Capabilities and Gaps in Integrated Human-Earth System Modeling at the Energy-Water-Land Nexus: Workshop Report

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Abstract:

What is the state of science for coupling models of human and environmental systems to study co-evolving infrastructure, socioeconomic, and Earth systems, and how can progress in integrating these models be accelerated? In July of 2016, a workshop on "Capabilities and Gaps in Integrated Human-Earth System Modeling at the Energy-Water-Land Nexus" was held in Snowmass, CO to explore these questions and improve scientific collaboration across relevant research communities. This workshop brought together researchers from a variety of scientific communities to discuss requirements and methods for *coupling models from different domains*, including climate science, integrated assessment, and impacts, adaptation, and vulnerability analysis. This workshop is one of a series of annual events sponsored by the U.S. Department of Energy (DOE)'s Integrated Assessment Research Program; this particular event was co-planned with the Earth System Modeling Program and members of that research community. This workshop built on results and questions developed in a prior workshop on opportunities and challenges for developing a multi-model framework to explore the systems dynamics of coupled infrastructure, socioeconomic, and environmental systems. The workshop started by examining research questions and societal issues that could not be addressed within any one modeling tradition but instead required coupling of diverse models. Three subsequent sessions explored the perspectives of three modeling communities—impacts adaptation, vulnerability; integrated assessment; and climate/Earth system. These sessions identified information and methods that each modeling community needed and/or could contribute to more integrated modeling/analysis, as well as information required from the other types of models, raising issues such as definitional differences, spatio-temporal resolution, tradeoffs between complexity and tractability, and other methodological concerns that needed to be addressed to facilitate coupling. A set of breakout groups provided an opportunity for participants to plan approaches to coupling models from the three communities to address specific use-inspired research questions related to energy systems, water resources, and land. A final set of discussions synthesized results from the previous sessions and included a panel discussion of coupling IAV models, IAMs, and ESMs. Over the course of the workshop, participants identified numerous challenges, new potential research ideas, and opportunities for community building.

1. Background and Introduction

The human and Earth systems are intricately linked, with human decisions influencing the evolution of the Earth and vice versa. However, these systems have historically been treated separately in research, analysis, and models. In recent years, researchers have identified the need to treat these systems simultaneously, including the interactions between the systems [*Hallegatte and Mach*, 2016; *Palmer and Smith*, 2014]. Several questions have emerged, including:

- What are the major interactions and feedbacks between human and Earth systems, and which ones are most important to represent?
- What are the most effective methods for integrating models to study different problems (e.g., what types of model coupling are appropriate for different system interactions)?
- What is the appropriate spatial and temporal resolution for different scientific questions? How do we handle differences in spatial and temporal resolution between models?

Ongoing interest in this topic has led to a series of workshops and meetings aimed at bringing together researchers from the various communities. For example, a 2015 summer workshop, hosted by the Stanford Energy Modeling Forum, focused on integrated impacts and scenarios and included researchers from the Integrated Assessment Modeling (IAM), climate science, and Impacts, Adaptation, and Vulnerability (IAV) communities [*EMF*, 2015]. A separate, side-meeting held during that workshop included both scientific researchers and program managers from various U.S. government agencies to discuss "Multi-sector IAV and IA-IAV Dynamic Modeling: Needs, Capabilities, and Gaps." A follow-on meeting, held in May of 2015, continued these discussions, identifying challenges and gaps in coupled modeling and analysis of interdependent energy, land, and water systems [*Moss et al.*, 2016].

The workshop on "Capabilities and Gaps in Integrated Human-Earth System Modeling at the Energy-Water-Land Nexus" is part of this series of meetings to discuss human-Earth system modeling. The workshop was held in Snowmass, CO from July 25, 2016 to July 29, 2016 as part of the Stanford Energy Modeling Forum's Climate Change Impacts and Integrated Assessment annual meeting. The overarching goal of the workshop was to explore opportunities for addressing emerging science issues associated with coupled human-environment systems affected by multiple stresses. The workshop focused on *coupling and complexity* among Earth System Models (ESMs), Integrated Assessment Models (IAMs), and Impacts, Adaptation, and Vulnerability (IAV) models, with respect to issues surrounding the energy-water-land-climate nexus. The workshop included 36 participants from nine countries with a variety of expertise and experience, including different modeling domains (e.g., climate, integrated assessment, impacts, adaptation, and vulnerability) and different sectoral domains (e.g., energy systems, hydrology, agriculture and land use). The workshop built upon previous Snowmass sessions that focused on integrating research across the IAM, IAV, and ESM communities as well as recent, related workshops sponsored by DOE to examine multi-model frameworks and a community of practice aimed at exploring dynamics and resilience in complex interdependent systems (see [*Moss et al.*, 2016]) and improved Earth system simulation.

This report summarizes and synthesizes the discussions at the workshop. Section 2 describes cross-cutting themes that motivated the workshop, particularly with respect to challenges, research opportunities, and suggestions for community building. Section 3 briefly summarizes each individual talk, as well as the break-out group discussions. Section 4 provides some conclusions.

2. Cross-Cutting Themes

2.1. Challenges Identified

Integrated models and analyses are built from major components representing key systems and their interdependencies. The evolution of models typically follows paths aligned with their major intended uses and user communities. Oftentimes this evolution seeks to enhance relevance and utility for the intended users while attempting to simplify less-central dimensions and to reduce unnecessary computational burdens. Increasingly, models (and analyses) are being called upon to explore complex issues and scientific questions at the boundaries of different uses and topics, oftentimes involving integrative capabilities with corresponding systems interdependencies. The resulting scientific challenges, bridging these various modeling domains, raise salient questions on how to involve and, as required, connect all or parts of different classes of models. In cases where feedbacks are strong and iterative, structural connections may need to be built between models, thereby creating a different, more integrative class of model within an agile modeling framework. In other cases, simulations or analyses may be facilitated through a single, or limited set, of information exchanges between the models and these may be simply handled through operator-facilitated input-output exchanges. In the latter case, no such structural connections are required as the two distinct models are merely made to "cooperate". Challenges associated with such convergence of models and cross-cutting topics were a major topic of this Snowmass workshop. Participants identified several challenges throughout the week. These challenges fall into five major categories: (1) terminology, (2) approach, (3) coupling, (4) data, and (5) validation and uncertainty characterization.

Terminology

One of the biggest challenges was that of terminology and lexicon. For example, the word "couple" was often used without a clear definition. Does "couple" refer to the direction of the interaction, the frequency of the interaction, the software engineering behind the interaction, or something else? A definition was suggested by Ian Kraucunas (PNNL), where different adjectives were used to address all of the above "coupling" decisions (Figure 1).

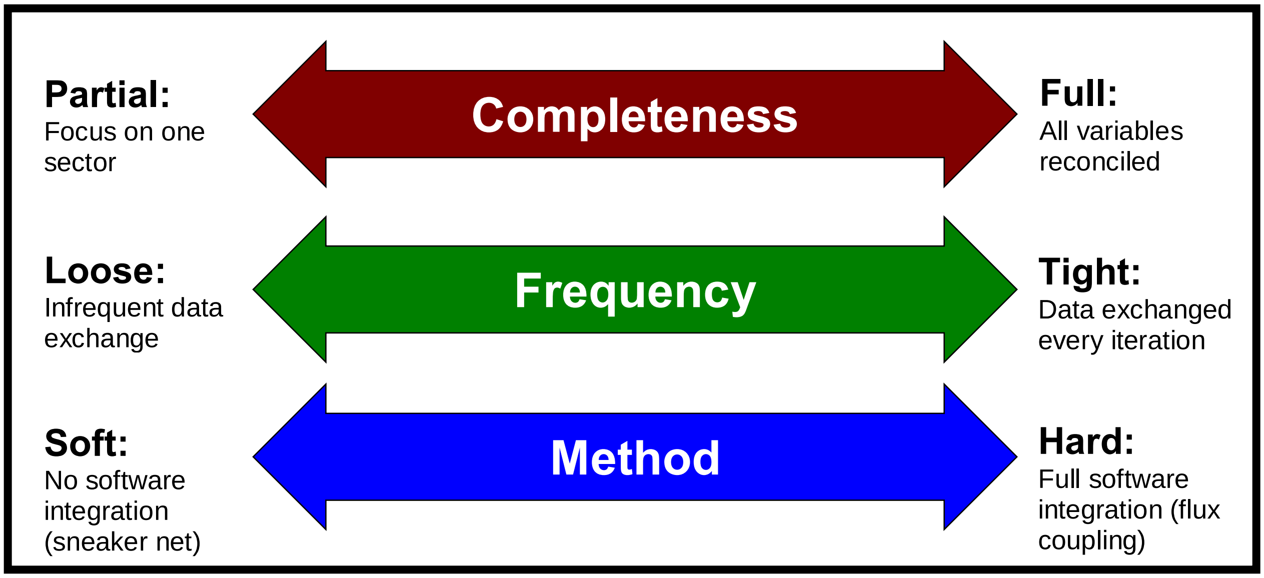

Figure 1: Coupling Spectrum

As these pairs of terms cover different aspects of the problem, it is anticipated that an individual modeling system or experiment will use multiple terms, choosing one from each color category above. Furthermore, this terminology suggests a spectrum of options for each aspect. For example, while loose coupling could refer to data exchanges every 100 years and tight coupling refers to every iteration, other options exist in between these extremes (e.g., daily, monthly, annually, decadally). Similarly, a spectrum of completeness lies between coupling a single variable and coupling all variables.

Choosing an Appropriate Approach

Participants noted that the appropriate modeling and coupling approach depends on the specific question being addressed. Even within a particular sector, different sets of questions may lead to different modeling and coupling needs. For each question, decisions must be made as to which systems to include, how complex the model representations of these systems should be, which information to exchange between modeling components, how frequently to exchange the information, etc. It is unlikely that a single model, modeling framework, or coupling construct will be appropriate for all situations. As a result, thinking about creating more adaptable modeling systems and/or modeling paradigms is more valuable than focusing on creating a perfect model. Flexibility to swap components in and out is also critical. An important consideration in choosing an approach is the tradeoff between complexity and computational expense. For questions where large-scale uncertainty quantification is required, a simpler, more computationally efficient approach is preferable. For questions where a small number of detailed simulations are required (e.g., studying interactions of complex infrastructure systems, hypothesis generation), a more complex, more intensive approach may be needed.

Challenges Due to Differences in Resolution and Language

Coupling existing models or model components introduces challenges because these models/components are developed with different spatial, temporal, and process resolutions. The choice of resolution for an individual model often depends on the process or system being modeled, the resolution of input data, and the question being addressed. However, coupling models of different resolution poses huge challenges. Methods for translating across scales must be developed and implemented, as differences in scale may prohibit exploration of certain phenomena in a coupled system, e.g., extreme events in a system with a model component with a long time-step or low spatial resolution. Furthermore, many models have overlapping domains; thus, when coupled, these modeling systems have multiple representations of the same process. For example, a presentation on the integrated Earth System Model (iESM, see Section 3.3) noted that the coupled model had multiple representations of the carbon cycle, as each of the three component models had their own native representation. Ideally, the duplicates would be disabled, leaving the modeling system with a single, internally consistent representation of each process. In practice, it is often difficult to disable subcomponents.

Identifying which representation to use in the final coupled system is not always obvious: individual models or model components may have inconsistent paradigms, posing challenges for coupling. One example is in how the future is incorporated into decision-making; that is, how does one couple simulation models (myopic foresight, solving each period sequentially) with inter-temporally optimizing models (forward-looking, solving all periods simultaneously)? Such a challenge was noted in a talk on energy impacts (Section 3.1) where energy-planning models (which consider the future when determining investments in capacity and infrastructure) are coupled with operational models (which simulate energy production as a function of weather). Finally, mechanical challenges in coupling models arise because these models are often written in different languages, with different software structures. For example, many ESMs are written in Fortran, while IAMs are often in GAMS or C++.

Data

Data are often not available at the right spatial, temporal, and process resolution for the models and questions of interest. This problem is further exacerbated by different needs from different users. For example, some decision makers may want distributions on a particular value, while others are only interested in the mean. Even when data is acquired, fidelity and quality control are problematic. Users are not always aware of these issues.

Validation and Uncertainty Characterization

Another challenge relates to validating the coupled modeling system and characterizing uncertainty in the system. In terms of validation, techniques must be developed to ensure fidelity in the individual component models, as well as the coupled system, in order to build confidence in the outputs generated by the system. The appropriateness of validation techniques was also raised; in particular, how does one know which models are "better"? Is a model that better replicates history a better model? Uncertainty in model forms and data are also challenges and will cascade through the coupled system, affecting results. Approaches to quantify this uncertainty and evaluate its implications for both research results and decision support are required. Additional challenges with respect to uncertainty include better characterizing the tails of the distribution and communicating/visualizing results.

2.2. Ideas for Future Research and Suggestions for Community Building

Several ideas for future research and community building were proposed, including (1) a community modeling framework and/or paper, (2) a typology of use and model configurations, (3) coordinated experiments, including methodological comparisons, and (4) methodological research in several domains.

A Community Modeling Framework and/or Paper

One suggestion surrounded the development of a community-modeling framework. This framework could catalog results, as well as metadata documenting what was done and what was learned in the experiment. Some participants felt that a dialogue with users was needed, or the establishment of a group of "translators", to ensure that needs are met and that users understood the limits to the data. Other potential aspects of the framework include:

- Repository/wiki of modeling components/capabilities
- Modeling tools/software environment
- Standards/nomenclature
- Evaluation/benchmarking tools
- Uncertainty characterization/communication research and tool development
- Computational resources
- Funding for collaborative research
- Resources for management of community data resources
- Facilitation of topical/technical working groups
- Case-study-focused meetings
- Mediated listserv.

Also suggested was the development of a framework or review paper focused on coupled IA-IAV-ESM modeling. Such a paper would define the overarching problem and establish the need for a coupled approach, identify useful methods and capabilities, and establish a common terminology.

Typology of Use and Model Configurations

Several participants noted that multiple groups are coupling models for a variety of science questions. However, their efforts are largely independent and could benefit from more communication. Participants thought the development of a typology of use cases and model configurations used in each case could facilitate information sharing. Such a typology would relate user needs (questions addressed, outputs or metrics required, key uncertainties, etc.) and the particular combination of models used, the mode of coupling, the degree of complexity, a description of the uncertainty characterization methodology, etc. to address each case. This information would be compiled in a database of completed and ongoing projects to facilitate future research.

Coordinated Experiments and Methodological Comparisons

A third idea involved designing and performing a set of coordinated experiments designed around a specific use case. Such experiments could help the community develop insights about what works and what does not work. Specific suggestions for these experiments included sensitivity tests to identify thresholds where feedbacks between systems/models are significant, and methodological comparisons between direct coupling of IAV models and use of the IAM as a coordinating device. Thoroughly documenting these experiments for use by future modeling teams is also necessary. The community-modeling framework or typology of use/model configurations noted above could facilitate this effort. Additionally, inter-method comparisons could illuminate issues of consistency across approaches and models. Finally, future workshops supporting detailed discussions of these experiments and comparisons could help advance the research community.

Methodological Research

Further methodological research is needed in several areas, including model coupling, uncertainty, communication, and emulation. In model coupling, experiments are needed to systematically test the sensitivity of various systems and determine when and where linking models add value. Research into uncertainty is also needed, focused on the exploration of extremes or tails of the distribution, as well as the development of a risk framework. For communication, a need for empirical social science research on communicating complexity was articulated. Finally, for emulation, identifying tradeoffs between emulation and more complex, process-based approaches is necessary.

Additionally, participants identified a need for emulation of impacts/human systems, as well as the climate system. A key research need is developing robust and efficient methods for developing emulators. One specific suggestion in the emulation arena was more community engagement. A variety of options were proposed, including a workshop or series of workshops. It was noted that these efforts should include process-based modelers, as well as emulation experts.

3. Summary of Individual Talks and Sessions

The first three days of the meeting focused on coupling challenges and needs from the perspective individual communities, with one day each focused on Impacts, Adaptation, and Vulnerability (Section 3.1), Integrated Assessment (Section 3.2), and Earth System Modeling (Section 3.3). The fourth day aimed at integrating the lessons that emerged, using break-out groups and a panel discussion (Section 3.4 and Section 3.5). The final day focused on synthesizing the discussions of the first four days. That synthesis is detailed in Section 2 and Section 4. Note that this section focuses on summarizing individual talks; the discussions that ensued after the talks are summarized in Sections 2 and 4.

3.1. Impacts, Adaptation, and Vulnerability Perspectives

The first day of the workshop began with introductory remarks, which provided a framing for the week. This introductory session was followed by four sessions focused on understanding existing methodologies and challenges of model coupling for impacts, adaptation, and vulnerability analyses.

Introduction and Meeting Goals: Kate Calvin (PNNL)

This first talk overviewed the goals for the week and framed the discussion. Since the goal of the workshop was to shed light on when and how to couple models (e.g., which components and what level of complexity is needed), the discussion was motivated by highlighting topics that might require a coupled approach to answer. The ultimate modeling framework will depend on the question being asked, who is using the information, how precise an answer is required, and when the information is needed.

Drivers for Federal Investment to Integrate IA-IAV-ESM-ABM capabilities: Gary Geernaert (USDOE)

The next talk provided a U.S. Federal Government perspective on the meeting. In particular, strategic planning within USGCRP, USDOE and other agencies was discussed. These agencies are in the planning phase for FY19 funding and are soliciting input on their strategic priorities. Some areas that have been identified: (1) complexity and scale resolution requirements when integrating IAMs and IAV models; (2) exploiting computational opportunities when conducting multi-model, multi-scale analyses; (3) filling the uncertainty gap and developing a next-generation capability (i.e., an integrative framework that combines IA-IAV-ESM).

Scientific Drivers, Needs, and Trends in Integrated Human-Earth System Modeling at the Energy-Water-Land Nexus: Bob Vallario (USDOE)

This presentation emphasized that the IA, IAV, and ESM communities are evolving individually and collectively, and stressed the importance of asking where we are headed and why. This presentation identified some key research areas, as well as desired characteristics of a model-coupling framework. The key research areas include: (1) identifying the type of information to exchange between models and communities, as well as the method and frequency of exchange, (2) creating a typology of uses and users, and (3) the potential uses of emulators. In terms of a model-coupling framework, the presenter identified several desired characteristics of a multi-model, multi-scale framework, including: problem-driven, modular, flexible coupling approach (adaptable to uses and users), tractable uncertainty characterization, embedded in consistent global boundary conditions, and regionally-transferable. Increasingly, different forms of model couplings (hard and soft) are evolving to respond to questions, but the focus should be on agile coupling methods, including software enablers as appropriate, rather than mega-models.

Capabilities and Gaps in Integrated Human-Earth System Modeling at the Energy-Water-Land Nexus: Dorothy Koch (USDOE)

This presentation described integrated human-earth system modeling efforts in the ESM community. The goals of climate and Earth system modeling at DOE include improving climate model fidelity and predicting the influence of climate on energy systems. Both involve interactions between humans and the Earth systems. Issues that emerge from such linkages include: (1) consistency in the assumptions between models, (2) the importance of feedbacks, (3) usefulness of using single models instead of ensembles, (4) need for complexity (e.g., full ESM), (5) type of coupling (e.g., one- versus two-way; hard- versus soft), (6) differences in temporal resolution, and (7) fidelity requirements for the ESM. This presentation also raised questions related to new directions for ESM development: are there new ways to develop ESMs to make them easier to couple with IAMs and IAVs? Should we deliberately co-develop IAM, ESM, and IAV? Do we need to design specific diagnostics in the ESM for IAV or IAM?

IAV Science Questions that Require Coupling and/or Inputs from IAM/ESM: John Weyant (Stanford)

The next presentation provided a history of some of the challenges in addressing IAV interactions in past IPCC experiences, noting that the emphasis in AR5 is risk framing. A background on how the IPCC has evolved was also provided, with a broader assessment of the set of impacts on different sectors and different regions. This presentation also included a summary of the US National Climate Assessment and the themes explored in that report. This presentation triggered a discussion on whether the ultimate goal is higher-resolution modeling and whether higher resolution is consistent with the risk and uncertainty framing.

Linking IAV, IAM, and ESM—Results of the Interagency Workshop: Richard Moss (PNNL)

This presentation summarized a May 2016 interagency workshop that assessed the possibility of developing a systems framework that brings together data, models, and analytic capabilities in a toolkit that enables independent teams to explore science and use-inspired questions in a coordinated way. The workshop was motivated by evidence of a need to couple IAV, IA, and ES models to explore human-environment systems affected by multiple stresses. What emerged from the workshop was a framework vision and approach centered around a community of practice that emphasizes "use" cases. In the discussion that followed, it was emphasized that coupling could involve data in addition to models. Additionally, not all of the IAV communities are at the same level of sophistication; therefore, we might not be able to capture everything about a specific use case.

Comparing Methods and Improving the Empirical Foundations of Agricultural Impacts—an Inter-method Comparison: Juan-Carlos Ciscar (EU-IPTS) and Karen Fisher-Vanden (PSU)

This presentation reviewed a recent exercise that brings together crop modelers, econometricians, and integrated assessment modelers who are estimating climate impacts on crop yields to conduct an inter-method comparison. All three methods estimate the effects of changes in climate on crop yields, but this is the first study to compare all three. A special issue of *Environmental Research Letters* is in development that would include papers from this inter-method comparison, due to be published in 2017. Following this presentation, participants discussed (a) how to design a formal protocol for carrying out inter-method comparisons; (b) how to broaden the exercise to include results other than yield results—e.g., price, employment, other economic outcomes; and (c) a suggestion that uncertainty be included in this inter-method comparison exercise (e.g., how do the different methods address uncertainty?).

Agriculture Model Intercomparison and Improvement Project: Alex Ruane (NASA)

This presentation provided an overview of the Agriculture Model Intercomparison and Improvement Project (AgMIP). Previous research in AgMIP has included an improvement track and a future track, focused on understanding risks associated with climate and assessing adaptation opportunities. This effort has resulted in development of point-based models, analysis of impact response surfaces, and ensemble results from global gridded agricultural models. AgMIP's new focus is on coordinated and global research assessments, where many distributed teams will address region-specific issues. Issues related to coupling, using common data, food security, and diet are faced by all of the different AgMIP building blocks.

ISI-MIP: Franziska Piontek (PIK)

Similar to AgMIP, the Inter-Sectoral Impacts Model Intercomparison Project (ISI-MIP) is a model intercomparison project of climate impacts; however, it includes other impact sectors in addition to agriculture. The models used in the exercise are harmonized to the same climate and socioeconomic data using a consistent scenario protocol. Currently, results include impacts on crop yields, net primary productivity, runoff, fish catch, malaria, and coastal infrastructure. Future work includes impacts from floods and extreme events, heating and cooling demands, labor productivity, and mortality. Longer-term plans include broader stakeholder involvement, improved accessibility and usability of the ISI-MIP results, and the development of emulators. The discussion following this presentation noted that ISIMIP provides a framework for linking impacts across sectors.

Coupling for IAV - Energy: Mort Webster (PSU)

This presentation focused on exploring why coupling matters for questions related to energy. In the energy sector, questions revolve around reliability (is supply always available?) versus resilience (are disruptions quickly resolved?). For example, changes in the hydrological cycle may lead to less water for cooling power plants. This raises questions related to ability to re-dispatch, availability of sufficient transmission capacity, and adaptation preferences. Challenges to coupling models in this sector include differences in time scales (power systems models are hourly; planning is decadal), differences in degree of foresight (e.g., forward-looking versus myopic models), and decision-making under uncertainty. To resolve these issues, we need better solution algorithms and approximation schemes to couple models; consistency of temporal flow and expectations; and better abilities to solve stochastic multi-stage problems.

Coupling for IAV - Water: Richard Lammers (UNH)

This presentation began with a review of the UNH Water Balance Model, used as an example of a process-based model of the hydrological system. In this type of model, surface dynamics are captured, but not atmospheric processes. These models estimate water availability across space and time, and can be used to calculate dependence on groundwater (i.e., the difference between water demand and surface-water supply). However, these models need better representations of human decision-making, including short-term decisions on water volume and long-term decisions on infrastructure. In sum, these models need more coupling, more information, and more constraints.

Coupling for Agriculture and Land: Alex Ruane (NASA)

This presentation provided an overview on modeling agriculture and land impact and issues with coupling. There are two standard approaches to modeling climate impacts on agriculture and land use: (1) point-based crop models that represent many weather, soils, and crop characteristics and (2) agricultural response surface models that statistically estimate changes in yields from changes in climate. Coupling is essential to understand land use and to add information on regional factors. For example, land use requires coupling to economics since the biophysical environment does not tell the entire story. Currently, sneaker-net is the preferred coupling method. Hard coupling of models is difficult due to biases in crop models. As a result, percent changes are used rather than absolute levels when information is exchanged between models.

Direct Coupling of IAV Models: Ian Kraucunas (PNNL)

This presentation focused on progress challenges and opportunities in coupling IAM-IAV-ESM through the PRIMA and RIAM projects. While recent interest has focused on multi-sector, multi-scale modeling frameworks, the presenter noted that the scientific question and/or desired outcome driving the analysis typically dictates what needs to be included in the modeling framework. IAMs are moving to higher resolution in order to incorporate impacts and resulting changes. ESMs are also moving to more detailed integration of human activities. Coupling these types of models, and including even more detailed sectoral models, is important for assessing unintended consequences of various response strategies. The presentation included a description of a new multi-institute project intended to develop a multi-scale, multi-sector modeling framework, focusing initially on three thrust areas (energy-water nexus, land use/land cover, and population dynamics). Finally, a proposal for coupling terminology, including definitions for full, partial, hard, soft, loose, and tight coupling, was presented (see Section 2).

IAM Incorporating IAV: Ian Sue Wing (BU)

This presentation focused on an integrated framework rather than on coupling, examining upstream needs for impacts analyses. In particular, the presenter discussed developing response surfaces of IAV systems, which can be used in IAMs. Some challenges include: (a) IAV models can be expensive to run; (b) the difficulty in using multiple ESMs; and (c) lock-in effects (i.e., all IAV model results are specific to a particular ESM, while a more generic response may be needed). One potential approach is to first determine how different economic sectors are affected by impacts, and then develop a reduced-form representation of these impact endpoints.

IAM as a Coordinating Mechanism to Integrate Impacts across Regions and Sectors: Kate Calvin (PNNL)

This presentation started with a discussion of differences between IAMs and IAV models, including differences in scale and overarching goal. IAMs are trying to capture interactions between nonlinear and complex sectors while IAV models focus on individual sectors. Translating across spatial, temporal, and process resolutions is a challenge. Additional challenges include bias correction forcing the use of deltas rather than levels, and incomplete information (i.e., IAMs may need more information than is available in the IAV model, such as impacts by technology or management practice). A review of the literature on impacts assessments in IAMs revealed lots of agricultural impacts studies, but not as many in the other sectors. The pros of capturing impacts in IAMs are that the framework is already in place and run-time is cheap so one can decompose the effects and examine interactions. The cons are that impacts are limited to the sectors represented in the IAM.

3.2. Integrated Assessment Modeling Perspectives

The second day of the workshop included sessions focused on existing methodologies and challenges of model coupling for integrated assessment analyses.

Scientific Drivers, Needs, and Trends - an EU Perspective: Miles Perry (EC)

This presentation provided input on the use of models in the European Commission, noting that models and political decisions set the direction for both European and global climate action. This process includes IPCC assessments, political agreements, policy support, INDC development support, and mid-century analysis support. The presenter noted that more integration is needed between modeling efforts and what is happening on the ground. Land Use, Land Use Change, and Forestry (LULUCF) policies are particularly challenging in this regard. In particular, questions/challenges emerge as to the appropriate baseline for these calculations, adding NDCs, determining whether there is enough land for bioenergy, the role of agriculture and consumption, and the impact of climate on all of these sectors.

Evolving Research Agenda for the IAM Community: Leon Clarke (PNNL)

This presentation provided a brief history and a summary of trends in IAM research, noting that research and model development are, and should be, problem driven. Research has evolved from quantifying the central role of carbon and human influences in the carbon cycle within an overarching Earth system context to energy-water-land interactions and impacts of a changing Earth system on both human and natural systems. With respect to the last effort, the two big challenges are (1) getting IAV elements into IAMs and (2) increasing the realism of integrated IAV analyses with respect to regional dynamics using IAMs. Meeting these challenges requires examining the whole problem, and then making tradeoffs in resolution and linkages to balance realism with computational burdens. The presenter also noted challenges with respect to data (including availability and processing) and communicating results to policy-makers and the public.

IAM Science Questions that Require Coupling and/or Inputs from IAV/ESM: Detlef van Vuuren (PBL)

This presentation identified IAM science questions that require coupling. The presentation began with an overview of IAMs, noting that IAMs integrate human and physical systems AND support policy decisions. Next, this presentation discussed different forms of cooperation between the IAM, IAV, and ESM communities, including coupling and emulators. A previous paper [*van Vuuren et al.*, 2012] defined several forms of coordination: (A) offline, (B) improved

IAMs, (C) improved ESMs, and (D) full coupling. Each approach has several pros and cons. The authors conclude that if feedbacks to human system are large, full coupling is needed. If not, off-line soft linkage is preferable. The presenter also noted that models must be ready for coupling, including the relevant processes. Some questions about IAMs where cooperation is needed include climate and land use, climate and energy use, air pollution, transport and shipping, infrastructure, water scarcity, and human health.

AGCI Workshop Remote Sensing for IAMs: Ghassem Asrar (PNNL)

This talk was a report on the AGCI 2015 workshop on "Opportunities for Integration of Remote sensing, Integrated Assessment, and Adaptation Science." The workshop focused on creating a dialog among the participants from the IAM, IAV, remote-sensing, and decision-support communities. The objectives were to identify ideas, opportunities, and effective practices that enable community building and greater progress in using remote-sensing observations. The two primary focus application areas were urban and water systems. The group proposed specific topics for interaction, such as land-use change, and water resources management. This led to the identification of types of needed new capabilities including dataset development, reduced complexity modeling and analysis approaches, mixed complexity modeling to couple human and natural systems, and urban systems science development.

The IIASA World in 2050 Initiative: Nebojsa Nakicenovic (IIASA)

This presentation described a new IIASA-initiated project entitled "The World in 2050: A Transformative Change Agenda." The motivation for this project was the unanimous approval of 17 sustainable development goals (SDGs) by the United Nations in 2015. Many of these SDGs are inter-related. Because the tradeoffs are hard and resources are limited, science is needed to figure out how to achieve SDGs. The IIASA initiative will employ an integrated systems approach studying possible ways to satisfy the SDGs. The world in 2050 initiative will address the following questions: (1) how to achieve global development in a safe and just operating space, (2) how to identify a safe space of interaction among SDGs, including sustainability narratives and integrated models, and (3) how to frame the above in terms of achieving multiple benefits simultaneously. Another key question relates to consistency of the 1.5 degree goal and the SDGs.

Update from European Commission's CD-Links Project: Valentina Bosetti (Boconi University/FEEM)

This presentation described another project, CD-LINKS, whose goal is to examine the possibility of simultaneously achieving the UN SDGs and the Paris UNFCCC Pledges. The vision of the project is to look at climate mitigation and adaptation along with other sustainable development objectives at global, national, and local levels, integrating findings in one unified framework. One challenge in this work relates to the presence of multiple objectives, associated uncertainties and communicating with policy makers. Specific components of this work include: (1) an emphasis on case studies, in addition to models, (2) a focus on current policies and pledges, (3) an integration of long-term and short-term goals and analyses, (4) consideration of multiple objectives, (5) analyses of future policies and their implementation, including challenges and political feasibility and (6) a number of high-level dissemination activities, including visualization tools.

Coupling for Energy: Keywan Riahi (IIASA)

This presentation noted that energy modeling has evolved from a response to oil price shocks in the 1970s to examining air pollution and climate. Recently, understanding the linkages of the energy sector with other sectors, especially land and water, has become a priority. IAM frameworks, like the MESSAGE model at IIASA, try to encompass various aspects of these linkages. The linkages emphasized depend on the particular questions that need addressing. At times, emulators of the more computationally intensive components (e.g., land, water management) are used. Additionally, exogenous inputs (e.g., stream flow, stream temperature) from other models are also used. This information is currently just a one-way linkage but could be included dynamically in future experiments. The speaker noted a need for bottom-up activities to collect detailed data, developing methods for nesting detailed local information and/or models, and incorporating adaptation options before linking with climate models.

Coupling for Water: Mohamad Hejazi (JGCRI/PNNL)

This presentation provided a status update on incorporating water in IAMs. The speaker noted the importance of ensure that information is not lost when models are connected. Two different approaches are taken: one-way, off-line coupling or the inclusion (either endogenously or through two-way coupling) of water as an explicit component with feedback. The speaker identified some cases (e.g., interactions between land, energy, and water) where two-way feedbacks are needed. However, such coupling has many challenges, including data availability (e.g., weather and weather extreme information, water use, groundwater cost, subsidies/regulation), model validation, and temporal resolution differences. Some lessons learned from previous research include the need for accounting for sub-annual temporal resolution, understanding when coupled frameworks are needed, and choosing which aspects of each model to turn off or reconcile.

Coupling for Land: Erwan Monier (MIT)

This presentation began with a conceptual schematic of how land systems are incorporated into IAMs. In the past, LULCC was driven only by energy, economic, and policy drivers, but MIT is starting to study the effect of climate impacts. They have found that it is important to include a representation of carbon and nitrogen dynamics, as well as a consistent representation of crops, in both a terrestrial ecosystem model and a global economic model. However, this representation does pose issues for uncertainty analysis. Additional coupling is needed to address climate and economic impacts on irrigation, which requires use of a water resources management model. Developing a fully coupled LULCC framework, with LULCC influencing surface hydrology and local climate, requires the use of a detailed ESM, raising additional challenges. The speaker noted tradeoffs between spatial resolution and uncertainty analysis, and between temporal resolution and coupling strategies.

Resolution Challenges in IPETS/CLM: Brian O'Neill (NCAR)

This presentation focused on Tools for Human-Earth System Interaction and Scaling (THESIS), a set of models and software tools to facilitate human-Earth interactions developed at NCAR. This system is aimed at facilitating offline, one-way linkages (Category A, van Vuuren et al., 2012). However, NCAR is also incorporating more human elements in ESMs (Category C, van Vuuren et al., 2012), specifically improving urban and agriculture representations in the CESM. The THESIS tools include translators for: spatial distribution, spatial properties, IAM consistency, outcome evaluation, specific sectors, population, urban systems, and agriculture. The speaker provided an example of the use of THESIS to study heat wave effects on urban populations.

Resolution Challenges in AIM: Kiyoshi Takahashi (NIES, Japan)

This talk focused on IAM-IAV-ESM linkages in the AIM project. The motivation for these linkages is to contribute to the SSP/RCP framework, to analysis of SDGs, and to the domestic sustainability research agenda. One example of this integration at NIES is in the AIM land allocation model, which includes climate downscaling, climate impacts, crop modeling, health modeling, and building energy demand modeling. In this work, differences in spatial resolution pose challenges, e.g., how do you weight different variables when aggregating?

Additional challenges include the limited number of IAV scenarios available and what to use for impact response functions.

Resolution Challenges in EPA's CIRA Project: Jim McFarland (USEPA)

This presentation described the Climate Change Impacts and Risk Analysis (CIRA) Project. A 2015 report was published on the project, oriented to policy makers and the public to demonstrate the benefits of mitigation. These changes are analyzed by comparing physical and monetized impacts between an RCP8.5 emissions scenario to those from an RCP3.2 scenario. The project analyzed different sources of uncertainty **(**e.g., climate sensitivity, spatial patterns of change, etc.) in six major impact sectors. The presenter noted that not all extremes or all channels of impact were considered, and that no attempt was made to combine sectors into a single total cost. The next round, CIRA 2.0, is intended to feed into the next National Climate Assessment (NCA) with a focus on estimating damage reductions across many sectors and ensemble members.

Uncertainty in IAV: Rob Lempert (Rand Corporation)

This presentation described an emerging decision-support kit for difficult problems, and some implications for IAV modeling. In approach described, uncertainty is managed through choice of strategy rather than through choice of models. Robust strategies can help manage cascading uncertainties. The presentation provided a few examples of such efforts, including studies on natural gas, the Colorado water basin, and climate resilience of African infrastructure.

The presenter noted differences in "for decision support" and "of decision support," where the former focuses on improving understanding and the latter focuses on coming up with better decisions. It was also noted that decision support often needs local, trusted models, and a flexible toolkit to link global/regional drivers to these types of models. Simple, reduced-form models (emulators) are often useful for representing system components for which more detailed representations do not exist.

Uncertainty in IAMs: Massimo Tavoni (FEEM)

This presentation discussed the extent to which the IAM community has responded to the challenge of incorporating uncertainty. Much of the uncertainty analysis has been through multi-model intercomparison projects (e.g., EMF), where uniform input assumptions are provided to models that are structurally different, or through sensitivity tests to particular components. BUT, much less emphasis has been placed on parametric uncertainty. Additionally, much of the effort has focused on developing scenarios (e.g., SSPs) without probabilities. In the future, expert elicitation can be used to confront model results and diagnostic model simulations can be used to augment analyses (e.g., decomposing differences between scenarios into individual factors). The speaker discussed the complexity versus uncertainty tradeoff, noting that both very simple and very complex models are highly uncertain. However, they may differ in the type of uncertainty, with structural uncertainty more important in simple models and parametric uncertainty more important in complex models. Communicating uncertainty to users, however, is important and challenging. Previous research has suggested that the format of information can influence decision-making.

Uncertainties in Earth System Models: Klaus Keller (PSU)

This presentation described current challenges in modeling uncertainty, provided some examples of projects, and discussed ways of overcoming challenges. The example described focused on designing strategies to reduce flood risk. Such a problem requires characterization of the tail of the distribution of flood risk, but scenarios based on ensembles of opportunity can miss decision-relevant details. Potential strategies include emulation, again noting the tradeoff between computational expense and process fidelity/spatial resolution. Simplifying models to reduce wall clock time can facilitate the increase in ensemble size needed to capture tail risks. Some challenges in this research include choosing which parameters on which to focus analytical efforts; communicating results given deep unknowns; navigating choices between model realism, resolution, and coverage of relevant uncertainties; and achieving required integration between ESMs, IAVs, and IAMs.

3.3. Earth System Modeling Perspectives

The third day of the meeting focused on model coupling from an Earth System research perspective. Participants discussed different methodologies for producing climate information and for coupling climate models to other models and frameworks. Additional discussion focused on science questions that require cooperation or coupling, as well as issues surrounding such cooperation or coupling.

Coupling for Earth System Models: Jean-Francois Lamarque (NCAR)

The day began with a high-level overview of Earth System Models (ESMs). ESMs aim to help understand and project climate-related processes at multiple spatial and temporal scales. These models by themselves link multiple component models together, using a coupler to handle communication and address differences in scales among components. Several topics were identified that require coupling between ESMs and other modeling frameworks. The topics included (1) air pollution and atmospheric chemistry, (2) water availability, (3) sea-level rise and storm surge, and (4) land-based carbon sequestration. Issues with respect to modeling each of these areas were noted.

Scenarios in CMIP6: Claudia Tebaldi (NCAR)

The next presentation described the role of scenarios in the 6th Coupled Model Intercomparison Project (CMIP6). The CMIP6 scenario activity coordinates and facilitates integrated research across IAM, IAV, and climate science communities. The scenarios developed for CMIP6 are based on the IAM community’s Shared Socioeconomic Pathways (SSPs). The selection of scenarios included in the experimental design span a wide range of forcing, ensure continuity with CMIP5, provide experiments to answer science questions about the effects of specific forcing (e.g., land use, aerosols), and facilitate uncertainty research.

DOE and ACME Scenarios: Dorothy Koch (DOE)

This presentation discussed a collaboration effort between GCAM (an IAM) and ACME (an ESM) to co-develop scenarios and experiments, that is, to develop scenarios tailored to science questions relevant to the DOE mission. Four topics were identified as areas where interactions between the two modeling efforts would be fruitful. Those topics are (1) land use and carbon, (2) water and energy, (3) low- and high-carbon-intensity pathways, and (4) settlement pathways in coastal regions.

AGCI High Resolution Summary: Andy Jones (LBNL)

The next presentation described a workshop hosted by the Aspen Global Change Institute in August 2015 focused on “Impact Relevance and Usability of High-Resolution Climate Modeling and Datasets”. The workshop brought together different communities, including climate modelers, impacts modelers, and decision makers, to discuss issues related to producing and using climate information. Discussion topics included an assessment of the information used, evaluation of the credibility of information, and tradeoffs across methods given limits to resources.

IGSM: Erwan Monier (MIT)

This presentation described climate modeling, and coupled human-Earth system modeling efforts with the Integrated Global System Modeling Framework (IGSM) at MIT. IGSM has multiple means of producing climate information, including an Earth System Model of Intermediate Complexity (EMIC), which can be paired with either pattern scaling or dynamical downscaling. Each approach to climate modeling has different strengths and weaknesses with respect to variables captured, spatial and temporal resolution, model fidelity, and computational expense. For this reason, MIT uses different methods for different questions.

CESM-IPETS: Peter Lawrence (NCAR)

This presentation described efforts to integrate the ESM at NCAR with an integrated assessment model, the iPETS model. This model coupling currently relies on a soft coupling strategy via the THESIS tool. This tool provides information on agricultural impacts that can be used in the iPETS model, as well as an assessment of exposure to heat stress. Such tools have been used to assess the benefits of reducing radiative forcing, by comparing impacts under an RCP8.5 world with impacts under a RCP4.5 world.

iESM: Bill Collins (LBNL)

This presentation described the integrated Earth System Model (iESM), which couples the GCAM integrated assessment model with the CESM Earth System model, focusing on lessons learned in exchanging information between models. In particular, difficulties were encountered in translating forest expansion in GCAM to the ESM when using the Global Land Model (the CMIP5 land harmonization model). Additionally, challenges were also faced in translating climate impacts from the ESM to GCAM, as GCAM needs a pure climate signal and many variables within CESM include both climate and land use.

CNRS-IMAGE: Detlef van Vuuren (PBL)

This presentation discussed two different projects that coupled the IMAGE integrated assessment model with climate models. The first project used the climate system in CNRM in a two-way coupled mode, where climate from CNRM was passed to IMAGE and emissions/land were passed from IMAGE to CNRM. Only a single experiment was performed with this framework due to limits on computing time. Findings from this experiment suggest that socioeconomics are more important than climate. The second project coupled IMAGE to EC-Earth and focused on interactions via land use and air pollution, in a one-way coupled mode. Findings from this project suggest large local effects, but not global.

Characterization of Extremes: Noah Diffenbaugh (Stanford)

This presentation discussed atmospheric conditions that lead to extreme events. The motivation for this work is to understand the physical processes that create extremes, the fidelity of climate models in representing these processes, as well as needs for bias correction and/or downscaling.

The research presented examined (1) individual extremes (e.g., the California drought), (2) the effect of extremely rare patterns on the probability of extremely rare events, and (3) the contribution of trends in atmospheric patterns on trends in extremes.

High-Resolution Climate Modeling: Ruby Leung (PNNL)

This presentation discussed advances and limitations in high-resolution climate modeling, contrasting the fidelity of three different model configurations (low resolution, high resolution, variable resolution) of a global variable-resolution modeling framework. Increasing resolution has notable positive impacts on simulating large-scale circulation features such as the jet stream, which has important effects on simulating extreme events such as atmospheric rivers. However, improving simulations of mesoscale convective systems or fine-scale, orographically forced precipitation requires much higher resolution, which currently is only computationally feasible using regional or global variable-resolution models.

Pattern Scaling and Statistical Climate Modeling: Claudia Tebaldi (NCAR)

This presentation described efforts to use statistical methods to emulate fine-scale climate information using coarse-scale (and cheaper) models. Such efforts could be used to create low-cost projections for scenarios that have not been generated by climate models. Several examples of such efforts exist, including reduced-form climate-carbon cycle modeling, intermediate complexity models, and modular uncertainty decomposition. The simplest of the approaches for spatial information is pattern scaling; however, it has only been validated for temperature and precipitation at seasonal scales. Other shortcomings of current emulation techniques were identified (e.g., difficulties in emulating coherent spatio-temporal and joint evolution of climate variables, accurate representation of tail behavior, untested performance for scenarios that involve stabilization or overshoots). The need for community building and more systematic exploration of current and future method development was highlighted.

Climate Information for Impacts, Adaptation and Decision-Making: Rob Nicholas (PSU)

This presentation discussed efforts to more effectively couple, integrate, and transfer climate information to IAMs, IAV analysis, and decision-making. Several difficulties in using climate information were identified, including acquiring data, spatial/temporal resolution, biases, and model fidelity. Additionally, potential paths forward were also noted, including shared tools/libraries and dedicated facilitators.

3.4. Break-Out Groups

The fourth day of the meeting provided an opportunity for participants to work together in three breakout groups to explore the potential for coupling IAV, IA, and ES models to address the needs of three specific use perspectives:

> Group 1: Electric power generation and distribution, given changing demand, prices, supply technologies, climate, land use, and other relevant factors
>
> Group 2: Water resources management, given changes in demand, population, land use, institutions, operating rules, and other factors
>
> Group 3: Productivity of agriculture and terrestrial ecosystems to meet changing demand for food, fiber, and other ecosystem goods and services

The idea was that these break-out groups could combine the insights and challenges identified over the first three days, providing an integrative perspective on coupling and complexity issues that arise in specific cases. Groups worked during the morning and reported back to everyone in the afternoon.

Each group was asked to:

1. Define a bounded science or user question related to their assigned topic, including specific quantitative metrics or criteria needed to evaluate potential answers or options
2. Identify the models, data, and capabilities needed to answer the question, including specifying levels of complexity, resolution, model flow, data, etc.
3. Consider tradeoffs between completeness/resolution and tractability
4. Consider the potential utility of a model framework to facilitate development of models to address these and similar issues, considering what model standards, software tools, data, analytic resources, and other elements of a framework could be useful.

Group 1: Electric power generation and distribution, given changing demand, prices, supply technologies, climate, land use, and other relevant factors

Participants: Leon Clarke (facilitator), John Weyant (rapporteur), Bob Vallario, Detlef van Vuuren, Erwan Monier, Franziska Piontek, Ian Kraucunas, Ian Sue Wing, Jim Sweeney, Mort Webster, Richard Lammers

This group addressed issues surrounding the co-evolution of the electric power system in the context of the broader coupled energy-water-land system, including changing demands in response to socioeconomic trends and human adaptation, reliability in the face of changes in extreme events as well as technologies, costs and benefits of needed investments, emergent constraints (e.g., power plant siting), impacts of adaptation in other sectors, etc. The specific user question formulated by the group was:

- What are the costs, benefits, co-benefits, and tradeoffs associated with specific actions or investments that could be taken to enhance the resilience of the electric grid against increases in droughts, flooding, and/or precipitation variability in a specific region (or two, or three) and accounting for additional long-term trends and short-term shocks/extreme events?

To better define modeling requirements, the group clarified several of the criteria noted in their question, including:

- "Costs", which were considered to be generally easy to quantify for near-term infrastructure investments, and harder for longer-term investments or policy/regulatory/institutional changes;
- "Benefits", which they defined to include any direct monetary benefits plus "avoided costs" due to withstanding disruptive events; the group judged these as generally difficult to quantify due to uncertainties in future climate as well as other influences on system evolution (e.g., technological change, resource utilization and availability, etc.);
- "Co-benefits" are outcomes that increase resilience against other hazards (e.g., heat waves), as well as benefits to other characteristics of electric system performance (reliability, flexibility, security);
- "Tradeoffs" involve negative effects on other metrics of system performance or on other systems/sectors; and
- "Specific actions or investments" include infrastructure hardening, relocation, or build-out (e.g., additional transmission), policy or regulatory changes, etc.

The group considered the capabilities and linkages that would be needed to create a system of sufficient breadth and resolution to address this question in a way that accounted for significant interconnections and feedbacks (see Figure 2). This system covered major areas of infrastructure (including electricity supply and grid operations), building energy and other components of energy demand, climate information with uncertainty characterization, and a hydrology model all driven by common climate and socioeconomic scenarios.

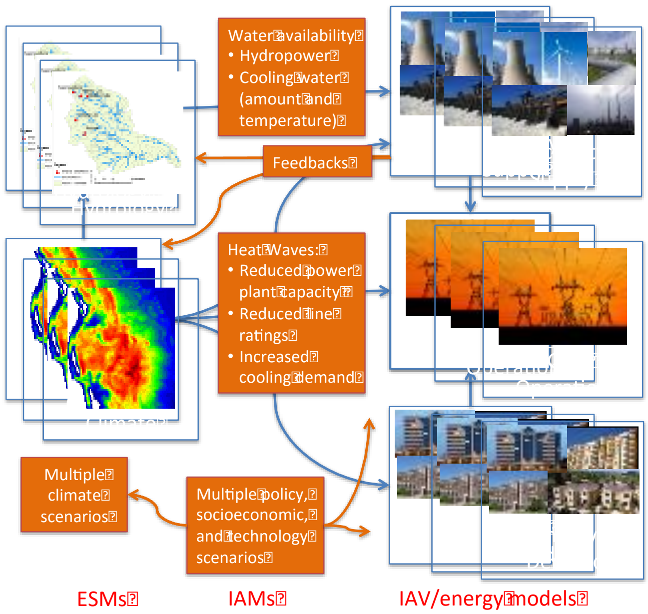

Figure 2: ESM-IAM-IAV Model Diagram and Connections for Energy

Participants identified a number of gaps and challenges, including:

- Determining the spatial allocation of future infrastructure, including the flexibility and adaptability of those mechanisms;
- Determining the required timescales to couple models of water availability (e.g., a hydrology model operating at hourly resolution versus longer time steps) with energy supply.
- Coupling and consistency between models representing long-term trends with models that represent short-term dynamics, such as extremes and shocks. This challenge is compounded by the fact that the integrating framework, IAMs, do not currently represent extreme events, as they are presently limited in spatial and temporal resolution and process details, although this is improving.
- Obtaining information on climate (e.g., frequency and occurrence of droughts) at the appropriate scales, including correlation of extreme events spatially and temporally. The participants identified a need for a focused research program on evolution of extreme events.
- Identifying ways to test the resilience and/or performance of different system configurations under different climate regimes and extreme events, including combinations of events;
- Projecting future technology change and innovation, especially disruptive technologies (e.g., large-scale storage);

- Accounting for political, behavioral, and institutional (including a hierarchy of regulatory and governance) constraints (e.g., in water management models), as well as the evolution of policy regimes;
- Understanding and incorporating human preferences when determining adaptation decisions;
- Advancing analysis of the consequences of extreme events and shocks through coupled modeling, including incorporation of such events in IAV and IA models and improvement of reduced-form information from Earth system models
- Identifying "hidden" assumptions (e.g., discount rates) and harmonizing assumptions across models;
- Systematically quantifying uncertainties; and
- Reconciling different timescales (e.g., operational decisions versus long-range planning/design).

Finally, as next steps, the group felt that it would be productive to evaluate existing capabilities available to address components of their use question. They would then identify an initial set of models and couplings and conduct parametric sensitivity tests to identify which linkages and feedbacks were strongest as a way of understanding where additional investment and long-term model development were needed.

Group 2: Water resources management, given changes in demand, population, land use, institutions, and operating rules, and other factors

Participants: Steve Frolking (facilitator), Karen Fisher-Vanden (rapporteur), Andy Jones, Haroon Kheshgi, Jim McFarland, Klaus Keller, Mohamad Hejazi, Rob Lempert, Rob Nicholas, Ruby Leung, Stephane Hallegate

This group addressed the complex system of interactions and feedbacks related to changes in water demand (municipal, industrial, energy, rural; storms) given existing environmental regulations (e.g., Endangered Species Act, CWA), water infrastructure (storage, desalination, waste water management, reuse, inter-basin transfers), management (water allocation and land use) under changing hydrological regimes (e.g., changing seasonality of runoff, drought combined with diminishing fresh water due to sea-level intrusion). They defined user groups to include state water agencies, cities/counties, regional water managers, and river basin commissions confronting the question of

- How do we manage water infrastructure investment, water allocation decisions, and land use decisions under novel hydrological regimes given existing environmental regulations?

They considered the challenges faced by Florida, including whether the state should be planning for more drought, more precipitation, or both? They noted that there is plenty of fresh water in the northern part of the state, but topography limits the potential of inter-basin transfer to meet needs in the south. There are a number of competing objectives and challenges including population growth and/or migration, reducing flooding problems compounded by localized intense storms, protecting the Everglades, adapting to impacts on agriculture, planning urban development including promoting "vertical" development to increase density, and addressing the consequences of sea-level rise (salt-water intrusion, loss of gravity-fed drainage resulting in extensive flooding, compromised septic systems, coastal flooding and restrictions on building sea walls),which is exacerbated by tropical storms.

In terms of modeling and data components to address this problem, the group identified a long list of capabilities needed, including:

- Migration
- Climate (long-term, seasonal, daily, and hourly temperature and precipitation; hurricane prediction; uncertainties)
- Sea-level rise and land subsidence
- Groundwater supply, flow, withdrawal
- Surface water
- Infrastructure (reservoirs, inter-basin transfers, desalinization, reuse, wastewater management, floodwater management, water distribution)
- Beach and coastal sedimentology and erosion
- Ecosystem quality and services
- Water quality
- Governance
- Water use policy for adaptation
- Economic growth
- Industry composition
- Intra- and inter-regional trade
- Human health
- Human preferences.

The group felt it would be useful to establish a community of practice to develop a model framework with model standards, software tools, data, analytic resources, and other elements that could be integrated to address particular use cases. This would require communities to work with each other and to develop and use interoperable models. They noted a tradeoff between needing to use context or location-specific models (many use cases would be specific, and have existing models) and generic or global models designed for coupling. They felt it would be useful to have a means of determining whether coupling would be important (e.g., sensitivity or screening analysis). They also suggested developing a checklist for location-specific applications that would allow one to identify important couplings and existing studies, based on input from the community of practice. The results of these sensitivity studies would then inform development of initial pilot projects.

Finally, this group identified a number of research needs on short, medium, and long time scales: In the short term, needs include:

- Pilot projects,
- An initial set of best practices (evolving) related to model coupling, including lessons learned from existing projects (e.g., iESM)
- An examination of sensitivities to determine where couplings are strong and required
- The development of tools to rapidly test sensitivities (e.g., water quality under drought conditions).

In the medium term, needs include:

- A toolkit to facilitate model coupling

- Better groundwater modeling and better geological data
- Better models on governance, decision-making, land use, and social transformation, as well as method of coupling these with existing models
- A better balance between model realism and uncertainty quantification
- Better modeling of sea-level rise and storm surge
- A better understanding and ability to evaluate options for managing the system
- Better data on water use and water allocations
- A better understanding of how to use the models to inform decisions and to communicate results.

In the long term, there is a need for better understanding of uncertainty propagation through the causal network, particularly with respect to human responses.

Group 3: Productivity of agriculture and terrestrial ecosystems to meet changing demand for food, fiber, and other ecosystem goods and services

Participants: Brian O'Neill (facilitator), Kate Calvin (rapporteur), Alex Ruane, Claudia Tebaldi, Stephane Hallegate, Dorothy Koch, Jean Francois Lamarque, Juan Carlos Ciscar, Kiyoshi Takahashi, Peter Lawrence, Wolfram Schlenker

This group focused on the implications of drought impacts on agriculture on households and ecosystem goods and services, in particular:

- What are the implications of drought-related changes in agriculture, and adaptations to them, for households and ecosystems? And how do those impacts/adaptations feed back onto other regions as mediated through markets, climate, or other mechanisms?

The group identified a number of outcomes of interest. On the household side, these included welfare, income, inequality, consumption, and poverty. For ecosystems, they considered the goods and services that support agriculture (see Figure 3). Regional economics and the land system were defined as primary influences, with regional climate, crops, hydrology, and water resources management as additional drivers. ESMs and IAMs would be needed to model larger-scale, longer-term aspects of the system. These models would be combined with a variety of IAV models related to the influences and drivers operating at higher resolution (temporal and spatial).

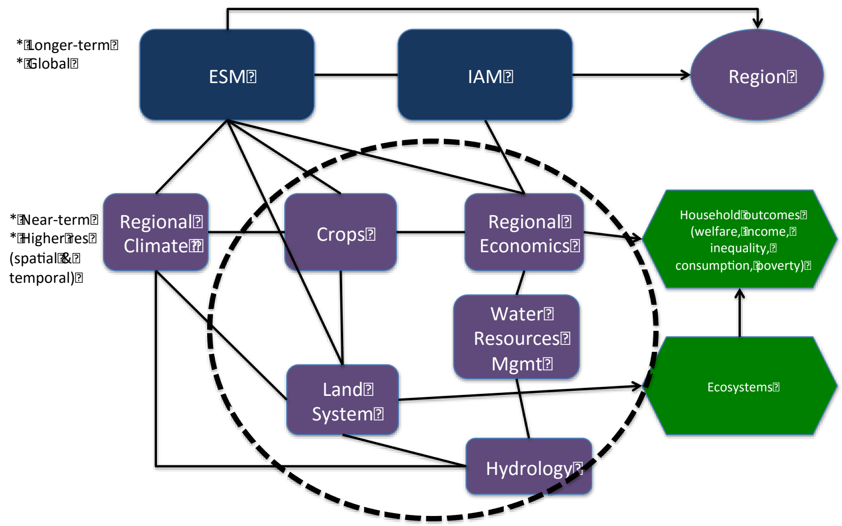

Figure 3: ESM-IAM-IAV Model Diagram and Connections for Agriculture

The specific models and capabilities identified by the group include:

- A global Earth system model (e.g., to produce drought information and to capture teleconnections)
- A method of climate scenario generation that would produce bias-corrected, apposite climate information, potentially including attribution (forced versus natural variability)
- Global integrated assessment models (e.g., to model international trade, links to energy and water, regional crop prices and consumption, LULCC, emissions, etc.), including both trends and shocks
- A crop/livestock/agroforestry model (e.g., to produce information on yield, water, energy, carbon, feedbacks to climate system, ecosystem services, etc.), including coupling to climate
- A hydrological model, including both surface and groundwater
- A representation of water resources management, including water allocations and water control
- A suite of regional and/or local economic models and/or microsimulations to produce information on welfare effects, local crop prices, consumption, income distributions, and effects on inequality/poverty, including both trends and shocks
- Land system models and/or geographic economic models to provide information on local land use.

In addition, this group identified a number of challenges and gaps. Their list of knowledge gaps includes:

- Precipitation, convective storms, and soil moisture in climate models
- The influence of agriculture on the carbon cycle
- Agricultural response to drought
- Economic response to drought-induced agricultural changes
- Groundwater availability
- Projecting socioeconomic change related to poverty and/or inequality.

They identified as set of modeling challenges, including:

- Developing a local-scale coupled economic, land surface, crop, hydrological, water resources management modeling framework

- Linking local-scale economic modeling to global IAMs
- Groundwater modeling
- Trade modeling
- Modeling crop response to drought
- How to determine which model handles what when domains and processes are overlapping (e.g., irrigation).

Finally, they identified some data gaps, including:
- Local-scale economic data, including household data
- Observational records for temperature and precipitation in developing countries to disentangle trends and shocks
- Crop management, including irrigation application and fertilizer use
- Sub-national data for variable-resolution IAMs.

Modeling extreme events was seen as particular important and challenging, particularly given the temporal and spatial resolution of models. Further challenges surround developing models to represent processes appropriately at these scales, modeling climate extremes and the impact of extremes on crop growth, and incorporating adaptive measures related to crop management.

The group felt that it would be challenging to manage the tradeoffs between completeness/resolution and tractability. As was the case with the other groups, they pointed to the importance of sensitivity studies to see which models, variables, and couplings matter at which scales. Other strategies for managing this tradeoff included variable-resolution models; modular frameworks that facilitate turning on and off different couplings to isolate the various effects; iterative development of separate components and couplings; and emulators for parts of the system (e.g., climate).

Finally, the group also agreed a community of practice would be useful. A major component of this community would include a variety of inputs (standard protocols to facilitate coupling, and a data repository); a common set of hardware and tools (including wrappers, facilities to enable calling subroutines/models in different software languages, maintaining the flexibility to swap components as needed); protocols to facilitate coupling outputs; and of course the people to make all this possible.

Synergies among Break-Out Groups

While each of the three break-out groups worked independently to tackle different problems, sometimes taking very different approaches, some common themes emerge across areas. The groups outlined a modeling framework that included IAMs and ESMs as linking frameworks that would provide boundary conditions for other regional and/or sectoral models (see Figures 2 and 3). Additionally, the three groups identified an overlapping group of capability needs, with multiple groups noting a need for climate information with uncertainty characterization, hydrological modeling, infrastructure modeling, trade modeling, and ecosystem services.

The groups also identified some similar challenges. Some overlapping gaps and challenges included groundwater modeling, data on water use, and a means of representing political, behavioral, and institutional constraints. Importantly, the groups discussed the challenge of uncertainty characterization, quantification, and propagation. In particular, groups noted that there were tradeoffs between completeness/resolution and tractability/uncertainty quantification.

All three groups proposed a set of sensitivity tests to identify strong linkages and feedbacks. These sensitivity tests could be used to determine which models, variables, and couplings matter for different scales and problems, as well as which uncertainties were most important and required more rigorous uncertainty quantification and analysis. One group noted that the development of a library of important couplings from existing studies and/or the development of tools to rapidly test sensitivities would be helpful. Another group noted that such a sensitivity experiment could help manage the complexity-versus-uncertainty tradeoff by identifying cases where complexity was required.

Two of the three groups noted a need for a community of practice. Such a community could include a common set of data, hardware tools, and protocols for facilitating coupling.

3.5. Panel on Coupling IAV Models, IAMs, and ESMs

Following the breakout group reports and discussion, a final set of presentations and discussion occurred on Thursday afternoon focused on coupling the three sets of models. The speakers were Juan Carlos Ciscar (EC), Peter Lawrence (NCAR), and Wolfram Schlenker (Columbia).

The first speaker described two projects being conducted in Europe: PESETA and Helix. PESETA has been conducted in several different stages, with the most recent (round III) being focused on adaptation policies/measures and extreme events. The project includes three coupling steps: ESM representation of high space/time resolution of important climate phenomena for the impacts sectors; use of sector bottom-up biophysical IAV models; and IAMs to integrate market impact results. There is a sub-project, PESETA-RISK, that is mimicking “Risky Business” to look at the tail risks that includes stochastic climate ensembles, biophysical impacts models of various degrees of complexity, including quick extensive models as well as emulators for topics such as agriculture, river floods, and coastal impacts. Helix addresses the question of what do 4C and 6C worlds like compared to a 2C future? And what are the implications of different adaptation choices? Coupling in this project is one-way, offline through data files and other approaches.

The second speaker briefly reviewed NCAR’s THESIS project, which couples a population model iPETS to CESM. This project takes a soft coupling approach in which model outputs are run through scripts to produce inputs to other models. Linkages among crop area, irrigation area, and nitrogen fertilizer are included.

The third speaker focused on one-way coupling of crop yield studies, climate, and economics. He described use of historical data as well as changes in yield simulated in models as a result of climate change, and noted that a key recent advance is use of fine-scale data on extremes. He described use of GDP as a proxy, noting its limitations as a welfare measure and its masking of impacts for some regions and vulnerable subgroups. He argued for focusing on first-order effects and keeping it simple by not including too many feedback loops.

General discussion of coupling the three sets of models ensued, touching on a number of points:

- How do we confront models with data? We have some experience with one model, but how do we do this with coupled models? It would be valuable to hear how different communities are dealing with validation (e.g., hindcasting, matching historical data, statistical approaches, testing elasticities of substitution, use of agent-based models). The view was expressed that there is a lot to learn on validation from the climate community.
- Several "public goods" were identified including highly resolved spatial population and income distributions.
- When coupling models, thinking about investments—what would have been made anyway and what does climate change induce?
- Problem with coupling is that the baseline becomes endogenous.
- Developing approaches to evaluate uncertainty and extreme events
- The importance of model intercomparison projects. Confront your models with other models and with observational data. Need a community of people working together
- The need to develop specific terminology and guidelines for coupling (e.g., with respect to validation, software engineering principles, terminology, etc.)?

4. Discussion and Conclusions

The final day of the workshop included participant reflections on what they learned and concluded from the presentations and discussion. Several key themes emerged. Many participants noted that tremendous progress had been made in the last five years in terms of problem-driven integration of IA, IAV, and ES modeling. The presentations included many examples of configurations of models and information from the three groups of models that were being integrated in different ways to explore specific problems. The participants saw this as evidence of the integration of the different research communities, and improving communication among them.

It was noted that a variety of coupling strategies were being used, and that efforts to define a common vocabulary were proceeding but needed to be continued. Several aspects of coupling were noted in an initial attempt to define strategies:

- Full coupling: resolved coupling and all variables are reconciled
- Partial coupling: the focus is on one particular sector, e.g., water.
- Tight coupling: pass info at every time period
- Loose coupling: exchange information across models less frequently
- Hard coupling: high degree with software integration (flux coupling)
- Soft coupling: low or no software integration (sneaker net).

Participants reflected on a number of key challenges, including:

- Putting this effort of integrating IAV-IA-ES models to better study feedbacks and interdependencies into context of SDGs and/or "adaptation science"
- Getting support for research on knowledge gaps (of basic processes to inform model development)
- Improving understanding of institutional issues and how to model them
  - Better representation of human decision-making
- Challenge of characterizing climate extremes

  - Working the problem backwards, especially to identify what climate extremes matter to focus climate research
- Managing complexity, not making things more complex/highly resolved than needed
  - Tools for sensitivity analysis, scoping multi-model configurations
- Hidden inconsistency in assumptions, scales (time/space)
- Evaluation/benchmarking
- Uncertainty characterization/quantification/communication methods in context of complexity.

Several future research efforts related to the challenges above were identified, including:

- Typology of use and model configurations:
  - Database of completed/ongoing projects
  - Analysis of models used, coupling modes, complexity, uncertainty, …
- Framework/review paper defining problem, approaches, terminology, etc.
- Joint project comparing single- versus multi-model impact results
- Empirical social science research on communicating complexity
- Integrated population/economic trends/projections at finer scales.

Many participants also reiterated the core strategy of building a community of practice that would establish a modeling framework from the bottom up through case studies and projects. They identified a number of aspects or elements that could be included, but no conclusions were reached about which were already being done under the auspices of different projects convened by DOE, and which needed to be developed as part of any new interagency initiatives as described during the workshop by several Federal participants. Aspects included:

- Repository/wiki of modeling components/capabilities
- Modeling tools/software environment
- Standards/nomenclature
- Evaluation/benchmarking tools
- Uncertainty characterization/communication research and tool development
- Computational resources
- Funding for collaborative research
- Resources for management of community data resources
- Facilitation of topical/technical working groups
- Case-study-focused meetings
- Mediated listserv.

A number of participants also touched on a set of needed capabilities during the final discussion, including:

- Approaches for sensitivity analysis
- Emulator development (climate, IAV, socioeconomic, …)
- Improved observational climate data products
- Scenario methods/diversity, topical/geographical focus.

5. Acknowledgments

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6. References

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Appendix A: Meeting Agenda

MONDAY, JULY 25, 2016

Introduction

Chair: John Weyant (Stanford University), Notetaker: Karen Fisher-Vanden

8:30-8:40	Welcome	John Weyant (Stanford University)
8:40-9:00	Introduction and Meeting Goals	Kate Calvin (Joint Global Change Research Institute/ Pacfic Northwest National Laboratory, JGCRI/PNNL)
9:00-9:10	Scientific Drivers, Needs, and Trends	Gary Geernaert (Department of Energy)
9:10-9:20	Scientific Drivers, Needs, and Trends	Bob Vallario (Department of Energy)
9:20-9:30	Scientific Drivers, Needs, and Trends	Dorothy Koch (Department of Energy)
9-30-9:45	OPEN DISCUSSION	

Impacts, Adaptation, and Vulnerability

Background *Chair: Kate Calvin (JGCRI/PNNL), Notetaker: Leon Clarke*

9:45-10:10	IAV Science Questions that Require Coupling and/or Inputs from IAM/ESM	John Weyant (Stanford University)
10:10-10:35	Designing a Model Framework from the Ground Up: Linking IAV, IAM, and ESM	Richard Moss (Joint Global Change Research Institute/ Pacfic Northwest National Laboratory, JGCRI/PNNL), Kate Calvin (JGCRI/PNNL), Karen Fisher-Vanden (Pennsylvania State University)
10:35-11:00	OPEN DISCUSSION	
11:00-11:15	MORNING BREAK	

Update from Existing Projects

Chair: Richard Moss (JGCRI/PNNL), Notetaker: Ian Sue Wing

11:15-11:35	PIAMDDI Method Comparison	Karen Fisher-Vanden (PSU), Juan Carlos Ciscar (European Commission, The Institute for Prospective Technological Studies)
11:35-11:55	AgMIP	Alex Ruane (National Aeronautics and Space Administration, NASA)
11:55-12:15	ISI-MIP	Franziska Piontek (Potsdam Institute for Climate Impact Research, PIK)

12:15-12:45	OPEN DISCUSSION
12:45-1:45	LUNCH

Coupling for IAV

Chair: Steve Rose (EPRI), Notetaker: Richard Moss

1:45-2:05	Energy	Mort Webster (Pennsylvania State University)
2:05-2:25	Water	Richard Lammers (University of New Hampshire)
2:25-2:45	Agriculture and Land	Alex Ruane (NASA)
2:45-3:15	OPEN DISCUSSION	
3:15-3:30	AFTERNOON BREAK	

Cross-Sectoral Challenges

Chair: Karen Fisher-Vanden (PSU), Notetaker: Mohamad Hejazi

3:30-3:50	Direct Coupling of IAV Models	Ian Kraucunas (Pacific Northwest National Laboratory, PNNL)
3:50-4:10	IAM Incorporating IAV	Ian Sue Wing (Boston University)
4:10-4:30	IAM as a Coordinating Mechanism to Integrate Impacts across Sectors and Regions	Kate Calvin (JGCRI/PNNL)
4:30-5:00	OPEN DISCUSSION	

TUESDAY, JULY 26, 2016

Integrated Assessment Models

Background

Chair: Keywan Riahi (IIASA), Notetaker: John Weyant

8:15-8:30	Scientific Drivers, Needs, and Trends	Tom van Ierland (European Commission)
8:30-8:55	Information Needs and Community Response	Leon Clarke (Joint Global Change Research Institute/ Pacfic Northwest National Laboratory, JGCRI/PNNL)
8:55-9:20	IAM Science Questions that Require Coupling and/or Inputs from IAV/ESM	Detlef van Vuuren (Netherlands Environmental Assessment Agency PBL)
9:20-9:45	OPEN DISCUSSION	

Update from Existing Projects

Chair: Jae Edmonds (JGCRI/PNNL); Notetaker: Mort Webster

9:45-10:00	AGCI Remote Sensing for IAMs	Ghassem Asrar (Joint Global Change Research Institute/ Pacfic Northwest National Laboratory, JGCRI/PNNL)
10:00-10:15	The IIASA World in 2050 Initiative	Nebojsa Nakicenovic (International Institute for Applied Systems Analysis, IIASA)
10:15-10:30	Update from CD-Links	Valentina Bosetti (Bocconi University)
10:30-11:00	MORNING BREAK	

Coupling for IAM

Chair: Leon Clarke (JGCRI/PNNL), Notetaker: Ian Kraucunas

11:00-11:20	Energy	Keywan Riahi (International Institute for Applied Systems Analysis, IIASA)
11:20-11:40	Water	Mohamad Hejazi (Joint Global Change Research Institute/ Pacfic Northwest National Laboratory, JGCRI/ PNNL)
11:40-12:00	Land	John Reilly (Massachusetts Institute of Technology)
12:00-12:30	OPEN DISCUSSION	
12:30-1:30	LUNCH	

Cross-Sectoral Model Coupling Challenges

Chair: Rob Nicholas (PSU), Notetaker: Andy Jones

1:30-1:50	Resolution Challenges in IPETS/CLM	Brian O'Neill (National Center for Atmospheric Research, NCAR)
1:50-2:10	Resolution Challenges in the AIM model	Kiyoshi Takahashi (National Institute for Environmental Studies, NIES)
2:10-2:30	Resolution Challenges in CIRA	Jim McFarland (U.S. Environmental Protection Agency)
2:30-3:00	OPEN DISCUSSION	
3:00-3:30	AFTERNOON BREAK	

Perspectives on Uncertainty

Chair: Erwan Monier (MIT), Notetaker: Jim McFarland

3:30-3:50	Modeling Uncertainty in IAV	Rob Lempert (RAND)
3:50-4:10	Modeling Uncertainty in IAM	Massimo Tavoni (Fondazione Eni Enrico Mattei, FEEM)
4:10-4:30	Modeling Uncertainty in ESM	Klaus Keller (Pennsylvania State University)
4:30-5:00	OPEN DISCUSSION	

WEDNESDAY, JULY 27, 2016

Earth System Models

Background

Chair: Ghassem Asrar (JGCRI/PNNL), Notetaker: Rob Nicholas

8:30-8:55	ESM Science Questions that Require Coupling and/or Inputs from IAM/IAV	Jean-Francois Lamarque (National Center for Atmospheric Research, NCAR)
8:55-9:07	CMIP and ACME Scenario Efforts	Claudia Tebaldi (National Center for Atmospheric Research, NCAR)
9:08-9: 20	CMIP and ACME Scenario Efforts	Dorothy Koch (U.S. Department of Energy)
9:08-9:45	OPEN DISCUSSION	

Update from Existing Projects

Chair: Ghassem Asrar (JGCRI/PNNL), Notetaker: Klaus Keller

9:45-10:00	AGCI High-Resolution Meeting	Andy Jones (Lawrence Berkeley National Laboratory)
10:00-10:30	MORNING BREAK	

Coupling for ESM

Chair: Andy Jones (Lawrence Berkeley National Laboratory),
Notetaker: Claudia Tebaldi

10:30-10:50	IGSM	Erwan Monier (Massachusetts Institute of Technology)
10:50-11:10	CESM and iPETS	Peter Lawrence (National Center for Atmospheric Research, NCAR)
11:10-11:30	iESM	Bill Collins (Lawrence Berkeley National Laboratory)
11:30-11:50	CNRM-IMAGE	Detlef van Vuuren (PBL)
11:50-12:20	OPEN DISCUSSION	
12:20-1:30	LUNCH	

Approaches for Climate Model Information

Chair: Klaus Keller (PSU), Notetaker: Erwan Monier

1:30-1:50	Characterization of Extremes (remote presentation)	Noah Diffenbaugh (Stanford University)
1:50-2:10	High-Resolution Climate Modeling	Ruby Leung (Pacific Northwest National Laboratory, PNNL)
2:10-2:30	Pattern Scaling and Climate Statistics	Claudia Tebaldi (NCAR)
2:30-	Tools for Climate Information	Rob Nicholas (Pennsylvania State University)

2:50		
2:50-3:20	AFTERNOON BREAK	
3:20-5:00	PANEL DISCUSSION	

THURSDAY, JULY 28, 2016

Breakout Sessions on Use Cases from the IA-IAV-ESM workshop May 24-26

9:00-10:00	Overview of Use Cases, Conceptual Diagrams, and Capabilities Needed	Richard Moss (JGCRI/PNNL) and Karen Fisher-Vanden (PSU)
10:00-1:00	BREAKOUT GROUPS	
1:00-2:00	LUNCH	
2:00-3:00	Report Back from Breakout Groups	Group Leads (TBD)
3:00-3:30	AFTERNOON BREAK	

Coupling IAV Models, IAMs, and ESMs:

Chair: Ian Kraucunas (PNNL)

3:30-5:00	Panel Discussion on Coupling	Juan Carlos Ciscar (European Commission) Peter Lawrence (NCAR) Wolfram Schlenker (Columbia University) Ian Sue Wing (Boston University)

FRIDAY, JULY 29, 2016

9:00-10:00	Conclusions/ wrap up/ next steps
10:00	MORNING BREAK
12:00	LUNCH
1:00-3:00	Writing session with co-chairs

Appendix B: Participant List

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