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Investigating the nexus of climate, energy, water, and land at decision-relevant scales: the Platform for Regional Integrated Modeling and Analysis (PRIMA)

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Abstract The Platform for Regional Integrated Modeling and Analysis (PRIMA) is an innovative modeling system developed at Pacific Northwest National Laboratory (PNNL) to simulate interactions among natural and human systems at scales relevant to regional decision making. PRIMA brings together state-of-the-art models of regional climate, hydrology, agriculture and land use, socioeconomics, and energy systems using a flexible coupling approach. Stakeholder decision support needs underpin the application of the platform to regional issues, and an uncertainty characterization process is used to identify robust decisions. The platform can be customized to inform a variety of complex questions, such as how a policy in one sector might affect the ability to meet climate mitigation targets or adaptation goals in another sector. Current numerical experiments focus on the eastern United States, but the framework is designed to be regionally flexible. This paper provides a high-level overview of PRIMA's functional capabilities and describes some key challenges and opportunities associated with integrated regional modeling.

1 Introduction

Global climate and integrated assessment models typically address large-scale questions, such as the geophysical consequences of greenhouse gas emissions (e.g., global warming and attendant changes in the global hydrological cycle) and the socioeconomic dimensions of climate change (e.g., the consequences of policy assumptions on economic and energy systems). Local to regional climate changes are generally obtained by downscaling global

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climate model (GCM) projections (see, e.g., Giorgi et al. 2001) or simply adding the changes simulated by a GCM to a regional observation baseline (i.e., the "delta method"), while sector-specific models are often used to assess the impacts on particular systems (e.g., water resources, energy production, etc.). Few attempts have been made, however, to include multiple human and natural systems in a single, integrated modeling framework at regional scales. Extant models are thus limited in their ability to resolve important regional feedbacks and interactions—for example, how regional crop prices might be affected by the combined effects of changes in air temperature, fluctuations in water availability, competition for water resources, changes in energy prices, and increasing demand for biofuels.

Hibbard and Janetos (2013) argue that a more integrated approach is needed to understand and evaluate coupled human and environmental systems at regional scales—one that captures the complex dynamics of and feedbacks among regional systems while maintaining consistency with global processes and conditions. They describe a general framework for integrated regional modeling that includes a suite of component models representing different human and natural systems, along with extensive stakeholder involvement to guide model development and ensure that results are relevant to regional decisions. Such a framework would provide more robust assessments of regional vulnerabilities and climate mitigation and adaptation options, especially those that involve energy, land, and water systems, which can interact in complex and unanticipated ways in response to climate change and/or management decisions (Skaggs et al. 2012).

The Platform for Regional Integrated Modeling and Analysis (PRIMA) initiative[1] at Pacific Northwest National Laboratory (PNNL) was initiated with the explicit goal of developing and linking open-source models of human and natural systems at scales relevant to regional decision making. In some cases we were able to build on existing community models, while in others the development of new models was required. Guided by extensive stakeholder research and built by an interdisciplinary team, PRIMA is a unique and powerful framework for assessing the impacts of and potential responses to climate change at regional scales. The following science questions (see Hibbard and Janetos 2013) have underpinned PRIMA's development:

- How do the intrinsic characteristics of a region enhance or constrain its ability to reduce greenhouse gas emissions or adapt to the impacts of climate change?
- How do projected changes in mean climate versus climate extremes affect planning and decision making on regional scales?
- How might interactions between management decisions and natural processes contribute to rapid or nonlinear regional-scale changes?
- How will mitigation and adaptation strategies interact over the next few decades in terms of achieving their respective goals?

The purpose of this paper is to provide a high-level overview of PRIMA. The next section provides an overview of the modeling framework. Section 3 briefly summarizes the capabilities of each component model and the software framework used to couple them, and provides references for those seeking additional details. An extensive stakeholder engagement process —described in Section 4—is used to identify relevant questions for analysis, determine the model components and data exchanges needed to address each question, and implement uncertainty characterization. Our initial numerical experiments are also outlined in this section.

[1] http://prima.pnnl.gov (formerly the integrated Regional Earth System Modeling, or iRESM, initiative)

The final section describes future work and lessons learned during the development of this unique modeling platform.

2 Overview of modeling framework

Figure 1 provides an overview of PRIMA, including the individual component models described in Section 3, the general approach for coupling these models, and the types of information exchanged. Some of PRIMA's key attributes include:

- *Stakeholder engagement*: To ensure relevance to regional decision making, we use stakeholder research to inform both the development and application of PRIMA. This research is used, for example, to identify desired modeling capabilities (e.g., sub-basin scale water availability) as well as the types of alternatives or scenarios (e.g., contrasting a carbon tax with a "business as usual" future) of interest to regional stakeholders—who include members of the scientific community as well as policy and decision makers from the public and private sectors. Section 4 provides further details.
- *Uncertainty characterization*: PRIMA's uncertainty characterization (UC) process is designed to address the fact that changes in climate and related human and natural systems are imperfectly understood and, in many cases, deeply uncertain (Lempert et al. 2004), especially at the level of resolution needed to support regional decision making. PRIMA UC research has yielded two critical insights. The first is that uncertainty arises from

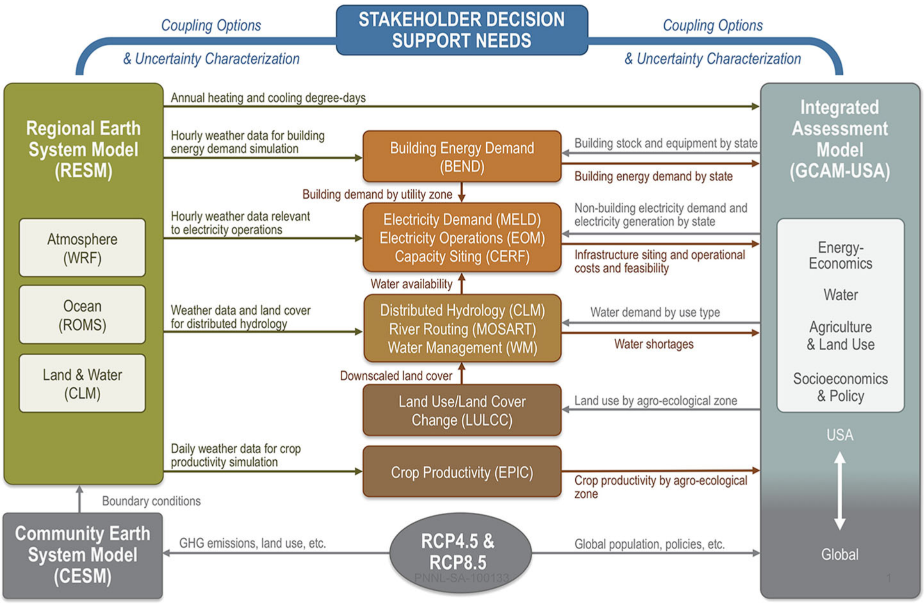

Fig. 1 The Platform for Regional Integrated Modeling and Analysis (PRIMA) includes a Regional Earth System Model (RESM; *left* hand side of figure), an integrated assessment model with enhanced domestic resolution (GCAM-USA; *right* hand side), and a number of individual sector models (*middle boxes*). The platform is flexible, portable, and modular—it can be applied to different questions, to different regions, and using different components. Stakeholder decision support needs are used to select the appropriate model components, information exchanges, and uncertainty characterization approach needed for a particular application of the platform. To ensure consistency of results, all components are ultimately driven by the same global scenario

multiple sources, including the skill and completeness of each component model, uncertainties in the input data used for model calibration or initialization, and "compound" uncertainties that arise when the output from one model is used to drive one or more additional models. The second insight is that it is only necessary to characterize the subset of uncertainties relevant to a particular application of PRIMA, and our stakeholder-driven decision framing process provides the information needed to determine that subset. In other words, rather than trying to characterize all sources of uncertainty across all models and model couplings, our UC process focuses only on the uncertainties relevant to a particular stakeholder decision.

- *Flexible coupling approach*: For most applications of PRIMA, only some of the component models will be needed, and only some of their outputs will be relevant to the problem being addressed. Moreover, the spatial and temporal resolution and uncertainty characterization approach needed to inform each stakeholder decision will vary. A flexible software architecture, described in Section 3.6, has been developed to facilitate model coupling and implement our numerical experiments.
- *Consistency with global boundary conditions*: PRIMA's regional Earth system model is driven by boundary conditions provided by a GCM, such as the Community Earth System Model (CESM),[2] that has been forced by a global emissions scenario or Representative Concentration Pathway (RCP; see van Vuuren et al. 2011). The regionalized integrated assessment model is run using global energy, land use, and socioeconomic conditions consistent with the same RCP. The sector models then "inherit" these boundary conditions, ensuring that their outputs reflect a consistent set of assumptions about the future state of the world (see Fig. 1).
- *Portable and modular*: PRIMA can be applied to any region in the world, as long as appropriate data can be obtained to parameterize, initialize, and evaluate the relevant component models—which is not an insignificant challenge in regions where accurate, publicly available data on key systems may be lacking. The platform also is modular in that any component can be replaced by a different representation of the same system—for example, several of our initial applications were conducted using statistically downscaled climate information from different GCMs. Additional model components can also be added.
- *Open source*: To facilitate use by both the research and decision making communities, each component of the PRIMA framework was developed from an existing community model or built specifically for the PRIMA initiative using an open-source approach.

3 PRIMA capabilities

3.1 Regional climate

Since the late 1980s, regional climate models have been used to study regional climate processes and provide dynamical downscaling of global climate projections (e.g., Giorgi et al. 1990). To provide a state-of-the-art regional climate modeling capability for PRIMA, we developed a regional earth system model (RESM) by using the CESM flux coupler to link the Weather Research and Forecasting (WRF) model,[3] a widely used community mesoscale

[2] http://www.cesm.ucar.edu/
[3] http://www.wrf-model.org/index.php

atmospheric model, with the Community Land Model (CLM)[4] and the Regional Ocean Modeling System (ROMS).[5] Integrating ROMS with WRF allows air-sea interactions to be represented at regional scale, which is important for simulating regional climate variability in regions such as the southwestern U.S., where moisture flux from the Gulf of California feeds the North American monsoon. Similarly, CLM provides RESM with a detailed representation of land surface biophysics and soil hydrology, including groundwater. RESM also takes advantage of other CESM software infrastructure, such as scripts to build and run on different computing platforms, which will facilitate the addition of other Earth system components in the future. When used as a dynamical downscaling tool, RESM can accept boundary conditions from any GCM, similar to the WRF simulations performed for the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al. 2013).

Ke et al. (2012) reports on RESM land-atmosphere coupling results over the western United States. To support PRIMA's initial numerical experiments (described in Section 4), we have applied RESM over the conterminous United States at 20 km resolution using large-scale conditions from CESM, including a historical simulation and two future climate projections following the RCP4.5 and RCP8.5 scenarios. The resulting regional climate change projections are being used to drive other models in the PRIMA framework (see Fig. 1). RESM results are also being evaluated by comparing them with CESM simulations and with observations to assess the importance of dynamic downscaling, especially for resolving extreme events such as heat waves, floods, and droughts. For example, Fig. 2 shows a comparison of cold and warm season 95th percentile daily precipitation from observations and CESM and RESM simulations for 1975–2004.

3.2 Regional hydrology

Water is a critical factor for many natural and human systems, from ecosystems to agriculture to energy production. While there are many models capable of representing different hydrologic processes, a key challenge facing the community is developing models that can address the multi-scale characteristics of the water cycle and integrate both human and natural processes (DOE 2013). In addition, the PRIMA initiative's goals, particularly the ability to represent interactions among energy, land, and other human and natural systems at regional scales, demand a more comprehensive and detailed treatment of hydrologic processes than available community tools could provide. To meet these challenges, we developed a scalable approach for hydrologic modeling based on CLM. This approach includes several new features and components.

- To improve model scalability, we developed a subbasin-based extension of CLM, called SCLM (Li et al. 2011). The computational units in SCLM are subbasins with boundaries defined by topography, rather than the quasi-rectangular grids typically used in land surface models. This allows for more explicit treatment of subgrid topographical heterogeneity and eliminates the need to include lateral water fluxes across computational units. SCLM noticeably improves scalability when simulating runoff in topographically diverse regions such as the Columbia River basin (Tesfa et al., publication forthcoming).
- A new scalable river routing model, the MOdel for Scale Adaptive River Transport, or MOSART, has been developed for both grid- and subbasin-based representations of CLM. MOSART is a physically based model with scale-consistent channel routing. A

[4] http://www.cgd.ucar.edu/tss/clm/
[5] http://myroms.org

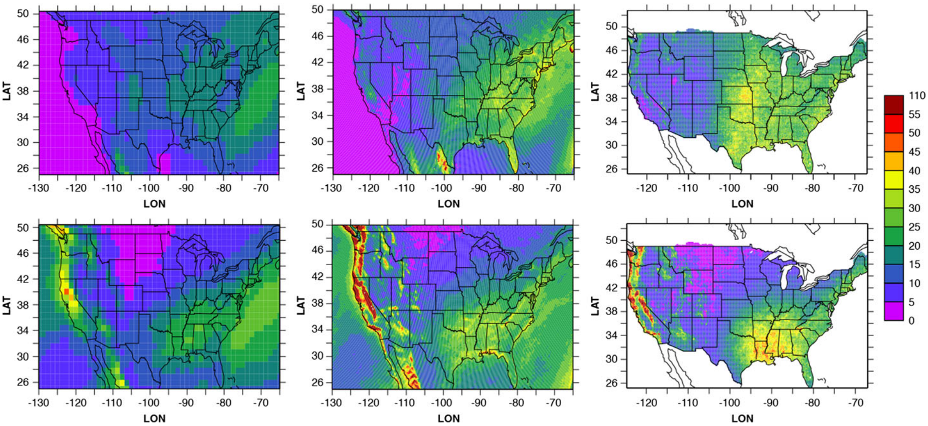

Fig. 2 95th percentile daily precipitation (in mm/day) over the U.S. for 1975–2004 in the CESM historical simulation (*left*), RESM driven with CESM (*middle*), and a 1/8° resolution observational dataset (*right*) for winter (December-January-February, *upper row*) and summer (June-July-August, *lower row*). The RESM simulation, with 20 km horizontal resolution, better captured the observed heavy precipitation than CESM, which is at T85 (~150 km) resolution, not only over the complex terrain of the western U.S. during winter, but also over the central to eastern U.S. during both seasons. The observational dataset was downloaded from the University of Washington Surface Hydrology Group. http://www.hydro.washington.edu/SurfaceWaterGroup/Data/web_grid.html

comparison of MOSART with CLM's default River Transport Model (RTM), which is a linear reservoir routing model with a prescribed constant channel velocity, shows that MOSART has much higher skill across a range of model resolutions (Li et al. 2013). MOSART also provides a framework that allows human influences, such as dams, reservoirs, and in-channel biogeochemistry, to be incorporated more easily into future model versions.

- Finally, we developed a new water resource management model, called WM, for both grid- and subbasin-based representations of CLM. WM uses generic reservoir operating rules and includes modules for water extraction from reservoirs and local surface water sources. Water demand at each grid or subbasin is distributed across reservoirs based on elevation constraints, capacity, and a distance-based buffer. WM has been coupled with MOSART and demonstrated to effectively simulate regulated flow and reservoir storage over the Columbia River basin (Voisin et al. 2013a). SCLM, MOSART, WM, and the water demand sector in PRIMA's integrated assessment model have also been linked and tested over the upper Midwest (Voisin et al. 2013b).

3.3 Regionalized integrated assessment

Integrated assessment modeling, in the context of climate change, is a form of analysis where relevant human systems—including the economy, energy, and land use—are brought into the same computational framework as natural systems. Integrated assessment models, or IAMs, have been used to study a range of global-scale processes and interactions. For example, they historically have been the basis for developing scenarios of future greenhouse gas emissions and global climate forcing. In order to represent so many different systems in the same framework, however, IAMs are forced to make certain tradeoffs, such as using reduced-form representations of complex processes, dividing the world into a relatively small number of large geographic areas, and using a comparatively large time step of years or even decades.

To provide a bridge between IAMs and the detailed sector models in the PRIMA framework, which typically require much greater spatial and temporal resolution, we developed a regionalized version of the Global Change Assessment Model (GCAM). GCAM, which is now a community model,[6] is a partial equilibrium global IAM developed primarily at PNNL over the past 25 years. The standard version of GCAM divides the world into 14 economic areas, with the United States treated as a single unit. We developed a sub-national version of GCAM, known as GCAM-USA, that retains the global capabilities of GCAM for regions outside of the United States while providing additional domestic resolution of energy, water, and land systems. For example, GCAM-USA can project state-level changes in building energy demands (Zhou et al. 2014) and electricity generation mix (Patel et al., publication forthcoming). As noted in the preceding subsection, the water demand module in GCAM-USA has also been linked with PRIMA's water sector models (Voisin et al. 2013b), and the next subsection describes how it is being linked with higher-resolution land systems.

3.4 Regional crop productivity and land use/land cover change

PRIMA simulates regional agricultural systems by combining the capabilities of a high-resolution crop productivity model with GCAM's agriculture and land use (AgLU) component, which simulates the supply and demand of agricultural crops on a worldwide basis. The high-resolution cropping model we selected is the Environmental Policy and Integrated Climate (EPIC)[7] model, applied using the Spatially Explicit Integrated Modeling Framework (Zhang et al. 2010). EPIC is a comprehensive, process-based agro-terrestrial ecosystem model that simulates how climate change and different agricultural technologies and management strategies affect crop yields. For PRIMA, EPIC is used to generate regional crop yield estimates for multiple climate mitigation practices, including no-tillage agriculture and bioenergy crops. These results then are used to parameterize the AgLU component in GCAM-USA, which projects corresponding changes in crop prices, land use, and agricultural greenhouse gas emissions. This combined capability can be used to project, for example, changes in the adoption of different technologies for corn production in a particular state over time (Thomson et al. 2014).

To downscale the economically constrained state-level projections of future land use produced by GCAM-USA, we developed a spatially explicit Land Use and Land Cover Change (LULCC) module (West et al., publication forthcoming). The LULCC module generates spatially explicit, dynamically linked projections of future land use and land cover change across the PRIMA framework. In this version of the LULCC module, land areas per land cover type from GCAM-USA are reconciled with MODIS Plant Functional Type land class areas for each region, thereby generating a gridded land cover realization that is consistent with total land class areas from GCAM-USA (Fig. 3). The gridded representations of future land cover provided by LULCC will be used by PRIMA's regional climate and hydrologic models to evaluate how surface fluxes and water supply and demand respond to simultaneous changes in climate and land cover. An additional, long-term goal for the LULCC module is to improve representations of economic and biophysical feedbacks in other land use assessment models.

3.5 Regional electricity infrastructure

The Regional Electricity Infrastructure Framework (REIF) is a new, open-source suite of models that address critical gaps in integrated planning tools for electricity infrastructure

[6] http://www.globalchange.umd.edu/models/gcam/

[7] http://epicapex.tamu.edu/epic/

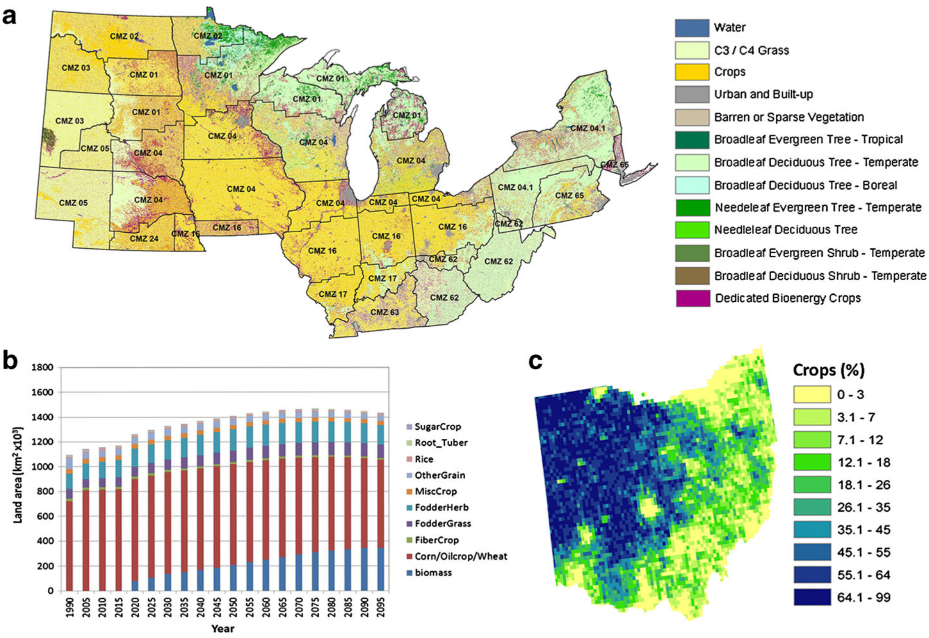

Fig. 3 Example of how the Land Use/Land Cover Change (LULCC) module downscales GCAM-USA land use projections to geospatially explicit land cover that can be used in regional Earth system models. GCAM simulates changes in land classes and respective land class areas in subregions delineated by a combination of state boundaries and USDA Crop Management Zones (*dark lines* in panel **a**). Panel (**b**) shows aggregated results across the 14-state region in panel (**a**) for ten broad land class categories in the GCAM reference scenario, which represents an approximate 7.5 W m^{-2} end-of-century climate forcing. These land class projections are downscaled to 500 m resolution (*colors* in panel **a**) based on MODIS Plant Functional Type land cover data and climate regions, and then processed to represent percentage land classes at 0.05° resolution (panel **c**, which shows percentage of cropland in Ohio)

development. One of these gaps is the ability to simultaneously address energy policy, demographics, load forecasting, land use, and environmental regulations in the context of evolving natural systems, especially climate, that affect energy supply and demand. Another gap in electricity infrastructure planning tools is the ability to bridge a broad range of time and space scales. For example, capacity expansion planning models typically use 30–50 years time horizons—consistent with asset lifetimes and planning lead time—while operational tools for ensuring the safety and reliability of the electric grid typically require hourly or sub-hourly resolution. Bridging these scales is increasingly important due to several, interacting factors: increasing electrification, which places new demands on aging infrastructure; the growing penetration of weather-dependent renewable resources (e.g., wind power), which may complicate grid operations; and climate trends, such as more severe heat waves, which result in demand spikes, often at the same time that supply is compromised (e.g., due to reduced winds and/or lack of cooling water), thereby reducing reserve margins and system reliability.

REIF addresses these issues by integrating climate-dependent electricity supply, demand, and operations models and coupling these with the PRIMA component models that simulate climate, water availability, and state-level trends in electricity supply and demand. REIF's primary role within PRIMA is to explore the technical and economic feasibility of GCAM-USA's projected electric sector expansion. REIF capabilities are also being used in other projects to explore, for example, the vulnerability of electricity infrastructure to changes in extreme events such as heat waves and droughts.

REIF includes four components:

- The Building ENergy Demand, or BEND, model simulates climate-dependent hourly building energy (electricity, oil, and natural gas) demands at resolution as fine as 1/8° and with the ability to aggregate up to any geographic area, including counties, states, electric utility zones, or census regions (Dirks et al., publication forthcoming). We developed BEND by combining the U.S. Department of Energy's EnergyPlus™ model[8] of individual building energy use with a geostatistical analysis of regional climate, population, building types, and building technologies (e.g., building envelope, heating and air conditioning systems, and plug loads). To date, BEND is the only comprehensive building model that simulates the thermal response of building stock at regional scales on an hourly basis—information that is critical for informing regional electricity infrastructure investments—while also accounting for how population shifts, technology changeover, energy efficiency standards, climate change, and other long-term trends will effect building energy consumption. BEND's results provide a higher temporal, spatial, and technological resolution of building energy demand than integrated assessment models such as GCAM-USA, and its projections of climate-sensitive hourly electricity demands are key inputs to REIF's operations and siting models, as described below.
- The Model of ELectricity Demand, or MELD, generates weather-dependent hourly electricity demand profiles for each utility zone based on building electricity demands from BEND and annual industrial and service demands (including electric transportation) from GCAM-USA. The electricity demand profiles generated by MELD reflect the impact of hourly weather at a user-specified spatial scale, as well as the broader-scale impacts of energy policy, technology change, and population growth represented in GCAM-USA. MELD is also capable of representing demand response programs, such as those enabled by smart grid technologies that allow customers to shift loads (e.g., electric vehicle charging) to off-peak hours or curtail some services in exchange for financial rewards.
- The Capacity Expansion Regional Feasibility (CERF) model simulates the geographic placement of power plants based on technical and economic considerations (Rice et al., publication forthcoming). CERF combines geographic information system (GIS) information on existing infrastructure, terrain, environmental policy, and natural resource availability; technology-specific siting suitability criteria; and geospatial economic analyses of grid interconnection costs and locational marginal prices (which are provided by EOM, described next). CERF's primary role within REIF is to downscale the GCAM-USA state-level electric expansion and determine specific locations for new power plants within utility zones. CERF is also integrated with PRIMA's subbasin-scale regional water modeling capability to address the impact of water availability on power plant siting.
- The Electricity Operations Model, or EOM, simulates the hourly operation of the electric grid at the zonal scale using the demand profiles generated by MELD and the zonal distribution of power plant resources generated by CERF (Kintner-Meyer et al., publication forthcoming).[9] The main function of EOM is to test the operational feasibility of the electricity system given a set of capacity additions from GCAM-USA and CERF,

[8] http://apps1.eere.energy.gov/buildings/energyplus

[9] For our initial numerical experiments with PRIMA, while we were developing the open-source EOM, we used a commercially available production cost model (PROMOD) that is widely used in the grid planning and utility communities. EOM has been validated and tested against PROMOD.

regionally distributed electricity demands from MELD, and environmental constraints. EOM is being linked with PRIMA's regional hydrology modeling capabilities to explore the impact of changing water resources on electricity operations and with RESM to address the impact of other climate-related factors, such as changes in heat wave frequency and intensity, on electricity operations. In addition, EOM produces locational marginal prices for each zone that indicate the economic value of additional generation within or transmission to each zone—information that is used by the CERF model to evaluate placement options for new power plants.

3.6 Software architecture

PRIMA's component models represent a broad range of scientific domains, resolutions, modeling approaches, and computational demands, which is not surprising given the disparate origins of each model. Coupling such a diverse suite of models presents a range of scientific, computational, and data challenges, including:

- Defining scientifically relevant data exchanges and feedbacks between models, including procedures to handle overlapping processes consistently across models;
- Providing a flexible framework for implementing data exchanges that can accommodate the inclusion of different models or different model coupling strategies, depending on the scientific question being addressed;
- Handling significant variability in spatial and temporal scales, programming languages, implementation approaches, computational requirements, etc.;
- Optimizing the operation of the component models and data exchanges for maximum efficiency and stability across multiple computational platforms and within existing computing allocations;
- Enabling large scale ensemble and UC calculation set up and execution; and
- Managing different data formats, structures, and variable names, as well as semantic differences between the different scientific domains involved.

To meet these challenges, we developed a flexible software infrastructure that is based on two main components: 1) the MeDICi Integration Framework (MIF) workflow system and 2) the "Velo" data management and analysis environment, both of which were developed at PNNL (Gorton et al. 2012). MIF is a computational workflow system specifically developed for data-intensive applications. MIF is able to flexibly couple different model components, including the required data transformations, analyses, and exchanges. Velo adds a collaborative data management and analysis environment where scientists can manage, share, and execute models, scripts, data, and workflows through easy-to-use interfaces. Velo also includes a comprehensive provenance system that enhances reproducibility and accountability by capturing critical information about each numerical experiment as it is conducted (e.g., models included, configuration details, data used for initialization and/or boundary conditions, output data location and format, etc.). The combination of Velo and MIF represents a comprehensive integration framework with capabilities, such as facilitating uncertainty characterization and propagation, that extend beyond a conventional workflow management system.

4 Application to regional decision making

4.1 Stakeholder decision support research

As indicated in Section 2, PRIMA's stakeholder research is used to guide model and platform development, inform experimental design, and provide context for the characterization and propagation of uncertainties. Incorporating stakeholder input into a model development and demonstration process has presented a variety of challenges that are themselves a rich research subject (Rice et al. 2012). PRIMA's stakeholder research has used structured stakeholder interactions (e.g., formal interviews) and literature reviews to develop a typology of regional mitigation and adaptation decisions (Moss et al., publication forthcoming). The typology captures commonly cited adaptation and mitigation issues within a region and links different types of stakeholders with different decisions, decision criteria, and decision processes. In this context, "decision criteria" refer to the metrics a decision maker might use to compare alternatives (e.g., net cost), while "decision process" refers to the sequence of steps that a decision maker goes through to collect and analyze information, select a course of action, and monitor results. Decision processes can range from individual deliberations to large consultative processes by legislative bodies.

As an example of how stakeholder decision support research has guided the development of PRIMA, our typology indicated that the penetration of wind generation and its associated transmission needs are key issues in the U.S. Midwest, so we made sure REIF could assess the interconnection costs of new generation resources and that we could explore the implications of an evolving generation technology mix by coupling REIF with GCAM-USA. In another example, our research indicates that some regional investment cooperatives are considering building additional bioenergy facilities, and that capital cost, plant efficiency, climate change/ policy impacts on feedstock prices and supplies, and electricity prices are among the key decision criteria. These criteria indicate that coupling RESM to GCAM-USA would be the minimum model configuration needed to provide relevant simulation outputs. The need for additional coupling with PRIMA sector models (e.g., to address water availability for power plant cooling) is currently being determined through additional stakeholder interactions.

4.2 Uncertainty characterization

The PRIMA UC process (Unwin et al. 2011) differs from traditional, single model-based uncertainty quantification techniques in that it uses stakeholder decision support needs to reduce the otherwise potentially overwhelming dimensionality of uncertainties that propagate across a multi-model framework. These uncertainties arise not only from each model's parameterizations, exogenous factors, skill, and completeness, but also from the data transformations needed to exchange information between two or more component models. Rather than attempt to characterize all of the uncertainties across the PRIMA framework, we use our stakeholder research to determine the subset of component models, and model outputs, needed to address a particular decision. Efficient deterministic sensitivity analysis techniques, such as fractional factorial analysis, are then used to identify the uncertainties with the largest impact on the relevant model outputs. It is only at this point in the process that we apply traditional Monte Carlo techniques for uncertainty propagation, and again, we only apply them for the key sources of uncertainty that have been identified. The PRIMA UC process is therefore tailored to the decision at hand and is designed to focus computational and analytical effort on the most relevant sources of uncertainty.

We have demonstrated the application of our UC process to a general policy decision of whether aggressive building standards should be required across the United States, with building energy service costs as the decision criteria (Scott et al. 2014). Using this decision framing, we found that GCAM-USA coupled to state-level climate information (from RESM or another source) was the minimum PRIMA configuration needed to reflect the impacts of a changing climate on the dynamics of energy demand. The next step was to identify the key drivers of uncertainty in building energy service costs and perform a fractional factorial analysis to highlight the most important uncertainties. Based on these results, we included the following uncertainties in a Monte Carlo analysis: future carbon emissions, choice of global climate model, future population change and GDP per capita at the state level, and building shell and technology cost and performance. Figure 4 shows an example of the results comparing building energy service costs under current versus aggressive building standards in residential buildings for a single U.S. state (Michigan).

4.3 PRIMA demonstration activities

Initial numerical experiments with PRIMA, which are documented in the references cited in Section 3, focused on testing and validating the model components in isolation and linking them with either GCAM-USA or with climate data provided by RESM or another source (including observations). Current activities focus on demonstrating full PRIMA framework coupling by linking multiple models to address complex stakeholder-driven questions, with the eastern United States as the focus of analysis.

In keeping with PRIMA's decision-focused design, regional stakeholder groups from the energy, agriculture, and water sectors are providing input regarding the types of scenarios and outputs that would be most useful for their decision making. These groups have expressed a particular interest in PRIMA's ability to explore integrated energy-water-land impacts at various scales and under different climate change/climate policy scenarios. For example, an entity responsible for evaluating regional transmission development options across the Eastern Interconnection—one of three electrical reliability regions in the United States—is interested in the PRIMA demonstration because they recently completed a study of transmission expansion alternatives under different policy futures that did not include the impact of climate or water availability on either costs or feasibility.

Based on this type of stakeholder input, the ongoing PRIMA demonstration project will include numerical experiments based on the RCP4.5 and RCP8.5 scenarios and will focus on the following simulation outputs from the PRIMA component models:

- Greenhouse gas emissions
- Electricity loads
- Energy prices
- Electricity generation technology mix (including market penetration of biofuels)
- Water availability for various uses (e.g., power plant siting, agriculture)
- Electric system reliability and generation costs
- Grid interconnection needs
- Crop yields and prices (including biofuel crops)
- Land use conflicts between food and fuel crops

The demonstration project will include regular interactions with stakeholder groups to review the specific design of the numerical experiments and review model outputs as they become available.

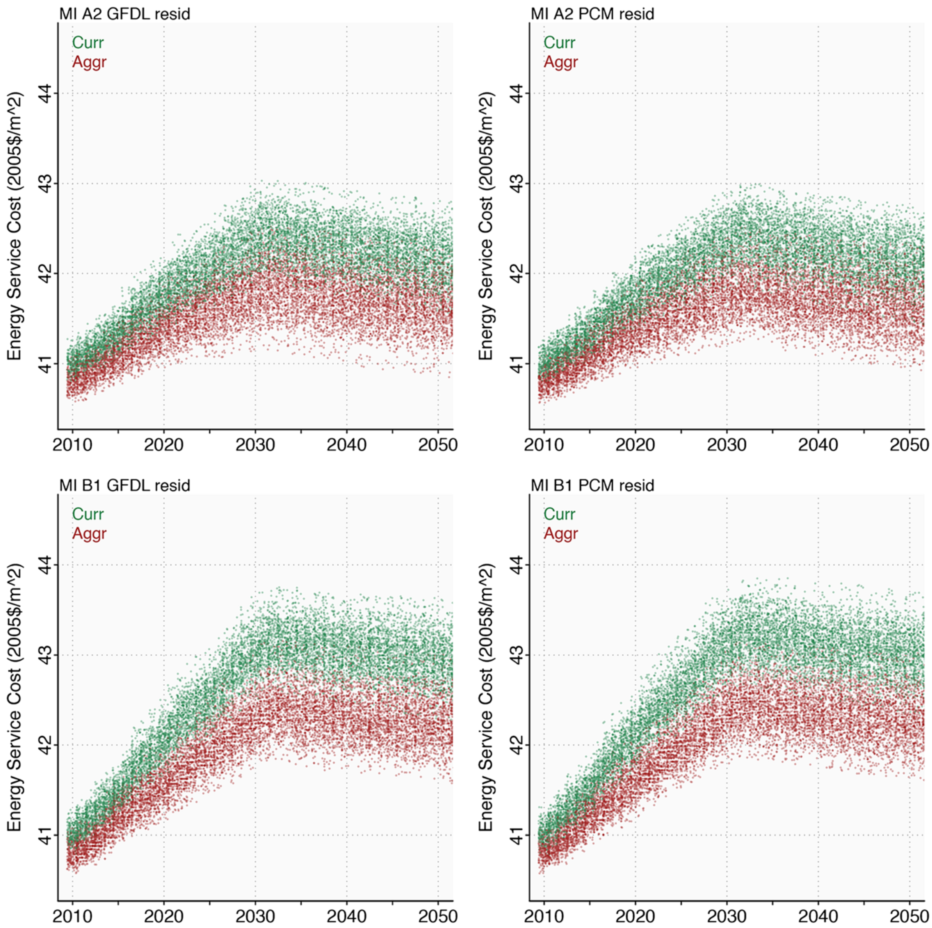

Fig. 4 Sample results of uncertainty propagation in GCAM-USA for energy service cost per unit of residential floorspace in a specific state (Michigan) during the 21st century—part of the uncertainty characterization (UC) experiment described in the text (Scott et al. 2014). The results were derived from 12,000 paired runs (aggressive and current building standards; *red* and *green dots*, respectively) of GCAM-USA with time-evolving uncertainties in population, wealth per capita, and cost and performance of building and equipment technologies, in the context of two different carbon emissions pathways (IPCC A2 and B1 scenarios, *top row* and *bottom row*, respectively) and two different climate models (GFDL and PCM, *left column* and *right column*, respectively). These results indicate that despite significant uncertainty in future population growth, wealth, and technological performance, aggressive building standards are projected to cost building owners less than current standards per unit of floorspace on average and across the majority of cases across all four of the emissions scenarios and climate model combinations considered

PRIMA also is being applied and extended through a separate project, “Development of a Regional Integrated Assessment Modeling Framework,”[10] or RIAM, that focuses on vulnerability and adaptation to climate change in the energy sector across the southeastern United States. The RIAM project has supported the development of the GCAM-USA 50-state electricity model (Patel et al., publication forthcoming), the Electricity Operations Model

10 http://climatemodeling.science.energy.gov/projects/developing-regional-integrated-assessment-model-framework

(Kintner-Meyer et al., publication forthcoming), the RESM RCP8.5 scenario, and their application to assess the vulnerability of the electricity sector—both current and future—to changes in the frequency of heat waves and droughts across the Eastern Interconnection (Rice et al., publication forthcoming). Additional capabilities being cultivated under this project include a high-resolution coastal storm surge model for the Gulf of Mexico (Yang et al. 2013) and, working in collaboration with Oak Ridge National Laboratory, a detailed exposure and impact models for extreme events—especially hurricanes—on current and projected energy infrastructure across the southeast (Preston et al., publication forthcoming). The project also includes experiments aimed at understanding the importance of resolving different regional-scale processes in an integrated modeling context—that is, establishing when integrated regional modeling is needed to assess climate change impacts and responses.

5 Lessons learned and future work

The PRIMA experience has inspired researchers from the engineering, social science, and Earth system modeling communities to work together towards a common goal—the development of a framework that enables better understanding of the options available to regional decision makers in the context of climate-energy-land-water interactions. We view this topic as one of the most important challenges facing our nation, and the world, and our ability to work across disciplines to address it is surely the biggest success of the PRIMA initiative to date. As with many interdisciplinary efforts, it was critical to overcome conflicting lexicons and domain preferences, such as data formats, and to find ways to bridge disciplinary divides, such as understanding which kinds of climate information are needed to inform different aspects of the modeling framework. Another, more technical challenge was developing the data transformations needed to bridge temporal scales ranging from 15 s to multiple decades and spatial scales ranging from tens of meters to watershed basins to 20-km fixed grids, as well as integrating geospatially-resolved component models with those that are not. From a scientific perspective, one of the key insights that our team has arrived at is that the definition of "regional modeling", and hence the domain of analysis and the resolution of the models required, varies depending on the question being asked—for electricity infrastructure planning, for example, utility zones or Interconnections are often the regions of greatest interest.

One of our top future priorities is representing the carbon cycle and other biogeochemical processes consistently across the platform. Several of the component models (e.g., CLM and EPIC) already include representations of biochemistry, but these need to be reconciled and resolved. We also recognize that PRIMA does not yet include high-resolution representations of some important components of the energy system (e.g., transportation, electricity distribution), ecosystem dynamics (e.g., biodiversity, invasive species), or aspects of human behavioral decision making, to name just a few systems with important regional-scale interactions. We also hope to apply PRIMA to other regions. While some of the biophysical models are already applicable globally (e.g., RESM, CLM, and MOSART), extending some of the detailed sector models outside the United States could be challenging due to data limitations. Finally, our research into stakeholder decision processes and uncertainty characterization across an integrated modeling platform has yielded insights into the information needs of different decision making communities. Future work stemming from this research may include the development of simplified surrogate models for selected PRIMA components for the purposes of computationally efficient uncertainty propagation and/or the development of advanced visualization tools to facilitate stakeholder engagement and enable scientific analysis of integrated modeling results.

In summary, we see an increasing need for understanding human-environment interactions and their uncertainties at regional scale to support decision making, and we think integrated regional modeling frameworks such as PRIMA can play a key role. The engagement of a wide range of experts, the development of more integrated and regionally-specific data sets, and the establishment of real interactions and feedbacks between the stakeholder and modeling communities will all be needed for successful implementation of this new class of modeling.

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