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

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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.

Graphical abstract

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The views expressed in this paper are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency.

Keywords

Integrated assessment model; Energy system; Emissions projection; Air pollutant; Air quality; Scenario

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 (SO₂), and carbon dioxide (CO₂), 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 SO₂ 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 GCAM-USA to represent current (~mid 2017) U.S. air quality and climate regulations.

2.1. Models: GCAM and GCAM-USA

GCAM is a dynamic-recursive, partial equilibrium model that emphasizes the energy, agricultural, and land use sectors, as well as the connections between sectors and with the global earth system. For over 30 years GCAM and its predecessors have been used to investigate future emission scenarios and energy technology pathways. GCAM applications include the U.S. Climate Change Science Program [40], the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (SRES) [41], the Representative Concentration Pathways (RCPs) [42,43], and the Shared Socioeconomic Pathways (SSPs) [44,45]. GCAM has also been used in studies examining climate change mitigation measures

[46], the consequences of specific policy and energy technology scenarios [40,47,48], and the climate benefits, including uncertainty, associated with reducing short-lived forcing agents [49].

Detailed descriptions of the model structure, data sources, and solution process are provided in online documentation [32]. Within GCAM version 4.3, the global energy-economic system is divided into 32 regions and covers the time period from 2005 through 2100 in 5-year time steps. Each region includes representations of the electric system, residential and commercial buildings, industry, transportation, and the economy. The model also includes 283 agriculture and land use regions. A climate system module represents carbon and gas cycles and translates emissions into concentrations, radiative forcing, and global temperature changes.

Inputs to GCAM include estimates of current and future regional populations, labor force size and productivity (which combine to produce GDP), energy supply curves, end-use energy demand parameterizations, and technology and land characteristics. Population and labor productivity are exogenous and are key drivers of future final service demands. GCAM outputs include regional technology utilization, fuel use, commodity prices, GHG and air pollutant emissions, and global temperature changes. Emissions of 24 species are modeled, including GHGs and certain traditional air pollutants. CO₂, NO_x, SO₂, black carbon (BC), organic carbon (OC), hydrofluorocarbons (HFCs), methane (CH₄), volatile organic compounds (VOC), carbon monoxide (CO), and ammonia (NH₃) are some of the species that intersect with EPA regulatory activities.

In each time step, the GCAM solution algorithm determines market-clearing prices—the prices at which supply equals demand—for all modeled goods and services. Modeled goods include fuels, food commodities, land, and technologies associated with energy supply and demand. Services include passenger and freight transportation, and building heating, cooling, and lighting. GCAM 4.3 is calibrated to 2010 technology and fuel market shares. National energy consumption data for the U.S. are obtained from the International Energy Agency (IEA). Technology shares for new builds are determined in each time step using a nested logistic formulation that computes the prevalence of competing options considering their relative costs.

GCAM-USA is built upon the base GCAM platform, but subdivides the U.S. energy system to represent each of the 50 states and the District of Columbia. With this additional resolution, GCAM-USA can be used to assess a suite of state-, multi-state-, national-, and international-scale energy and environmental management measures. These measures could include taxes or caps on emissions, technology and fuel standards, taxes or subsidies, energy efficiency targets, and renewable energy portfolio standards. With these features, GCAM-USA can explicitly represent current regulations and future policy alternatives in modeling the evolution of the energy system.

Another important feature is that GCAM-USA also supports geographic- and vintage-specific EFs allowing consideration of national- and state-level emission standards and turnover of existing stock. More generalized paradigms can still be applied for other global

regions. Together, these features enable a shift away from GDP-based EFs toward representations of specific environmental and energy regulations that drive U.S. emission trends.

As with most such models, GCAM model projections and model behavior have been generally evaluated through multi-model comparisons [40,41,43,47,50]. As a result of such comparisons GCAM projections have been used in a variety of national and international contexts. Formal model evaluation through hindcast experiments that compare model results over a historical period to reported energy statistics have not been commonly performed, due to fundamental incompatibilities between socioeconomic system projections and requirements for model validation [51,52], data issues, and model structural limitations. However, a few hindcast experiments have now been performed focusing on the GCAM-USA buildings model [53], and the GCAM AgLU (Agriculture and Land Use) module [54]. Such experiments can also be useful in model calibration [55]. Differences in energy projection details between GCAM, GCAM-USA, and other models, such as those used by EPA, are to be expected unless results are specifically calibrated to a common reference projection.

2.2. Model updates

Modifications to GCAM-USA implemented in this study are discussed in this subsection. These modifications include harmonizing future EFs, representing on-the-books air quality and energy regulations, and incorporating air pollutant controls. Within this paper, the scenario that is referred to as the GCAM-USA Policy Base Case incorporates these updates into GCAM-USA version 4.3. Thus, this represents a global scenario with U.S. state-level resolution. The GCAM Base Case contains no changes from version 4.3 of the base GCAM model. Thus, GCAM Base Case also is a global scenario, but represents the U.S. as a single region.

2.2.1. Future-year EFs—The source of EFs for technologies of future vintages (i.e., 2015 and later) depends on the sector. Several key sectors are summarized below. A more detailed description of the sources and calculation of sectoral EFs is provided in the Supplemental Information (SI).

The EPA regulatory model for the electric sector is the IPM, which has been used in the development and analysis of regulations such as the CSAPR. Electric generating unit (EGU) emission factors for NO_x and SO₂ from coal, gas, and biomass are obtained from the documentation for IPM versions 5.13 and 5.14 [1,56]. All other electric sector EFs (i.e., NO_x and SO₂ from oil boilers and turbines, as well as PM_{2.5}, CO, and VOC from all technologies) are obtained from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model [57]. GREET EFs reflect a comprehensive review of a wide range of data sources and consideration of various New Source Performance Standards (NSPSs) [58].

Refinery EFs in GCAM-USA also are obtained from GREET. Other industrial emission factors are calculated from results of the EPAUS9r2014 MARKAL energy modeling framework [8], which includes EFs by fuel and technology with greater specificity than

GCAM-USA. For example, MARKAL EFs are different for boilers, turbines and engines, while GCAM-USA currently supports only fuel-specific industrial EFs. From the MARKAL results, composite EFs are calculated that account for market share projections of each technology.

Applying the refinery and composite industrial EFs directly within GCAM-USA results in 2010 industrial emissions that differ considerably from the 2011 U.S. National Emissions Inventory (NEI) [59], with -26% , 132% and -57% differences for NO_x , SO_2 , and $\text{PM}_{2.5}$, respectively. To address these discrepancies, state- and pollutant-specific adjustment factors are applied to industrial emissions. Adjustment factors are not applied more broadly since GCAM-USA emissions for other sectors approximate the 2011 NEI more closely.

In the transportation sector, light- and heavy-duty vehicle EFs are obtained from results of MOVES 2014 [2], which is the EPA regulatory model for on-road transportation. MOVES produces vintage- and year-specific EFs through 2050, accounting for the impact of promulgated regulations, such as the Tier 3 vehicle emission and fuel standards [60]. Light- and heavy-duty EFs are characterized as increasing over the lifetime of the vehicle as both pollution control equipment and engine performance degrade. Several additional changes were introduced to represent U.S.-specific conditions, including adjusting vehicle lifetimes and heavy-duty load factors (e.g., the average tonnes of freight per vehicle). These changes are discussed in the SI. For non-highway vehicles, such as marine vessels and railway cars, future-year NO_x and $\text{PM}_{2.5}$ EFs are derived from the NONROAD model [3]. Future-year SO_2 EFs from domestic marine vessels are assumed to be reduced by 90% from their 2010 SO_2 EFs, in accordance with marine fuel sulfur limits mandated by MARPOL Annex VI [61].

2.2.2. State-level emission caps—The CSAPR was implemented as a set of constraints that cap electric sector NO_x and SO_2 emissions in a subset of U.S. states, most of which are east of the Mississippi River. The specific provisions of CSAPR, such as the distribution and trading of emission permits, are not modeled explicitly. Instead, state-level, electric sector emission trajectories of NO_x and SO_2 are obtained from IPM results [56], and GCAM-USA state-level electric sector emissions are constrained to be less than or equal to these trajectories. This cap-based representation is able to simulate important dynamics of how emission caps function in practice. For example, if a zero-emissions technology such as solar photovoltaics displaces a small-to-moderate fraction of combustion-based power generation, overall emissions would not necessarily decrease. Instead, the remaining generators could opt to use fewer controls such that the total emissions still just meet the cap. An EF-only approach for modeling regulations would not simulate this rebound effect. The CSAPR state-level caps are provided in the SI. The proposed Clean Power Plan is not included in this study.

2.2.3. Electric sector controls—A marginal abatement curve (MAC) characterizes the monotonically increasing marginal cost (e.g., in \$/ton) associated with each incremental reduction in pollutant emissions. In this paper, MACs for electric sector NO_x and SO_2 for existing plants are derived using control characterizations from IPM version 5.13 [1]. Utilization of controls in 2011 is assessed by analyzing the control information within the

2011 NEI, and new control application is allowed only on the uncontrolled fraction of emissions. Details of the MAC calculation and implementation can be found in the SI.

An important feature of this implementation is that it allows the electric sector to respond to policy targets by simultaneously considering the application of additional controls, switching to cleaner fuels, and adopting more efficient technologies for electricity production and to meet end-use energy demands. GCAM also includes demand side responses, including explicit representation of energy efficiency options in the building sector [62] and elasticities that modify end-use energy service demands as a function of price.

2.2.4. Transportation sector fuel economy regulation—The Corporate Average Fuel Economy (CAFE) standard reduces fuel consumption by requiring that new vehicles achieve a specific average fleet efficiency [63]. Light-duty CAFE targets for 2015 through 2040 are obtained from the 2015 Annual Energy Outlook [64] and extrapolated through 2050. The CAFE constraint is applied to each state in the GCAM-USA Policy Base Case. A table of efficiency requirements for the on-road performance of new light-duty vehicles can be found in the SI. Efficiency requirements for medium or heavy-duty vehicles, as outlined by the National Highway Traffic Safety Administration and Environmental Protection Agency [65], are not yet included in the model. These standards would decrease fuel use and thus CO₂ emissions. However, technology-specific air pollutant EFs for medium- and heavy-duty vehicles are tied to distance traveled instead of fuel used. Thus, these standards would likely have only a very minor impact on air pollutant emissions.

2.3. Scenario design

The air pollutant emissions outputs of the GCAM Base Case and the GCAM-USA Policy Base Case are evaluated and compared to the emission inventory from version 6.2 of the 2011 U.S. EPA Emissions Modeling Platform [66]. The focus of these comparisons is on NO_x, SO₂, and primary (directly emitted) PM_{2.5}, which are three air pollutants whose emissions are subject to regulation. NO_x is a precursor to photochemically produced ozone, while NO_x and SO₂ contribute to the atmospheric formation of PM_{2.5}. Both ozone and PM_{2.5} cause damage to human health and sensitive ecosystems.

The 2011 Emissions Modeling Platform, which was used in the analysis of a revised National Ambient Air Quality Standard for Ozone [67], includes county-level, source-specific pollutant emissions for 2011, 2017, and 2025. The 2011 inventory is referred to here as the 2011 Modeling Inventory, or 2011 MI. The 2017 and 2025 projections incorporate CAFE, CSAPR and Tier 3, as well as various industrial NSPSs. Following regulatory convention, emissions in these projection years are referred to as the 2017 and 2025 inventory projections.

The 2011 MI is derived from the 2011 NEI, which is a detailed listing of emission estimates that are submitted to EPA by states. The 2011 MI differs slightly from the NEI by including some modifications to improve consistency from one state to another and to incorporate the impacts of recent legal settlements with emitters. For the electric sector, emissions data for major sources are recorded by continuous emissions monitoring equipment. Other data may

be obtained from industrial air quality permits, derived from models, or developed by multiplying standardized emission factors by economic or other activity data. Much of the inventory is summarized at the county level, although large industrial sources are handled separately as “point” sources.

For the 2017 and 2025 inventory projections, electric sector emissions are estimated using IPM. IPM has more technological and spatial detail than GCAM or GCAM-USA, explicitly representing the fleet of existing coal-fired boilers, emission control technologies, and the electric grid. Industrial emissions are largely held constant, but emissions from some sources are adjusted to account for NSPSs and other factors. On-road transportation emissions are estimated using MOVES. A variety of models and methods are used to produce emission projections for other sources, and the level of sophistication in projection methodology differs considerably by sector [68].

2.4. Evaluation approach

The first step in comparing these inventories and modeling results is the development of a crosswalk mapping the Source Classification Code categories within the inventories to their corresponding GCAM and GCAM-USA emission categories (SI). This crosswalk facilitates comparison of emissions at various spatial and sectoral aggregations. Where there are discrepancies, subsectors can be evaluated to investigate the underlying causes. Sectors compared in this paper include the electric, industrial, combined residential and commercial buildings, and transportation sectors. To evaluate the transportation sector further, emissions are disaggregated into the following subcategories: light-duty vehicles, heavy-duty trucks, and non-highway transportation sources, which include aircraft, shipping, and rail.

Comparisons are made both graphically and via a quantitative QM, which is devised to quantify the agreement between the inventories and modeled results in a single value. The QM is useful in its ability to evaluate and compare performance across pollutants, sectors, and spatial resolutions. Values can provide insights regarding the suitability of the model for various applications. Furthermore, this metric helps identify where additional refinement may be warranted and facilitates examining how various changes to the model or assumptions affect the comparison of its emissions with the inventories.

The QM is the sum of two components, Q1 and Q2 (see Table 1). The first component, Q1, is a linear function of the relative difference between the GCAM-USA emissions at 2010 and the EPA 2011 MI. Q1 ranges between 0 (values differing by more than a specified tolerance, 10%) and 1 (indicating perfect agreement). The second component, Q2, is a function of the difference in slope between 2010 and 2025 (and 2011 and 2025 for the inventories). Q2 is 0 for slope differences greater than a specified tolerance, 20%, and has a maximum value of 1 if the slopes match. Thus, the QM for an emissions category will range from 0 if both tolerances are exceeded to 2 if both absolute magnitudes and slopes agree exactly. To account for the large relative differences that can occur when comparing small absolute quantities, the QM is calculated only for sectors that comprise at least 5% of the total emissions for that species. Pollutant-specific QMs are calculated at the national and sectoral levels for GCAM and GCAM-USA. QMs are also calculated at the state level for

GCAM-USA. The graphical and quality metric results are provided and discussed in the next section.

3. Results

In this section, the results of the GCAM Base Case and GCAM-USA Policy Base Case scenarios are compared to the EPA inventories. The comparison is first carried out at the national and sectoral levels, followed by an assessment of state-level results.

3.1. Evaluation of national-scale results

Fig. 1 shows NO_x and SO_2 emissions from the GCAM Base Case, 2011 MI and projected inventories. Fig. 1a and b depict national totals, while Fig. 1c–f examine sector and subsector emissions. Primary $\text{PM}_{2.5}$ is not output by GCAM, so these comparisons are for NO_x and SO_2 only. Total NO_x from GCAM in 2010 is 27% greater than the 2011 MI, but the fit improves for 2017 and 2025. Total SO_2 emissions in 2010 from GCAM are 74% higher than the 2011 MI, and projected values are higher as well. At the sectoral level, NO_x and SO_2 from EGUs, light- and heavy-duty vehicles are higher in GCAM than the inventory, and substantial discrepancies are evident in the industrial and non-highway sectors. GCAM industrial NO_x emissions are well below the inventory, while industrial SO_2 is higher.

The GCAM-USA Policy Base Case provides a much improved fit with the national-scale inventory for NO_x and SO_2 , as illustrated in Fig. 2. Fig. 2a and c indicate that national-scale NO_x and $\text{PM}_{2.5}$ match the inventories nearly perfectly, and Fig. 2b shows that SO_2 is a much closer fit with the modified GCAM-USA than with GCAM. Fig. 2d–i further evaluate the GCAM-USA Policy Base Case performance at the sectoral level. In 2010, NO_x , SO_2 , and $\text{PM}_{2.5}$ from EGUs and industrial sectors are very similar to the 2011 MI. Industrial NO_x , SO_2 , and $\text{PM}_{2.5}$ are also very similar, although this fit benefits from the application of the state-level adjustment factor to better match the inventory in the base year. In the transportation sector, GCAM-USA Policy Base Case NO_x and SO_2 from light-, heavy-duty, and off-highway vehicles are much closer to the inventory than GCAM, as are the air, marine vessels, and railway subsectors. Sectoral $\text{PM}_{2.5}$ generally agrees well with the 2011 MI. Future-year GCAM-USA Policy Base Case projections differ from the inventory to varying degrees, depending on pollutant and sector. In general, sectoral agreement is best for NO_x . EGU, industrial, and residential and commercial $\text{PM}_{2.5}$ projections diverge from the inventory trends in 2025.

National-scale QM results are shown in Table 2. The GCAM Base Case has QM values of 0 for both NO_x and SO_2 for all emissions sectors, indicating that neither the 2010 values nor the slopes fall within the specified tolerances. For the GCAM-USA Policy Base Case, all sectoral NO_x , SO_2 and $\text{PM}_{2.5}$ categories that make up at least 5% of the inventory fall within the 10% tolerance for 2010. There is greater variability in the fit of the slopes, with some key differences in heavy-duty vehicular NO_x , industrial SO_2 , and $\text{PM}_{2.5}$ from EGUs, heavy-duty vehicles, and the industry sectors. Greater differences farther out in time are to be expected since GCAM and GCAM-USA have not been harmonized to have the same driver data as assumed in the inventory projections, such as population and energy consumption.

EGU QMs for the GCAM-USA Policy Base Case compare well to those of other sectors. Nonetheless, EGU NO_x and SO₂ are slightly higher than the projected inventories, and EGU PM_{2.5} exceeds the projected inventory value by 33% in 2025. Industrial PM_{2.5} is lower than the inventory, while industrial SO₂ is higher. Fig. 3 provides a potential explanation for the EGU results. The overall electricity generation is higher in the GCAM-USA Policy Base Case than in IPM, and much of the additional generation is produced from coal combustion. Discerning the underlying cause of differences in the industrial sector is more difficult since the EPA inventory does not include fuel use estimates. Also, note that the industrial sector representation within GCAM-USA is being revised. The new version, which was not yet available for the work presented here, will differentiate among fuel being used in boilers, process heaters, engines, and other industrial applications in key industrial sectors. As these technologies have very different EFs, the resulting projections should be closer to the more detailed model results for this sector.

3.2. Evaluation of state-level results

State-level QMs for NO_x, SO₂, and PM_{2.5} are depicted in Fig. 4. Also, pollutant- and sector-specific QM values (equivalent to Table 2) for all 50 states are provided in the SI. These values provide a number of insights about the utility of the model for particular purposes. For example, the QMs for NO_x, SO₂, and PM_{2.5} from light-duty vehicles in California are low. Analyses specifically of the response of these outputs to a state-level policy would benefit from additional refinement to correct for the underlying causes of the low QMs. In contrast, California's electric sector SO₂ emissions have a QM of 2.0, suggesting that baseline assumptions and trends of the inventory are captured well for that pollutant.

Note that a high QM does not eliminate the need to assess whether modeled responses to additional stimuli are realistic. For example, in sensitivity runs not presented here, an increase in electric vehicles in California resulted in higher electric sector SO₂ emissions due to increased electricity production from biomass. Such a result should then provoke questions such as "Is this a realistic response, or are there unmodeled considerations that would prevent it?" Thus, QMs inform but do not obviate critical interpretation of modeling results.

QMs can also reveal interesting spatial patterns in the results. For example, EGU QM values are generally higher for the states within the eastern half of the U.S. The factor driving this result is the application of EGU NO_x and SO₂ caps on most eastern states to represent the CSAPR. Thus, total EGU emissions have an upper limit regardless of electricity demand growth projections. The CSAPR-applied states have an average EGU NO_x QM value of 1.7 and an average EGU SO₂ QM value of 1.9, while the rest of the states average only 1.1 for EGU NO_x and 1.0 for EGU SO₂.

While EGU QMs for the non-CSAPR states are typically lower, they are much better than the national QMs from the GCAM Base Case, which are zeros. Thus, even without capped emissions, state-level resolution generally improves emission projection performance. Examining state-level emissions (see the SI), EGU emissions for non-CSAPR states tend to be greater than the inventory. A hypothesis for this result is that there are additional considerations limiting the inventory projections that are not included in GCAM-USA.

Examples include regulations such as New Source Review [69], which limits emissions in nonattainment areas, and the Regional Haze Rule [70], which requires reductions to address visibility.

Differences in the structure and operation of GCAM and GCAM-USA and the models used in projecting future inventories also lead to discrepancies. For example, IPM is an optimization model with foresight of the effect of emission constraints in the future. The technology choices that it makes anticipate these constraints and act to minimize net present value over time. In contrast, GCAM-USA solves each time step sequentially, deciding the best choices at the moment without foresight. The two models may thus take different strategies to meeting emission constraints. Furthermore, GCAM-USA and IPM results indicate very different projections of the quantity of electricity demands in the future. More investigation is necessary to determine why GCAM-USA electricity production is higher and to attribute the difference to specific factors.

When comparing modeled emission projections with projected inventories, it is important to note that there are considerable uncertainties in the projected inventories. Uncertain assumptions include estimates of future population and economic growth, technology development, and how each sector will respond to various policies. Another consideration involves the comparison years. The 2011 MI is being compared with 2010 model results. The time period between 2005 and 2015 is one in which many regulations were being implemented. Thus, calibrating GCAM-USA and evaluating its results for two different years within that period complicates the comparison.

There are a number of additional model enhancements that could improve the ability of GCAM-USA to produce state-level emissions projections. For example, adding technological-, industry- and state-specific resolution to the industrial sector could greatly improve its fuel use and emission projections. Another potential improvement would be to disaggregate energy supplies and demands by season and time of day. Doing so would allow GCAM-USA to more fully capture energy system dynamics. For example, natural gas use increases in the residential sector in the winter as it is used for space heating. In the summer, however, residential gas uses decreases substantially. Instead, natural gas use in the electric sector increases, producing additional electricity that is used within residential heat pumps for space cooling. Capturing dynamics such as these may improve GCAM-USA's simulation of technology and fuel choices. Both of these enhancements are currently under development. Additional areas for improvement include adding representations of state and regional policies that are not currently being captured and improving the representation of electricity transmission capacity and constraints.

4. Conclusions

IAMs with increasingly high levels of technological, spatial, and temporal resolution have enabled estimation of air pollutant emissions for various scenarios of the future. This study demonstrates the use of GCAM and GCAM-USA for this purpose. Relative to the GCAM Base Case, the GCAM-USA Policy Base Case adds state-level resolution to the energy system, emission factor updates, characterization of EGU pollutant controls, and

representations of several air quality and energy regulations. As a result, GCAM-USA produces emission estimates for key air pollutants that are considerably closer to EPA base and future-year emission inventories than what is produced using the base version of the GCAM model. A QM is introduced to assist in evaluating model performance. Based upon its performance, we believe that GCAM-USA is currently able to produce national-scale NO_x , SO_2 , and $\text{PM}_{2.5}$ emissions in a manner generally consistent with the EPA inventory and its projections, with accuracy sufficient for research activities in which the model's limitations are understood.

GCAM-USA has the added benefit of producing state-level air pollutant emission projections. The QM is applied to evaluate state-level performance as well, indicating that there is better consistency with EPA projected inventories in some states than others. For state-level applications, care should be taken to ensure that the model is performing well for the sectors and regions to be assessed. No specific QM threshold is proposed here to be "good enough" to support a particular analysis; however, the ability to quantify how well emissions match the inventory may be useful in facilitating such examinations on a case-by-case basis. The QM results could also be used to help focus efforts to refine the model.

In summary, GCAM-USA is fast and flexible and potentially useful for examining a wide range of future technology, policy, and socio-economic scenarios. Thus, GCAM-USA can support both high-level air quality management decision-making, as well as strategic energy system planning. Furthermore, GCAM-USA could potentially support more detailed air quality modeling activities by producing the future inventories that could be modeled through SMOKE and CMAQ using, for example, the Emission Scenario Projection (ESP) methodology [12,13]. While this analysis is specific to the U.S., the results indicate more generally the importance of considering state-level energy system detail and country- and state-specific air pollutant policies and regulatory constraints. Furthermore, by more closely replicating expected air pollutant emission trajectories for the U.S., GCAM-USA could potentially provide improved support for more typical global-scale IAM applications.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1. GCAM Base Case emissions projections (lines) compared to EPA 2011 emissions modeling inventory and projections (squares). Units are metric tons $\times 1000$.

Fig. 2. GCAM-USA Policy Base Case emissions projections (lines) compared to EPA 2011 emissions modeling inventory and projections (squares). Units are metric tons $\times 1000$.

Fig. 3. U.S. electricity generation from the GCAM Base Case, GCAM-USA Policy Base Case, and the IPM inventory.

Fig. 4. State-level quality metric for NO_x (left), SO_2 (middle) and $\text{PM}_{2.5}$ (right), aggregated across all emission sectors as well as for EGUs, industry, and on-road transportation sources. States where that sector constitutes less than 5% of the emissions are shown in transparent color.

Table 1

Definition of quality metric components, $QM = Q_1 + Q_2$.

$z1=y-xx$	$Q1(z1)=$	$1-z1\beta1$	$0 \quad z1 \quad \beta1$
		0	$z1 \quad \beta1$
$z2=x'-xx-y'-yy$	$Q2(z2)=$	$1-z2\beta2$	$0 \quad z2 \quad \beta2$
		0	$z2 \quad \beta2$

Quality metric components in terms of GCAM-USA modeled emissions at 2010 and 2025 (y and y' , respectively) and inventory values at 2011 and 2025 (x and x' , respectively). Scaling parameters $\beta1$ and $\beta2$ define acceptable tolerances for $Q1$ and $Q2$, and here are chosen as 10% and 20%, respectively.

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Table 2

Comparison between national, annual emissions totals modeled by GCAM-USA Policy Base Case, GCAM Base Case and EPA modeling inventories.

	Percent of Inventory	Difference between GCAM-USA and the Inventory		Difference between GCAM and the Inventory		GCAM-USA Quality Metric	GCAM Quality Metric
		2010	2010–2025 Slope	2010	2010–2025 Slope		
	%	%	%	%	%		
NO_x Total	100%	3%	3%	27%	–117%	1.6	0.0
EGUs	18%	0%	5%	169%	–129%	1.7	0.0
Industrial	18%	0%	1%	–56%	–138%	1.9	0.0
Residential & commercial	5%	0%	8%	38%	–132%	1.6	0.0
Light duty vehicles	23%	1%	4%	77%	–96%	1.7	0.0
Heavy duty vehicles	23%	11%	2%	–25%	–93%	0.9	0.0
Air, marine and rail	13%	–2%	3%	–55%	–125%	1.7	0.0
SO₂, Total	100%	0%	11%	74%	–93%	1.4	0.0
EGUs	80%	0%	6%	85%	–89%	1.7	0.0
Industrial	14%	0%	33%	55%	–114%	1.0	0.0
Residential & commercial	4%	–3%	55%	–36%	–98%		
Light duty vehicles	0%	29%	–3%	350%	–110%		
Heavy duty vehicles	0%	–7%	43%	1136%	–169%		
Air, marine and rail	2%	–2%	5%	–57%	–77%		
PM_{2.5} Total	100%	1%	3%	N/A	N/A	1.8	N/A
EGUs	16%	0%	33%	N/A	N/A	1.0	N/A
Industrial	32%	0%	–14%	N/A	N/A	1.3	N/A
Residential & commercial	33%	0%	10%	N/A	N/A	1.5	N/A
Light duty vehicles	5%	–11%	–5%	N/A	N/A		
Heavy duty vehicles	10%	12%	–2%	N/A	N/A	0.9	N/A
Air, marine and rail	4%	–1%	10%	N/A	N/A		