].

A new class of IAMs is emerging with increasingly high levels of technological, spatial, and temporal resolution. In addition to greenhouse gases (GHGs), these models now often include air pollutant emissions, which also impact climate. With these new features, IAMs have the potential to project national- and sub-national emissions into the future with a level of detail that can support air quality management. Furthermore, since all include climate considerations and many also include representations of water supply and demands, these models facilitate examination of additional environmental endpoints. Examples of these more detailed IAMs include the Integrated Global System Model (IGSM) [26,27], U.S. Regional Energy Policy (USREP) model [28,29], Global Change Assessment Model (GCAM) [30–32], and its state- and provincial-level versions, GCAM-USA [33,34] and GCAM-China [35].

State-level resolution is of particular interest for U.S. applications since that is the scale at which many environmental, climate, and energy policies have been implemented. For example, the Cross-State Air Pollution Rule (CSAPR) [36] involves state-level, electric sector emission caps for NO_X and SO_2 emissions. Similarly, energy efficiency and renewable portfolio standards are often specified by states [37]. State-level resolution is also closer to the level at which climate change and the co- or dis-benefits of mitigation affect daily lives through impacts such as heat waves, drought, flooding of roads and communities, and air pollution [38].

Because IAMs were developed for a different set of purposes, many have limitations in the context of state-level environmental analyses. For example, IAMs typically treat air pollutant emissions in a generalized manner. In USREP, air pollutant emission factors (EFs) are included for various economic activities. However, in a recent application [39], these EFs did not change over time and thus did not represent the influence of environmental regulations such as emissions caps or rate-based emission standards. In GCAM, EFs are calibrated for a base year, after which they decline via a function that is dependent upon, for example, per-capita gross domestic product (GDP) and whether the economy of a country is developed or developing. While this relationship may capture historical global trends well, it does not explicitly represent the policies and regulations of any particular country.

The overall goal of the work presented here is to demonstrate that IAMs can be modified to incorporate factors to improve their applicability to air quality management. To accomplish this, representations of several current U.S. air pollutant emission and energy regulations are added to the GCAM-USA model and air pollutant EFs are harmonized with EPA assumptions.

To be used as a surrogate for more detailed models in air quality management, it is important for GCAM-USA to be able to provide similar baseline emission projections to those models. Projections do not need to match completely, but it is important that differences are understood. A second goal of this work thus is to present and demonstrate a methodology for comparing GCAM-USA emissions to inventories. The Quality Metric (QM) is used to evaluate pollutant- and sector-specific performance, both nationally and at the state level.

In Section 3, GCAM and GCAM-USA emission projections are compared to EPA regulatory projections for the U.S. These results are followed by a discussion of caveats and potential future directions. Section 3 summarizes the results and discusses the utility of this research.

2. Methodology

Overviews of GCAM and GCAM-USA are provided in the following sub-sections, followed by descriptions of the modifications made to