DISCLAIMER

A MULTI-MODEL, MULTI-SCALE RESEARCH PROGRAM IN STRESSORS, RESPONSES, AND COUPLED SYSTEMS DYNAMICS AT THE ENERGY-WATER-LAND NEXUS AND FOR CONCENTRATED, INTERDEPENDENT INFRASTRUCTURES: TOWARD NEXT GENERATION CAPABILITIES IN INTEGRATED IMPACTS, ADAPTATION, AND VULNERABILITY (I-IAV) MODELING AND A COMMUNITY OF PRACTICE

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COVER PAGE

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"A Multi-Model, Multi-Scale Research Program in Stressors, Responses, and Coupled Systems Dynamics at the Energy-Water-Land Nexus and for Concentrated, Interdependent Infrastructures: Toward Next Generation Capabilities in Integrated Impacts, Adaptation, and Vulnerability (I-IAV) Modeling and a Community of Practice"

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Summary /Abstract

A Multi-Model, Multi-Scale Research Program in Stressors, Responses, and Coupled Systems Dynamics at the Energy-Water-Land Nexus and for Concentrated, Interdependent Infrastructures: Toward Next Generation Capabilities in Integrated Impacts, Adaptation, and Vulnerability (I-IAV) Modeling and a Community of Practice

Project Director / Principal Investigator: John Weyant, Stanford University

Objectives

The goal of this research program was to build a next generation integrated suite of science-driven modeling and analytic capabilities, and a more expanded and connected community of practice, for analyses of the stressors, impacts, adaptations and vulnerabilities of global and regional change. The emphasis was on understanding energy-water-land interactions and feedbacks and interdependent infrastructures at appropriate regional and temporal scales. Although the scope spans many complex facets of data, modeling, and analysis, as well as scales appropriate for integrated impacts and adaptation research, the focus of this effort was the development of multi-model, multi-scale capabilities spanning the domains of Multi-Sector Dynamics (MSD) models; Impact, Adaptation, and Vulnerability (IAV) models; and Earth System Models (ESMs).

Overview of Research Program

The new capabilities and interactions developed in the research program whose results are summarized here were achieved by pursuing research within four interrelated project elements:

I. The development of a use-inspired, innovative and adaptive framework for multi-model multi-scale research and analysis of integrated impacts, adaptation, and vulnerability.

II. The development of foundational modeling integration methods and capabilities with the requisite coupling software, emulators, advanced computational and statistical methods, and translational tools.

III. The assessment and establishment of best modeling practices, and development and testing of evaluation tools, via diagnostics, methods comparisons and integrated uncertainty analyses.

IV. The creation of a better organized community of practice created by promoting systematic engagement between the MSD, IAV, and ESM communities, advancing team-based methodological developments and integrated modeling experiments in integrated multi-sector, multi-region, vulnerability and adaptation analyses.

Research Results

Program element I was the largest of these elements and it provided key building blocks for the other three program elements and vice versa. In it a use-inspired, innovative and adaptive framework for multi-model, multi-scale research and analysis of integrated impacts, adaptation, and vulnerability (IAV) was developed. The framework was adaptable because developing one framework to capture all important use cases is neither possible nor desirable, with a different platform required depending on the scale of the problem and the use case to be addressed. Recognizing this, the project team pursued a multi-pronged approach to assessing multisector, multi-scale impacts which spans the spectrum of uses and approaches. This enabled us to compare these approaches with each other and to assess the strengths and shortcomings of each, along with developing the coupling required in order to better represent multi-sector impacts and adaptation within coupled energy-water-land systems. This also allowed the team to uncover gaps that were not addressed in any of the frameworks that were initially explored and, thus, identify important areas for future research.

The research conducted within program element I was organized into the development of three distinct modeling platforms that varied in scope and level of spatial disaggregation, depending on the use cases to be addressed. The application of the platforms to the use cases was used to demonstrate the efficacy of the modeling methods employed and the kinds of results that they can be used to produce. The first platform was built around a gridded U.S. scale architecture and was used to study the effects of extreme weather events on the energy-water-land system, and adaptation options in the contiguous U.S. The second platform focused on the western U.S. in more detail and was used to study how governance, as well as institutional and system constraints would affect regional economies under alternative climatic futures, and how relaxing these constraints and addressing market failures could alleviate these economic impacts. The third platform was built on a global platform using an architecture with much larger grid cells and emulators that were calibrated to more dis-aggregated observations and/or the results from more detailed regional and sectoral models. It was focused on assessing at global scale the risks of cascading adverse impacts on the energy-water-land systems posed by global changes.

In order to support the building of a next-generation integrated suite of science-driven modeling and analytic capabilities, a key research direction addressed in program element II was improving the representation of feedbacks and interactions in MSDs and IAV models in a way that also accounts for decision-relevant uncertainties in two areas: (1) impacts on the coupled energy-water-land system from changes in precipitation and (2) impacts on energy and connected infrastructure resulting from extreme weather events.

Program element III in the work plan produced two closely interrelated products. The first was the development of methods comparisons, diagnostics and integrated uncertainty analysis methods to improve the development of the integrated impacts assessment and emulator/coupling/downscaling tools described above. The second was to demonstrate the value of these evaluation tools in improving the credibility of the modeling systems that were developed.

Program element IV was focused on creating a better organized multi-sectoral/multi-regional/multi-model community of practice by promoting systematic engagement between the MSD, IAV, and ESM communities, advancing team-based methodological developments and integrated modeling experiments in IAV research.

This research program has helped to improve integrated multi-sector impact/adaptation /vulnerability (I-IAV) assessments. At the same time, it was done in a way that makes its results as transparent and credible as possible to the other global change research communities, and to those involved in research management and policy development using the outputs of the analyses conducted by these communities.

Final Report on Grant # DE-SC0016162 "A Multi-Model, Multi-Scale Research Program in Stressors, Responses, and Coupled Systems Dynamics at the Energy-Water-Land Nexus and for Concentrated, Interdependent Infrastructures: Toward Next Generation Capabilities in Integrated Impacts, Adaptation, and Vulnerability (I-IAV) Modeling and a Community of Practice"

PROGRAM OBJECTIVES

The overarching goal of this research program is to build a next generation integrated suite of science-driven modeling and analytic capabilities, and a more expanded and connected community of practice, for analyses of the stressors, impacts, adaptations and vulnerabilities of global and regional change, with an emphasis on understanding coupled energy-water-land system dynamics and interdependent infrastructures.

PCHES-FRAME RESEARCH OBJECTIVES IN EMERGING RESEARCH AREAS

Program Element I: Developing a use-inspired, innovative, and adaptive framework for multi-model multi-scale research and analysis of integrated impacts, adaptation, and vulnerability (I-IAV).

Leads: Karen Fisher-Vanden, Thomas Hertel, and Ian Sue Wing; Contributors: Noah Diffenbaugh, Steve Frolking, Richard Lammers, Erin Mansur, Sheila Olmstead, Wolfram Schlenker, Mort Webster, Douglass Wrenn. Key Collaborators: Chris Forest, Murali Haran, Klaus Keller, Robert Nicholas, Patrick Reed, Ryan Sriver, John Weyant

In this program element, we seek to develop a use-inspired, innovative and adaptive framework for multi-model, multi-scale research and analysis of integrated impacts, adaptation, and vulnerability (I-IAV). However, developing one framework approach to capture all use cases is not possible. A different approach is required depending on the scale of the problem and the question and use case to be addressed. Recognizing this, our project team takes a multi-pronged approach to assessing multisector, multi-scale impacts which spans the spectrum of uses and approaches described in the introduction. This allows us to compare across these approaches to assess the strengths and shortcomings of each of these approaches, along with the coupling required in order to accurately assess extreme weather impacts and adaptation within the EWL nexus. This will also allow us to uncover gaps that are not addressed in any of the approaches and, thus, identify important areas for future research.

Subproject 1.1: Gridded modeling of the energy-water-land dynamics

Investigators: Thomas Hertel (Lead), Noah Diffenbaugh, Steve Frolking, Richard Lammers, Wolfram Schlenker and Mort Webster

Project 1.1. is focused on questions related to extreme weather events, their effects on the energy-water-land system, and adaptation options in the contiguous U.S. To address these questions, fine-scale spatial and temporal analysis of the EWL system is necessary in order to capture the frequency, intensity and impacts of extreme weather events, as well as to understand the infrastructure needs for adaptation to these events. Therefore, the proposed approach involves coupling fine-scale process models (water balance, power system and agricultural impact models) with a simplified gridded economic model (SIMPLE-G) of the U.S. Note that this program element is tightly focused on these three sectors in order to allow for analysis at high resolution.

The goal of this subproject is to develop a fine scale analysis of the energy-water-land system which is capable of capturing the impact of extreme weather events as well as to understand the infrastructure needs for adaptation to these events.

Subproject 1.2: Capturing governance, institutional, and system constraints related to energy-water-land in an integrated modeling framework

Investigators: Karen Fisher-Vanden (Lead), Steve Frolking, Richard Lammers, Sheila Olmstead, Mort Webster, and Doug Wrenn

Project 1.2 is focused on understanding how governance, institutional and system constraints will affect regional economies under alternative climatic futures, and how relaxing these constraints and addressing market failures could alleviate these economic impacts. To do this requires incorporation of local and regional physical and economic detail. Therefore, we are coupling fine-scale process models (water balance and power system models) with a sectoral-detailed economic model focused on the Western U.S. and Texas which acts as the coordinating mechanism to facilitate the interlinkages 14 between the fine-scale IAV models, with an emphasis on governance, institutional, and system constraints.

The goal of this subproject is to develop a multidisciplinary multi-model, multi-scale framework focused on the US that couples downscaled weather information with sectoral MSD models of water, electric power, agriculture, and population/demographics, which are all tied to a regional economic model to capture economic feedbacks through prices and demand. Importantly, these sectoral models will incorporate important governance, institutional, and system constraints, which are often overlooked yet important factors when modeling integrated impacts. These constraints can lead to situations of maladaptation to impacts such as water shortages or extreme weather events (e.g. extreme temperatures, drought, and floods). Not only is it important to represent these constraints individually in a framework for modeling integrated impacts, it is also critically important to model how these constraints interact to exacerbate an already strained system. We focus initially on the regional scale, with the intention of generating "rules of thumb" that could be aggregated to the larger scale (e.g., Western US).

Subproject 1.3: Integrated modeling of weather and climate impact risk on coupled food-energy-water dynamics

Investigators: Ian Sue Wing (Lead), Erin Mansur

Project 1.3 is focused on assessing, globally, the risks of cascading adverse impacts on the energy-water-land nexus posed by climate variability and change. Addressing questions at this scale requires a different approach than in Projects 1.1 and 1.2 since direct coupling of detailed process models is typically not feasible at this scale. Therefore, in this project element we emphasize the building of large scale statistical and process emulators that can be directly incorporated into a global MSD.

The goal of this subproject is to develop an infrastructure capable of simulating the economic and environmental drivers and consequences of energy-water-land interactions at regional to global scales, encompassing three components: (1) Reduced-form emulators of responses of energy and agricultural systems to weather shocks, econometrically estimated using historical observations of weather, crop yields, and energy consumption. (2) Ensemble projections of energy- and agriculture-system impacts under different socioeconomic and climatic scenarios by linking emulators to Earth system model projections of future meteorology. (3) A global computational general equilibrium (CGE) modeling framework incorporating regionally and sectorally aggregated ensemble impact projections. This infrastructure is exercised using computational experiments to elaborate causal chains of influence within the context of climatic uncertainty.

Subproject 1.F: Integrated modeling and assessment of behavioral responses to combined flood risk for coastal communities

Investigators: Sheila Olmstead (lead), Douglass Wrenn, Klaus Keller

This project develops a cross-disciplinary, integrated approach to assessment and modeling of behavioral responses to actual and perceived flood risk. The project focuses on the Tampa Bay, FL and Houston, TX metro areas, both of which experience combined flood impacts from extreme precipitation, sea level rise, and storm surge. This subproject was added later into the project.

<u>Program Element II</u>: Building foundational, modeling integration methods and capabilities with the development of coupling software, emulators, advanced computational and statistical methods, and translational tools.

Co-Leads: Robert Nicholas and Klaus Keller; Contributors: Chris Forest, Murali Haran, Patrick Reed, and Ryan Sriver. Key Collaborators: Noah Diffenbaugh, Karen Fisher-Vanden, Thomas Hertel, Wolfram Schlenker, Ian Sue Wing, and Mort Webster, with inputs from and collaborations with many other MSD/IAV project participants

Our long-term vision is to support the building of a next-generation integrated suite of science-driven modeling and analytic capabilities. The key step towards this goal addressed in this program element is to improve the representation of feedbacks and interactions in MSDs and IAV models in a way that also accounts for decision-relevant uncertainties in two areas: (1) impacts on the coupled energy-water-land system from changes in precipitation and (2) impacts on energy and connected infrastructure from extreme weather events. We focus on producing deliverables of more easily-shareable, open-source, and well-documented products (e.g., data products, software tools, as well as manuscripts) that are targeted at helping answer key scientific and technical questions (discussed below in example project vignettes) at multiple spatial and temporal scales. This work leverages ongoing analyses (discussed in several examples elsewhere) in the areas of Earth system modeling, uncertainty quantification, emulation, downscaling, data distribution and curation, and extreme event analysis. The project serves as a conduit for integrating the results of these investments more widely into IAV analyses within the project and beyond. In other words, this project is a key avenue to strengthen the much needed connections between applications and scientific as well as technical questions. The current design addresses interconnected questions that are addressed in multi-disciplinary projects that bring together a diverse set of skills spanning disciplines such as economics, Earth sciences, engineering, and statistics. These subprojects are discussed, in turn, below.

<u>Subproject 2.1</u>: Improving the quality and ease of use of climate information

Lead: Robert Nicholas. Key Collaborators: Chris Forest, Klaus Keller, Murali Haran, Ryan Sriver, and Patrick Reed.

The current representation of Earth system model projections has made tremendous progress in the recent past, but these methods still face considerable challenges. For example, two largely open questions that we address in this project (in collaboration with many others working on MSD/IAV analyses) are: (i) How skillful are current empirical-statistical downscaling tools in their representation of decision-relevant information (e.g., modes and tails of relevant probability density functions or the spatio-temporal correlation structure) on regional to local scales? (ii) What are the inherent trade-offs between downscaling and emulation strategies (e.g. statistical emulators based on observational data versus mechanistic/process emulators based on model ensembles) for generating weather and climate information for IAV?

The central goal of this subproject is to improve the quality, ease-of-use, and utility of weather and climate information within the integrated modeling frameworks being developed throughout the various PCHES subprojects. To this end, this subproject aims to: (1) develop tools and datasets that allow modeling teams to better characterize the sensitivity of their models to key climate system characteristics, (2) improve the representation of extreme events and key uncertainties in weather and climate data products, (3) develop translational tools to simplify and standardize the exchange of weather and other information between models, and (4) provide a shared cyberinfrastructure environment that supports and promotes collaboration between modeling teams and across disciplinary boundaries.

Subproject 2.2: How does an improved sampling of known uncertainties influence the tails of climate projections on decision-relevant spatial and temporal scales?

Co-Lead: Klaus Keller and Ryan Sriver. Key Collaborators: Chris Forest, Murali Haran, Robert Nicholas, and Patrick Reed.

The goal of this subproject is to analyze how known weather and climate uncertainties influence the tails of projections on decision-relevant spatial and temporal scales. Our aim is to improve the reliability and robustness of projections of extremes using a multi-faceted approach synthesizing comprehensive observational data products and model output from global and regional products. We aim to diagnose and evaluate model skill in capturing the statistics of weather extremes for the current and potential future climate states and characterize uncertainties due to factors such as coupled internal variability, model structure, biases in large-scale dynamics, and resolution. We are also developing new diagnostic tools (focusing on extremes) for model evaluation and to guide regional impacts analyses that rely on these data products. This effort fits within the broader themes of PCHES by improving hindcasts and projections of decision-relevant weather and climate variables, quantifying uncertainty surrounding extremes, and informing regional efforts.

<u>Subproject 2.3</u>: Developing regional climate projection tools to incorporate high risk events into decision-tools.

Lead: Chris Forest. Key collaborators: Klaus Keller, Patrick Reed, Ryan Sriver, and Robert Nicholas.

One limitation of current climate emulation methods is that global mean surface temperature is only one of several factors that may be relevant for changes in regional weather conditions. It is well known that sea surface temperatures (both tropical and extra-tropical) drive large-scale teleconnection patterns that influence regional climate on seasonal and inter-annual time-scales. Primary examples are droughts over North America driven by El Nino or La Nina events which provide a tropical-wide forcing of the global climate system. Previous work (Tsai et al. 2014, Li and Forest 2014) has focused on developing statistical methods to emulate large-scale regional variability and change driven by such SST variability. Additionally, large-scale changes in patterns of snow cover, sea ice,and land cover are also known to drive large-scale atmospheric teleconnection responses influencing regional weather patterns. However, the teleconnection characteristics (primarily, spatial and seasonal changes) of these other factors are expected to differ from those for SST-driven teleconnections such as ENSO. Driven by the combined regional and global scale response over the coming century, potentially high risk events such as those described above must be included in scenarios where regionally-resolved variability and change is important for careful IAV assessments.

Building upon prior work under PCHES-IAMDDI, the goal of this subproject is to develop teleconnection response functions which can serve as emulators, mapping patterns of sea surface temperature variability (as well as patterns of variability in land surface properties) to application-relevant Earth system responses.

<u>Program Element III</u>: Establishing best modeling practices, and developing framework evaluation tools for modeling frameworks via methods comparisons, diagnostics, and integrated uncertainty analyses.

Co-leads: John Weyant, Noah Diffenbaugh, David Lobell, Patrick Reed. Key Collaborators: Karen Fisher-Vanden, Thomas Hertel, Ian Sue Wing, Robert Nicholas, Klaus Keller

This element of our work plan has two closely interrelated objectives. The first objective is to develop methods comparisons, diagnostics and integrated uncertainty analysis methods to improve the development of the integrated impacts assessment and emulator/coupling/downscaling tools described in the two previous sections of this proposal. These developed model evaluation tools aim to assess the usefulness of the three modeling frameworks in addressing the specific research questions and use cases included in Element I of this proposal. The second objective is to demonstrate the value of these model evaluation tools in improving the credibility of the modeling systems being developed. The structure of our overall research program provides some unique opportunities to establish best practices for developing both multi-method modeling frameworks and best evaluation practices for them in parallel.

Subproject 3.1: Base research program for developing evaluation tools for modeling frameworks.

Lead: John Weyant. Key Collaborators: Noah Diffenbaugh, David Lobell, Patrick Reed, Karen Fisher-Vanden, Thomas Hertel, Ian Sue Wing, Robert Nicholas, Klaus Keller.

Standards for model development and evaluation have been developed within a large number of academic disciplines and application communities. Most, but not all, of this work has focused on single models developed within the boundaries of a single discipline without considering uncertainty in a systematic way. We draw on this broad range of concepts and methods to develop multi-method, multi-disciplinary, multi-scale best modeling and model evaluation practices.

This subproject is focused on developing evaluation tools and methods for uncertainty characterization for integrated energy, land and water impacts assessments. These tools and approaches will be applied to the methods and models being developed in Program Elements I and II above, but should also be generalizable to many other model platforms.

Subproject 3.2: Climate projections method intercomparisons and model diagnostics.

Co-Leads: Patrick Reed and Klaus Keller. Key Collaborators: Karen Fisher-Vanden, Chris Forest, Murali Haran, Robert Mendelsohn, Robert Nicholas, and Ryan Sriver.

This subproject aims to explore and understand the implications of uncertainty in human-Earth system interactions, focusing on issues associated with interactions between energy, water, land systems, and the way that climate and human decisions influence these interactions.

Subproject 3.2 focuses on refining the global sensitivity-based diagnostic tools and link with key IAV / MSD / ESM team leaders to set up a suite of proof of concept analyses to quantify the effects of improving projections of weather extremes on risks, vulnerabilities, and impacts and to determine which (interacting) uncertainties matter the most. Major factors shape this integration challenge including computational demands, difficulties in choosing appropriate methods that can distinguish controlling uncertainties, and the difficulty of understanding how to consistently tailor model information in a manner that has relevance to real operational and planning challenges across multi- sector demands and services.

<u>Subproject 3.3</u>: Quantifying the influence of global temperature change on unprecedented extreme events

Lead: Noah Diffenbaugh. Collaborators: Karen Fisher-Vanden, Thomas Hertel, Ian Sue Wing, John Weyant.

This subproject seeks to better understand the processes that control the response of extreme weather and climate events, and the impacts of changes in extremes on energy-water-land dynamics.

Effective weather and climate risk management requires robust quantification of the probability of different kinds of hazards, such as heat waves, droughts, floods, and severe storms. This work on projecting extreme weather and climate events has two major elements: (1) testing the extent to which temperature changes that have already occurred have increased the probability of extreme events, and (2) using a multi-level nested Earth system model projection scheme to project the extent to which future temperature changes will increase the probability of extreme events.

<u>Subproject 3.4</u>: Understanding adaptation in climate impacts analyses

Lead: David Lobell.

One of the most difficult challenges in modeling weather impacts using any methodology is projecting the adaptation of the impacted sectors to evolving weather extremes. Technical, institutional and management changes are occurring continuously in the impacted sectors and those trends are usually included in projections of baseline productivity trends in integrated modeling systems that are input to impact assessments and treated as adaptation in process models of these impacts. Thus, there is a risk of double counting technological, management, and or institutional changes when examining weather and climate impact projections, and this risk can only be reduced if one understands at a more detailed level: (i) the drivers of sectoral activity and productivity levels in the integrated models and (ii) the drivers of adaptation benefits in process model studies of impacts in those sectors.

Key goals of this subproject are: (1) To examine the underlying drivers of yield gains in major agricultural regions and the changing sensitivity of yields to weather over time, with a particular focus on the role of irrigation in each. (2) To determine the degree to which existing efforts to model adaptation may double count technology or management changes.

Program Element IV: Creating a better organized multi-sectoral/multi-regional/multi-model community of practice by promoting systematic engagement between the integrated modeling system and Earth system modeling communities, advancing team-based methodological developments and integrated modeling experiments in IAV research.

Leads: Fisher-Vanden and Weyant.

Subproject 4.1: Planned research community engagement activities

Leads: Karen Fisher-Vanden and John Weyant. Contributors: Thomas Hertel, Ian Sue Wing, Robert Nicholas, Klaus Keller.

Our research team includes individuals from a wide array of disciplines and institutional perspectives and is geographically dispersed. On the other hand, the work of the team represents only a small fraction of the integrated modeling and IAV work going on globally. Thus, it is important to create opportunities both for our project team to coordinate its work internally by bringing the different research teams within the project together, as well as to provide opportunities for cross fertilization with researchers doing related in other leading MSD and IAV research groups in the U.S. and abroad, as well as important I-IAV user communities. These challenges are met with a number of different engagement initiatives.

This subproject seeks to create opportunities for our project team to coordinate its work internally, across the different research teams within the project, and with other leading MSD research teams in the US and abroad. In the latter case, it is critical to engage major international modeling teams to maintain cognizance and leverage insights and capabilities for US methodological applications, just as these communities are able to build from US methodological capabilities.

PROGRESS ON RESEARCH PROJECTS

Program Element I

Subproject 1.1: Gridded modeling of the energy-water-land dynamics

This subproject has made great progress through linked studies that aimed to create a fine-scale understanding of the energy-water-land system to capture the impacts of extreme weather events and identify infrastructure needs for adaptation.

The creation of high-resolution datasets and models was central to our work. Baldos et al. (2020) introduced SIMPLE-G, a model that links global agricultural markets with local land and water resources. This framework enables the analysis of how global changes in population and income drive U.S. agricultural production and how local policies influence global markets. While there are other models that use a grid-resolving approach to a global economic analysis of sustainability challenges, SIMPLE-G is the first that is fully open-source and available to run in the cloud. It is designed to be readily adapted by other researchers working at the interface of the land-water-energy nexus. The model makes it possible to better understand both global-to-local and local-to-global interactions for informed policy-making. Grogan et al. (2022) described advancements in the Water Balance Model (WBM), now fully open-source, which simulates global water cycles, irrigation water use, and includes a unique water source tracking feature that provides transparent insights into the mechanisms behind water distribution. The ability to use both WBM and SIMPLE-G models together has greatly enhanced our research capabilities in answering questions about interconnected systems. To that end Woo et al. (2022) focused on model integration, presenting C3F, a cyberinfrastructure framework designed to link complex models like WBM and SIMPLE-G efficiently. This framework enhances the reproducibility and modularity of model coupling, providing a scalable solution for other projects exploring the energy-water-land nexus. Adding to the modeling toolkit, Grogan et al. (2022a) introduced a new set of high-resolution global gridded crop datasets that provide detailed information on crop production, harvesting, and yield patterns at a 5-minute resolution, using the Global Agro-Ecological Zones (GAEZ) model data. These datasets are crucial for Earth System and Multisector Dynamics models and offer the necessary granularity for analyzing the energy-water-land system.

The implications of these foundational modeling tools are explored in several following studies. A study by Liu et al. (2017) delves into the trade-offs between irrigation water use and global food security by coupling a global SIMPLE-G with the WBM. Their findings reveal that restricting unsustainable irrigation without productivity improvements could exacerbate food insecurity and increase carbon emissions, emphasizing the interconnectedness of water management and other sustainability goals. Haqiqi et al. (2023) examined the impact of growing global food demand on U.S. groundwater sustainability. Their analysis with the SIMPLE-G-US model shows that international market forces drive over half of U.S. groundwater stress, and sustainability policies in the U.S. can have unintended global environmental consequences. Furthermore, in a different example study, Haqiqi et al. (2021) used WBM to show that measures of compound hydroclimatic extremes are more accurate than metrics of individual extremes in forecasting changes in corn output. The U.S. is the world's top food exporter, producing a large share of essential crops like corn, soybeans, wheat, and rice, which provide 75% of the calories people consume. In fact, the U.S. grows over 40% of the world's corn. However, extreme weather events, such as heatwaves and heavy rainfall, can disrupt crop production, affecting food supplies, prices, and farmers' incomes. As these extreme events become more frequent and intense worldwide, understanding how they impact crop production is crucial for ensuring global food security now and in the future. This study examines how extreme weather events, such as drought and heatwaves, affect corn yields in the U.S., focusing on how these factors combine rather than just looking at them individually. By using detailed weather and soil moisture data from 1981 to 2015, the researchers found that compound extremes—like heat stress and water shortage happening together—are more accurate predictors of crop yield changes than looking at these factors in isolation. In particular, seasonal mean soil moisture performs better than average precipitation in statistically predicting corn yield. Additionally, heat stress is significantly more damaging to corn yields when combined with water stress, with the average yield damage from heat stress being up to 4 times more severe when combined with water shortage. Therefore, the value of water in maintaining crop yield is up to 4 times larger on hot-dry days. This study emphasizes the importance of accounting for multiple interacting factors when predicting future crop yields, particularly as climatic variability and change intensifies these extremes.

Further exploring the connections between climatic drivers and agricultural productivity, Lafferty et al. (2021) compared Earth system model outputs for U.S. corn yields with respect to the prediction of variables critical to extreme events in agriculture. A multi-model ensemble analysis showed that historical annual corn yields in the U.S. are overstated by CMIP5 models and underestimated by bias-corrected and downscaled models because of variations in temperature and precipitation hindcasts. Complementing this, Hogan and Schlenker (2024) investigate the importance of accurately modeling weather extremes for agricultural yields. They demonstrate that global datasets like GMFD and ERA5-Land effectively capture the impact of daily temperature extremes, which is crucial for global agricultural price modeling, given that global supply determines agricultural prices.

Schlenker and Taylor (2021) offer a financial perspective on climate dynamics by comparing Earth system model predictions with weather derivatives markets. Their findings suggest that financial markets incorporate scientific Earth system model projections into their pricing, indicating that market participants are increasingly accounting for climate variability. This insight could aid in developing market-based strategies for adaptation.

Adopting a holistic view of energy-water-land systems in a policy context, Sun et al. (2020) examine the effects of energy policies, such as biomass co-firing mandates, showing that localized policies can have wide-reaching impacts on land use and environmental outcomes. Researchers applied a novel detailed, regionally focused model to examine how coal plants in the upper Midcontinent Independent System Operator (MISO) region might respond to a rule requiring the burning of biomass along with coal. They found that some power plants would likely stop operating, unable to compete due to high biomass costs and increased operating expenses. This would, in turn, affect local corn production, nitrogen fertilizer application, and water quality with effects reaching even regions not involved in biomass co-firing. Critically, Sun et al. (2020) found that using only broad-scale averages could miss significant local environmental impacts, such as the large spike in nitrate pollution in certain areas already prone to leaching. The mandate's demand for corn residues disrupts traditional crop rotations, increasing continuous corn planting and fertilizer use, which exacerbates nitrate leaching into groundwater, particularly in pollution hotspots.This study underscores the importance of balancing fine-scale and broader regional analyses to fully capture the environmental and market impacts of energy policies including intricate interactions between energy, agriculture, and environmental systems.

Together, these studies adopt a comprehensive approach to understanding and managing the energy-water-land system. By integrating high-resolution datasets, advanced hydrological models, economic and agricultural simulations, and policy impact assessments, this subproject is well-positioned to inform strategies for adapting infrastructure to extreme weather events and management of interconnected resources.

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Subproject 1.2: Capturing governance, institutional, and system constraints related to energy-water-land in an integrated modeling framework

This research subproject was aimed at creating an integrated, multi-disciplinary framework to assess the U.S. energy-water-land system, combining downscaled climate information with sectoral models for water, power, agriculture, and demographics. A central focus was on capturing economic feedback loops through pricing and demand, allowing for a holistic approach to analyzing adaptation needs. Each study contributes distinct elements—governance, market dynamics, hydrology, infrastructure stressors, and population shifts—that are necessary for understanding the U.S. energy-water-land system's resilience.

The studies by Cacccese and Fowler (2020), Rimsaite et al. (2021), and Lisk et al. (2024) lay the groundwork for understanding water governance and rights in the Western U.S., where complex and often disparate legal structures challenge resource management amid shifting hydrological and population dynamics. To improve our understanding of real-world water flows through the system, Cacccese and Fowler's (2020) research emphasizes how important it is to incorporate the governance and allocation of water in the Pacific Northwest into coupled multi-sector models. Building on these governance insights, Rimsaite et al. (2021) investigate the economic efficiency of water rights markets, finding that pricing mechanisms in some regions, like California's Mojave Basin, better reflect scarcity and value in water use. There is significant potential for efficiency improvements in water rights markets in the western U.S., which could lead to higher welfare gains from the reallocation of water. The research highlights the role of well-functioning water markets in redistributing resources to meet demand under scarcity, a critical factor as the project aimed to model economic feedbacks within the water sector. Bringing these concepts together, Lisk et al. (2024) developed the HarDWR database, harmonizing water rights records across 11 states to enable standardized analysis of water rights trading. This database supports modeling efforts to realistically depict water allocation, providing critical inputs for evaluating water scarcity and economic impacts on regional agriculture and power generation.

Further exploring the subject of how water scarcity is related to agricultural resilience in the U.S. West, Zuidema et al. (2020) used WBM with explicitly parameterized irrigation technologies to quantify the effects of enhanced irrigation efficiency and aquifer recharge strategies on water sustainability in the Upper Snake River Basin. Their findings indicate that, without adequate recharge, even improvements in irrigation technology can lead to aquifer depletion, because the volume of water required to stabilize regional aquifers can surpass the gains realized from enhanced irrigation efficiency.

Higher water temperatures can lead to a causal chain of events from electric power generators offline because of cooling water intake temperature limits to higher electricity costs and unmet electricity demand to economic adjustment to productivity reductions in electricity using sectors. Webster et al. (2022) explore how climate-related water stress and higher water temperatures, can disrupt power generation and impact the broader economy in the Western U.S. Using a detailed model that links water, power, and economic systems, this study found that when water temperatures exceed safe levels for cooling, power plants may need to shut down, causing ripple effects. They also find that not all reductions in reserve electricity generation capacity result in impacts and that when they occur, intermittent interruptions in electricity supply at critical times of the day, week, and year account for much of the economic impacts. Importantly, the effects of these disruptions aren't always felt where they begin—issues in one area can lead to shortages and economic impacts elsewhere. The study highlights the importance of modeling these complex, overlapping interactions in detail to capture specific events that drive economic costs, showing that impacts are not uniform and vary by location, time, and industry.

Incorporating demographics into the project's modeling framework is critical for realistic representation of interconnected sectors. A study by Wrenn (2024) provides insights into how population growth in disaster-prone areas influences demand for resources and adaptive infrastructure. Natural disasters have increased in the U.S. in recent decades. At the same time, there has been a shift in population away from the states in the Northeast and Midwest to areas in the Sunbelt. This study examined how people's choices about where to live are influenced by the risk of natural disasters, especially in the U.S. Sun Belt, a region more prone to extreme weather and disasters. By analyzing data on disasters, weather patterns, and household economic outcomes, the study finds that people are not indifferent to the risks of living in disaster-prone areas but instead expect higher incomes to compensate for the increased risk. On average, households are willing to pay about 0.4% of their annual income to avoid an additional disaster over a decade. However, this willingness to pay varies by household income and skill level, with higher-income, higher-skilled households willing to pay significantly more to avoid disaster risks. These findings suggest that policies addressing weather extremes and disaster preparedness need to account for how people make trade-offs between risk and income, and highlight the need for compensation through higher wages or lower rents in disaster-prone areas.

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Subproject 1.3: Integrated modeling of weather and climate impact risk on coupled food-energy-water dynamics

The objective of this subproject was to build a comprehensive infrastructure capable of simulating the economic and environmental impacts of energy-water-land (EWL) interactions on regional to global scales. This infrastructure includes econometric emulators that assess energy and agricultural responses to weather shocks, projections of weather and climate impacts under diverse scenarios, and a global computational general equilibrium (CGE) model to account for economic feedbacks.

van Ruijven et al. (2019) provide an analysis of how anticipated mid-century climatic conditions will influence global energy demand. By modeling the response of energy use to temperature extremes across multiple countries and sectors, this study reveals that climate-induced demand for energy, especially for cooling, could increase by 25-58% under aggressive warming scenarios. This research promoted incorporating energy demand projections into our EWL framework, as changes in temperature will profoundly affect electricity use, with implications for economic and environmental systems. Building on the understanding of energy demand, Romitti and Sue Wing (2022) assess how urban electricity consumption consequences of decreased cool-season heating and increased warm-season cooling will shift in response to more extreme future temperatures. Their work projects that such increases in consumption impacts will be largest in the mid-latitudes, as opposed to the tropics, and will depend on the structure of energy demand in addition to the heat extremes that cities will experience. The study also suggests the unequal distribution of electricity demand impacts, emphasizing the need for detailed temporal and spatial modeling to inform urban adaptation strategies.

Two studies—Romitti et al. (2022) and Colelli et al. (2023)—further investigate air conditioning (AC) as a primary adaptation to heat stress. Romitti et al. (2022) map intra-urban disparities in AC availability across U.S. cities, revealing that areas with lower AC prevalence often overlap with regions of higher social vulnerability and urban heat island amplification. By 2050, cities will be home to 68% of the world's population, placing them at the forefront of adaptation efforts. As the climate varies, the frequency, severity, and duration of extreme heat events are expected to rise, increasing high-temperature exposure for urban populations. This will drive up peak and total electricity demand worldwide as more people rely on space cooling to cope. Residential AC, one of the most common and accessible forms of heat adaptation, plays a crucial role in determining individuals' vulnerability to heat. This study examines the availability of residential AC in U.S. cities, highlighting how its distribution can affect people's ability to cope with rising temperatures. While it's known that AC prevalence varies between different cities, this research focuses on how it differs within metropolitan areas, specifically among neighborhoods. Using data from the American Housing Survey and the American Community Survey, Romitti et al. (2022) constructed census tract-level probabilities of any residential AC across a large sample of U.S. metropolitan areas that reflect 67% of the total country's population. The results revealed that urban core areas tend to have lower rates of AC compared to suburban regions, which is concerning given that these core areas often experience higher heat exposure due to the urban heat island effect. The study found that the disparity in AC availability is strongly correlated with disparities in social vulnerability and urban heat amplification. Communities with less access to cooling often face higher risks related to poverty and health, highlighting the need to address these inequalities to safeguard public health. Meanwhile, Colelli et al. (2023) analyzed the tradeoffs between AC adoption and greenhouse gas emissions in Europe and India. They found that while AC expansion reduces heat-related health risks, it also significantly increases electricity demand and emissions, and the tradeoff varies across space and income groups.

Extending the analysis globally, Falchetta et al. (2024a) at a fine spatial scale project a significant increase in the share of households with AC, leading to a doubling of residential cooling electricity consumption by 2050. However, up to 4 billion people may still lack adequate AC, implying significant disparities in cooling access. Falchetta et al. (2024) further explore the intersection of demographic change and climate impacts, showing that the global aging population will face increased heat exposure. By mid-century, more than 23% of people over age 69 will live in climates that exceed critical heat thresholds—twice today's figure. Asia and Africa, which have limited capacity to adapt, will be most affected. Where temperatures rise and where populations grow older will ultimately shape health risks for older adults, pinpoint areas of heightened vulnerability, and underscore the need for targeted interventions.

Understanding how climate variability and change affects agriculture was another prominent component of research under this subproject. Mistry et al. (2017) compared crop yield responses derived from global gridded crop models (GGCMs) and empirical observations, developing a method for diagnosing differences in GGCMs' responses, and for attributing these differences to model characteristics. Their econometric analyses revealed notable differences—both among different GGCM simulations and between models and observations—in how major U.S. crops respond to heat and moisture, with up to 60% of the variance in simulated and observed yields attributable to weather variation. Addressing future impacts of changing crop yields on agricultural production at a finer scale, Waldhoff et al. (2020) address the need for spatially detailed yield shock projections by modeling the effects of year-to-year weather patterns on 12 major crops. Their work provides annual, country-specific projections of shocks to crop yields by century's end under six warming scenarios, which can be used in a wide range of economic models to explore the local and global impacts of evolving climatic conditions on agriculture. This advancement supports subproject's goal of understanding how sudden weather fluctuations, as opposed to gradual trends, can disrupt food systems. To estimate farmers' short- and long-term adaptation responses to changing weather patterns, Sue Wing et al. (2021) used high-resolution global data. This study informs modeling of adaptation and adjustment by U.S. farm regions by emphasizing the risks to global food security and the potential economic consequences of reduced domestic and overseas supplies of crops responsible for 75% of global calories. Adapting agriculture to climate variability and change is essential for future food security, yet global crop yields are expected to decline significantly in response to warming and altered rainfall patterns. Using detailed weather data and crop yield records, Sue Wing et al. (2021) developed a model to analyze how farmers' short- and long-term responses to temperature and precipitation vary across different climates worldwide. Under a high-warming scenario, the results indicate that by mid-century, crop yields could decrease by 3-12% by 2050, with even larger declines of 11-25% by 2090. These yield drops are especially pronounced in regions where temperatures are expected to rise the most, such as the tropics, where 40% of the global population resides. The limited capacity for adaptation observed suggests that global calorie supplies may struggle to keep up with growing demand. Yield responses and global gridded multi-model projections of impacts generated by this study facilitate further research to identify and address barriers to adaptation and investigate the multi-sector consequences of the agricultural impacts of climatic variability and change, for the U.S. as well as its major trade partners.

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Subproject 1.F: Integrated modeling and assessment of behavioral responses to combined flood risk for coastal communities

This research subproject focuses on developing a cross-disciplinary approach to assessing and modeling behavioral responses to flood risk. The following studies add to understanding of how flood risk is perceived, communicated, and managed across communities by integrating findings on loss estimation, risk pricing, insurance equity, and risk component analysis. Through highlighting the importance of data precision, policy effectiveness, and regional variations in risk factors, this subproject lays the groundwork for more effective flood risk management and adaptation strategies.

Accurate estimates of economic losses from large-scale flooding are crucial for guiding hazard mitigation and adaptation measures. Pollack et al. (2022) emphasize the important role of spatial resolution of inputs in flood loss calculations, revealing that aggregation biases significantly impact loss estimates for flood-prone properties. They examine 1.3 million Massachusetts single-family homes, estimating flood losses based on state-of-the-art high-resolution hazard and structure inventory data as a benchmark against which to compare three types of aggregation: aggregate structures, aggregate structures and hazard, and aggregate structures and hazard filtering out properties not at risk. Results show that large overall aggregation biases can arise from aggregation procedures that underlie estimates of communities' exposure to flood losses. This can lead to substantial inaccuracies with which measures such as insurance premiums or adaptation spending may be targeted. Economic damages from riverine flooding are expected to grow because of changes in hydroclimate extremes. To advance the understanding of flood risk at a granular level study by Cisneros-Pineda et al. (2024) examined the economic impacts of river flooding in the United States by analyzing three key factors: hazard (such as river discharge levels), exposure (the amount of property at risk), and vulnerability (susceptibility based on physical infrastructure and community preparedness). Few studies have looked at these factors independently at a local level, limiting precise predictions for future flood damage. By gathering data on flood events, property damage, and housing characteristics across U.S. counties from 1999 to 2018, the researchers identified distinct patterns: flood risk in the Mississippi River area is mostly hazard-driven, while exposure dominates in areas like the West Coast and Texas, and vulnerability is highest in the Great Plains. This approach by Cisneros-Pineda et al. (2024) offers a practical framework for anticipating flood damages across different regions and highlights the importance of targeted policies—such as stricter building permits in densely populated areas—to reduce future damage from anticipated increases in flood events.

Brent et al. (2024) extends flood adaptation economic analysis into a policy domain, examining the equity and redistribution impacts of FEMA's Community Rating System (CRS), which provides premium discounts to communities with proactive flood management practices. The study finds that while CRS reduces premiums in high-risk areas, the financial impact on individual households is minor. This redistribution mainly affects lower-income communities and encourages residence in flood-prone areas by lowering insurance costs. The findings emphasize the role of federal subsidies in shaping local flood risk management and housing decisions, supporting the project's focus on economic influences in flood behavior and adaptation.

Linking policy with individual economic decisions, a study by Pollack et al. (2023) focuses on improving how flood risk is integrated with housing markets. Most U.S. homebuyers gauge a property's flood risk based on whether it falls within the National Flood Insurance Program's (NFIP) Special Flood Hazard Area (SFHA). However, these SFHA boundaries can mislead buyers, as they often provide an incomplete or inaccurate picture of actual flood hazards. This research evaluates how more complete and accurate flood hazard information in property markets might help mitigate economic losses from flooding, which has cost the U.S. over $650 billion since 2017. By analyzing nationwide data on property transactions, flood hazards, and state disclosure laws, the study reveals that SFHA designations can be misleading and result in inefficient pricing of flood risk. Pollack et al. (2023) found that homes in flood-prone areas marked within SFHA boundaries experience a "risk discount" in their pricing, but this discount is often inconsistent with the actual flood risk. Extending SFHA boundaries to cover all flood-prone homes and requiring sellers to disclose a property's flood history could better signal true flood risks. These changes would enable buyers to make more informed decisions, and could improve the market's ability to internalize flood risk, potentially reducing socialized costs associated with flooding.

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Program Element II

Subproject 2.1: Improving the quality and ease of use of climate information

During the reporting period, our efforts on this subproject primarily focused on assessing the needs of project personnel and modeling teams for datasets, translational and coupling tools, high-performance computing (HPC) resources, and collaboration platforms. This assessment enabled us to collaborate with colleagues at Penn State's Institute for Computational and Data Sciences to develop and launch the project's shared HPC environment and facilitate the onboarding of personnel to Penn State's shared cyberinfrastructure resources. Separately-funded work on the development of new gridded observational climate products, downscaled climate datasets, and ensembles of synthetic weather realizations has been coordinated with the project and informed the development of new custom datasets in support of Program Element I subprojects. Work on this subproject was scaled back in Years 3-7 due to funding cuts imposed by DOE.

Subproject 2.2: How does an improved sampling of known uncertainties influence the tails of climate projections on decision-relevant spatial and temporal scales?

Researchers have made considerable progress toward achieving goals of this subproject. At the University of Illinois, researchers have been post‑processing daily Earth system model output from the Coupled Initial Conditions CESM ensemble (CICCESM), CMIP5 models, and gridded observational data sets. Using post‑processed daily ESM output from the Coupled Initial

Conditions CESM ensemble, CMIP5, and gridded observations, they characterized internal variability within these models across multiple decision‑relevant spatial scales and investigated its influence on interannual variability associated with ENSO (Vega-Westhoff et al., 2017) and decadal trends in thermosteric sea‑level rise (Hogan et al., 2017). Because El Niño-Southern Oscillation (ENSO) strongly influences global climate patterns and its future behavior is difficult to predict due to internal variability and limited observations, modeling approaches that incorporate natural variability are crucial for understanding its response to varying climate. Vega-Westhoff et al. (2017) use a low-resolution CESM ensemble to assess how coupled internal variability affects ENSO behavior under pre-industrial, historical, and future climate conditions. They find that ENSO characteristics remain relatively stable across different climate conditions, but individual simulations show large variations due to internal ocean-atmosphere variability. By quantifying the uncertainty in ocean heat uptake and the associated steric sea-level rise using global Earth system model ensembles, Hogan et al. (2017) demonstrate that spread in multi-decadal sea-level trends is significantly influenced by both internal "natural" variability and model uncertainties. The findings provide helpful limitations on projections of sea level rise on a global and regional scale, especially for upper bound estimates that are pertinent to assessments of the risk of coastal flooding.

Furthermore, using results from recent ensembles of projections sampling internal variability and different model structures/resolutions, the researchers developed new statistical tools (in R) and analyzed variability surrounding extreme temperature projections in the U.S. (Hogan et al., 2019) and interannual-to-decadal ocean variability (Hogan and Driver, 2019). Despite increasing evidence that warm extreme temperatures are becoming more frequent and severe across the U.S., accurately estimating these changes and the uncertainties involved remains a significant challenge. Hogan et al. (2019) use a block-maxima statistical approach to assess how different global Earth system model ensembles represent warm temperature extremes in the U.S., revealing substantial variability and uncertainty due to structural model differences, resolution, and internal variability. Results indicate that both contribute significantly to the uncertainties surrounding extreme temperature and precipitation, and the effect is amplified for decreasing spatial scales. Additionally, the tail area characteristics tend to vary in space and time (and under external climate forcing), suggesting that characteristics of extreme warm events may change substantially in the future. Representation of warm temperature events varies considerably among Earth system models, which has important consequences for estimating how regional temperature extremes may be changing. Results by Hogan et al. (2019) can help inform regional analysis that is particularly sensitive to extreme temperature events (e.g. agriculture). Accurately measuring ocean heat uptake at various scales is crucial to comprehending how the Earth system is responding to warming since the ocean's enormous heat capacity and circulation drive global heat uptake, transport, and temperature variability. Building on their previous ocean study, Hogan and Driver (2019) demonstrate that internal ocean variability strongly influences how quickly the global ocean absorbs heat, with global temperature adjustments taking hundreds of years. By comparing two CESM ensembles initialized differently—one capturing ocean–atmosphere variability and the other only atmospheric variability—they find that ignoring internal ocean variability leads to slower ocean temperature evolution. These results have important implications for accuracy of Earth system model ensemble projections.

Researchers also investigated effects of parametric model uncertainty (e.g. climate sensitivity, ocean heat uptake) on extreme sea-level rise projections including deep uncertainties surrounding melting land ice (Vega Westhoff et al., 2020). Rising sea levels threaten coastal communities but reliable projections are limited by uncertain factors like land-ice melt and observational/computational constraints.Researchers in this subproject examined how uncertainties in Earth system model parameters—such as climate sensitivity and ocean heat uptake—shape projections of extreme sea-level rise, including deep uncertainties tied to melting land ice (Vega Westhoff et al., 2020). By applying the reduced-complexity Earth system model Hector-BRICK and calibrating it with historical data, the researchers estimated the upper bounds of future sea-level rise, reflecting uncertainties in both Earth system evolution and physical processes. Combined reduced-complexity Earth system and semiempirical sea-level modeling approaches help generate a range of possible future sea-level outcomes, offering valuable support for informed decision-making, particularly in the "upper tail"—less likely but potentially more severe outcomes. They found that higher climate sensitivity along with rising carbon dioxide levels significantly increases estimates of extreme sea-level rise scenarios, essential for adaptation planning. This work demonstrates that uncertainties in equilibrium climate sensitivity strongly influence sea-level projections, potentially affecting regional variability and the timing of future exceedance events.

Researchers then expanded these approaches to examine how differences in climate projections can impact agriculture yields in the midwestern U.S. and the implications for domestic and global markets (collaborating with subproject 1.1). They used this information to develop new statistical models to emulate gridded temperature projections using quantile regression, which incorporates effects of internal variability and can be used to estimate differences between large initial conditions ensembles (Haugen et al., 2018, 2019). Haugen et al. (2018) introduce a quantile regression method that leverages large Earth system model ensembles to more accurately characterize seasonal changes in temperature distributions under warming conditions. By analyzing data from multiple simulations with varied initial conditions, their approach provides deeper insights into the shifting probabilities of extreme temperatures and can be extended to other climate variables like precipitation or humidity. Reliable future climate projections often require blending numerical simulations and observed data, as current Earth system models alone cannot perfectly capture local conditions. In a 2019 study, Haugen and colleagues introduced a broad statistical approach called quantile regression that compares multiple Earth system model predictions and is especially useful for studying the most extreme outcomes. They analyze daily temperature at different levels, taking into account both seasonal patterns and long-term changes, innovatively treating the most extreme temperatures as "exceedances" beyond slightly less extreme ones, which simplifies the model for very rare temperature events.

The researchers on this subproject also developed, tested, documented methods to (i) assess the effects of model structural uncertainty and mixed distribution of dam safety (Roop-Eckart 2018, thesis), (ii) enhance spatial flood probability quantification and communication through higher resolution mapping (Zarekarizi et al., 2019), and (iii) improve the calibration of computationally expensive computer models (Lee et al., 2020).

A tool that generates continuous flood probability maps (FLOPIT), offering a more nuanced depiction of flood risk than conventional discrete flood zones, was developed by Zarekarizi et al. (2021). By interpolating flood probabilities between known return periods, FLOPIT can improve flood hazard communication, inform better decision-making, and potentially lead to more accurate flood insurance rates. Their results show that traditional discrete zones often underestimate actual flood probabilities, highlighting the value of continuous mapping. Further, working with subproject 1.F, researchers applied this method to provide flood hazard characterizations as inputs to econometric analyses.

Lee et al. (2020) developed a fast particle-based Bayesian calibration approach that efficiently assimilates modern observations into a moderately complex Antarctic ice sheet model. They find that overlooking substantial uncertainties in model parameters can lead to significantly low estimates of future sea-level rise. By harnessing high-performance computing, the method offers a computationally feasible and more realistic path to refining uncertainty quantification in complex, computationally intensive, and decision-relevant models. Delving further into model calibration approaches, Srikrishnan and Keller (2021) examine agent-based models (ABMs), which are commonly used to understand how complex, system-wide behaviors emerge from individual-level decisions and interactions, such as socio-hydrological feedbacks that exist in flood-prone areas. However, ABMs are often not statistically calibrated to data, which can result in overconfident interpretations of their simulations. With a perfect model experiment, Srikrishnan and Keller (2021) demonstrate that limited or aggregated historical data can fail to sufficiently constrain even simple ABMs with a small number of parameters, leading to biased parameter estimates and difficulty in identifying the correct model structure. Each additional parameter or interaction within an ABM significantly increases the amount of data needed for reliable calibration. As a result, ABM projections may heavily depend on prior assumptions. The findings underscore the need to combine multiple, independent sources of information to improve priors and more accurately capture the uncertain, complex, path-dependent nature of human-environment interactions in ABMs.

Building on the subproject team's expertise in uncertainty characterization and model calibration, several initiatives have applied these techniques to enhance flood risk modeling. Riverine floods pose significant dangers to many communities, and their projections often remain uncertain due to imprecise model parameters. By improving parameter calibration, employing more comprehensive modeling approaches, and gaining deeper insights into key risk factors, it is possible to produce more reliable and informative flood risk projections. Roth et al. (2022) develop a multiresolution calibration approach that uses information from both high- and low-resolution model runs to improve parameter estimation in riverine flood models. This method enhances inference for parameters that retain consistent meaning across resolutions and yields more accurate flood projections for certain variables. Their method is general and can be a promising path forward for efficiently calibrating complex, high-dimensional models with limited computational resources. Accurately forecasting flood risks also requires thoroughly characterizing uncertainties—beyond just a few known unknowns—since overlooking key variables can lead to underestimating extreme events and making poor decisions. Sharma et al. (2022) show that using a Bayesian data-model fusion framework to calibrate a distributed hydrologic model leads to better flood hazard estimates compared to simpler methods (stepwise line search and pre-calibration), highlighting the importance of accounting for key uncertainties. Hosseini-Shakib et al. (2024) systematically quantify and attribute uncertainties in riverine flood risk projections by examining how hazard, exposure, and vulnerability factors interact. By sampling key uncertainties and performing a global sensitivity analysis, they find that flood hazard uncertainties dominate the resulting risk estimates. This result suggests that efforts to reduce hazard-related uncertainties can substantially improve confidence in future flood risk projections.

Using results from recent ensembles and downscaled data products, researchers also analyzed variability surrounding extreme temperature and precipitation projections in the U.S. They examined how uncertainties contribute to agricultural yields and variability in the midwestern U.S. (collaborating with subproject 1.1) using new statistical approaches accounting for extreme events (Ye et al., 2021). Since crop yields are highly sensitive to changes in temperature and precipitation, improving our understanding of the underlying mechanisms and uncertainties is crucial for better yield forecasting. Ye et al. (2021) show that accounting for both model parameter and forcing uncertainties significantly affects projections of future corn yields, particularly increasing the likelihood of extremely low yields. By using a pre-calibration approach for parameter uncertainties and an ensemble of downscaled Earth system model projections, the study finds that model parameter uncertainty contributes more to projection variance. Roth et al. (2023) advance previous research on crop yield projections by developing an approach that accounts for both spatial correlation and parametric uncertainty. They use two Bayesian spatial statistical models, each treating spatial correlation differently and integrating Earth system model outputs with various temperature data products, to estimate future U.S. corn yields with changing weather conditions. Both models confirm a downward yield trend, but the novel PICAR model produces lower projected losses and uncertainty while being more computationally efficient, whereas the simpler county-intercepts model offers slightly higher predictive accuracy. Differences in model outputs based on different temperature data sources further underscore the importance of considering uncertainty, model structure, and weather data choice in yield projections.

Haugen, M. A., M. L. Stein, E. J. Moyer, and R. L. Sriver, 2018: Estimating Changes in Temperature Distributions in a Large Ensemble of Climate Simulations Using Quantile Regression. *Journal of Climate*, **31**, 8573–8588, https://doi.org/10.1175/JCLI-D-17-0782.1.

Haugen, M. A., M. L. Stein, R. L. Sriver, and E. J. Moyer, 2019: Future climate emulations using quantile regressions on large ensembles. *Advances in Statistical Climatology, Meteorology and Oceanography*, **5**, 37–55, https://doi.org/10.5194/ascmo-5-37-2019.

Hogan, E., and R. Sriver, 2017: Analyzing the Effect of Ocean Internal Variability on Depth-Integrated Steric Sea-Level Rise Trends Using a Low-Resolution CESM Ensemble. *Water*, **9**, 483, https://doi.org/10.3390/w9070483.

Hogan, E., and R. L. Sriver, 2019: The effect of internal variability on ocean temperature adjustment in a low-resolution CESM initial conditions ensemble. *Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2018JC014535.

Hogan, E., R. E. Nicholas, K. Keller, S. Eilts, and R. L. Sriver, 2019: Representation of U.S. Warm Temperature Extremes in Global Climate Model Ensembles. *Journal of Climate*, **32**, 2591–2603, https://doi.org/10.1175/JCLI-D-18-0075.1.

Hosseini-Shakib, I., A. Alipour, B. Seiyon Lee, V. Srikrishnan, R. E. Nicholas, K. Keller, and S. Sharma, 2024: What drives uncertainty surrounding riverine flood risks? *J. Hydrol.*, **634**, 131055, https://doi.org/10.1016/j.jhydrol.2024.131055.

Lee, B. S., M. Haran, R. W. Fuller, D. Pollard, and K. Keller, 2020: A fast particle-based approach for calibrating a 3-D model of the Antarctic ice sheet. *The Annals of Applied Statistics*, **14**, 605–634, https://doi.org/10.1214/19-AOAS1305.

Roth, S., B. S. Lee, R. E. Nicholas, K. Keller, and M. Haran, 2023: Bayesian Spatial Models for Projecting Corn Yields. *Remote Sensing*, **16**, 69, https://doi.org/10.3390/rs16010069.

Roth, S. M., B. S. Lee, S. Sharma, I. Hosseini-Shakib, K. Keller, and M. Haran, 2022: Flood hazard model calibration using multiresolution model output. *Environmetrics*, **34**, e2769, https://doi.org/10.1002/env.2769.

Sharma, S., B. S. Lee, I. Hosseini-Shakib, M. Haran, and K. Keller, 2022: Neglecting model parametric uncertainty can drastically underestimate flood risks. *Earth's Future*, https://doi.org/10.1029/2022ef003050.

Vega-Westhoff, B., and R. L. Sriver, 2017: Analysis of ENSO's response to unforced variability and anthropogenic forcing using CESM. *Scientific Reports*, **7**, 18047, https://doi.org/10.1038/s41598-017-18459-8.

Ye, H., R. E. Nicholas, S. Roth, and K. Keller, 2021: Considering uncertainties expands the lower tail of maize yield projections. *PLoS ONE*, **16**, e0259180, https://doi.org/10.1371/journal.pone.0259180.

Zarekarizi, M., K. J. Roop-Eckart, S. Sharma, and K. Keller, 2021: The FLOod Probability Interpolation Tool (FLOPIT): A Simple Tool to Improve Spatial Flood Probability Quantification and Communication. *Water*, **13**, 666, https://doi.org/10.3390/w13050666.

Subproject 2.3: Developing regional climate projection tools to incorporate high risk events into decision-tools.

This subproject was never launched due to funding cuts imposed by DOE.

Program Element III

Subproject 3.1: Base research program for developing evaluation tools for modeling frameworks.

The scope of this subproject was scaled back because the originally proposed funding for several of the main collaborators (Reed, Diffenbaugh and Lobell) was discontinued after the first year or two of the five year collaborative research agreement. Nonetheless, significant progress was made in several important directions.

Recognizing that model development, evaluation, and uncertainty characterization should be done systematically and in parallel to maximize the credibility of the modeling process, we: (1) refined a taxonomy for identifying the kinds of uncertainties (e.g., structural, parametric, external drivers, initial conditions) considered in MSD research; and (2) have continued identifying possible alternative approaches drawn from many scientific disciplines, including decision and risk analysis. Although several important parts of the Earth systems and related human modeling communities have produced relevant and important literature on uncertainty characterization and its use in risk assessment, this work has so far not been either systematic or comprehensive within and across these domains. In response, this led us in two research directions: (1) developing a systematic framework for model diagnostics and evaluation, and (2) working towards the development of a systematic approach to model development, uncertainty quantification & diagnostics. Although we have not yet developed a completely unified framework for the many challenges in either of these research directions, we have made progress in both by restricting the range of all possible model assumptions in pragmatic and useful directions. These more restricted frameworks have allowed us to draw conclusions to key model choices within those bounds and to develop insights about how to consider these choices in more generalized frameworks.

This research subproject supported: (1) a paper that provides general guidance on choosing the best level of spatial and temporal disaggregation to use in MSD (other other types of) modeling; (2) a PhD dissertation on the cost of supply chain disruptions that can result from extreme weather events as another way to measure their economic costs and adapt to those types of disruptions; and (3) a PhD dissertation that scopes out wildfires that are made worse by extreme weather events as an important "use case" for MSD modeling, with and demonstration application to California on the expected threat there and an evaluation of one possible adaptive response that is currently being pursued by the state.

In one project, Merrick and Weyant (2018) developed a general framework for thinking about the level of spatial and temporal aggregation to employ in multi-sector dynamics (MSD) modeling which focuses explicitly on assessing the tradeoffs between model fidelity and the computational burden of increased disaggregation. Although the choice of the level of spatial and temporal aggregation in sectoral and multi-sectoral models are viewed as critically important determinants of model credibility and impact, these choices are typically made on an ad hoc basis with limited and incomplete testing. This study proposes a more systematic approach to making these choices for normative models based on fundamental optimization and information theory concepts. It develops principles for trading off the accuracy of representation versus parsimony and a 'modeling roadmap' to help the modeling community apply the ideas. Simple examples of the application of this methodology and possible extensions of it to non-normative models are included. This approach and possible extensions to it should help the modeling community improve the credibility and impact of MSD modeling systems.

In another project, Reed (2023) explored and provided preliminary diagnostics for an alternative way of projecting the economic impacts of extreme weather events using supply chain data. Extreme weather events are becoming more common and more extreme. A new literature on production networks shows that direct effects from extreme weather spread over supply chains and lead to indirect effects at distant companies. However, existing papers have not driven home their relevance for extreme weather event damage estimates. In Reed (2023) the direct and indirect effects of extreme heat and extreme precipitation on public companies in the U.S. were examined. Twenty years of quarterly financial data and more than 600,000 firm location records are used to econometrically estimate the direct effect of extreme weather at a company's establishments. Next, the indirect effect of extreme weather at a company's suppliers' establishments were estimated. Data from CMIP6 were used to project changes in the incidence of extreme heat and extreme precipitation at each company's establishments over the next twenty years. It was found that the projected indirect effects have been roughly half the size of the projected direct effects. The direct effects for different subgroups were then estimated, and the effects of extremes with the effects of warmer or wetter weather than average were compared. Substantial heterogeneity in how different types of firms are affected by extreme weather was found. The dissertation closes with a review of Earth system modeling for near-term predictions as the climate deviates from its historical norms. The climate projections data from the firm level analysis is then used to review the accuracy and uncertainty of these models, with the goal of helping provide an operational guide to individuals who will be using these data for adaptation and planning.

In a third project, Horing (2023) developed a framework for studying wildfires in California to set the stage for assessing adaptive responses to them. Wildfires pose a significant threat to the state of California. While climate variability and change is likely contributing to increased fire risk, human activities, including ignitions, alterations to natural landscapes, and development patterns, also play a substantial role in shaping the risk. Moreover, the management actions taken in response to this risk have societal impacts themselves. This dissertation first frames the challenge of wildfire risk management by considering the tradeoffs between the cost of taking action, the reduction in wildfire damages, and welfare losses. It explores how misaligned incentives and the uneven distribution of costs and benefits lead individual decision-makers to undertake suboptimal mitigation measures. The dissertation then delves deeper into two specific management strategies: the efforts of investor-owned utilities to reduce powerline ignition risk and the actions of individuals in protecting their homes and safety. Using a variety of data collection techniques and methods from economics, risk analysis, and data science, this research provides insights into the costs, drivers, and effectiveness of these strategies. The findings highlight the need for aligning policies and incentives to minimize the impact of both wildfires and mitigation measures and ultimately seek to inform research and decision-making towards effective wildfire management.

Merrick, J. H., and J. P. Weyant, (2019). "On choosing the resolution of normative models." *European Journal of Operational Research*, **279**, 511–523, https://doi.org/10.1016/j.ejor.2019.06.017.

Reed, Brian (2023). "Direct & Indirect Effects of Extreme Weather in a Warming World," Ph.D. Dissertation, Stanford University, Stanford, CA, Fall.

Horing, Jill (2023). "Interdisciplinary Approaches to WildfireI Risk Management" Ph.D. Dissertation, Stanford University, Stanford, CA, Fall.

Subproject 3.2: Climate projections method intercomparisons and model diagnostics.

Research on this subproject overall aimed to identify the most critical interacting uncertainties while addressing integration challenges such as high computational demands, selecting appropriate methods to distinguish key uncertainties, and ensuring that model information is tailored to meet the operational and planning needs of multiple sectors. Researchers have made significant progress across several areas to improve understanding and forecasting of flood risks and their impacts on integrated water/energy systems. Towards that end, they worked on developing a computationally efficient, potentially nonstationary model of river flow to help resource managers identify weather and climate scenarios that may compromise integrated water and energy systems. Cornell, in collaboration with UNH, has adapted the Water Balance Model (WBM) for high-performance computing to facilitate ensemble-based diagnostics. Meanwhile, Penn State worked on enhancing flood hazard mapping at finer resolution probabilities and examining how model structural uncertainties influence streamflow and flood hazard forecasts. Activity on this subproject has ceased in 2019 due to funding cuts imposed by DOE; related activities co-led by Keller are now described in subprojects 1.F and 2.2.

Coordinated management of multi-reservoir systems is crucial for handling water variability and extreme events in complex river basins worldwide. However, large-scale hydrological models often overlook these coordinated processes, despite their significant impact on water balance and flow dynamics. Study by Rougé et al. (2021) reveals that common large-scale hydrologic models, which often assume that reservoirs operate independently rather than in coordinated networks, can inaccurately predict flood and drought risks. Using the Water Balance Model (WBM) in the Upper Snake River Basin, the study shows that this independent operation assumption leads to artificial extreme events, such as false droughts and floods. In reality, coordinated reservoir management, as seen in this region, helps balance water levels during extreme weather, providing water during droughts and reducing peak flows during heavy rains. By analyzing reservoir operations and incorporating simple coordination rules based on actual practices, the researchers improved model accuracy, demonstrating the critical role of coordinated reservoir management. The findings of Rougé et al. (2021) underscore the need for more sophisticated modeling of reservoir networks which includes coordinated human decision-making in large-scale models to better assess and prepare for future water-related risks in river systems in a changing world.

Rougé, C., P. M. Reed, D. S. Grogan, S. Zuidema, A. Prusevich, S. Glidden, J. R. Lamontagne, and R. B. Lammers, 2021: Coordination and control – limits in standard representations of multi-reservoir operations in hydrological modeling. *Hydrology and Earth System Sciences*, **25**, 1365–1388, https://doi.org/10.5194/hess-25-1365-2021.

Subproject 3.3: Quantifying the influence of global temperature change on unprecedented extreme events

Activities of the subproject included work on: (1) statistical analysis of historical climate data and Earth system model simulations; (2) interfacing with crop, water and land use data and models; and (3) interfacing with historical economic data to improve understanding of influence of climate variability on economic output. Activity on this subproject ceased in Year 3 due to funding cuts imposed by DOE, nevertheless significant progress has been made on the initial goals.

The study by Goss et al. (2018) investigates how tropical weather patterns, particularly those associated with El Niño and La Niña events, influence atmospheric conditions far beyond the tropics. While it is well known that El Niño–Southern Oscillation (ENSO) events impact global weather conditions over timescales of seasons or years, this study reveals that even short-term variations in tropical precipitation can trigger significant atmospheric changes over the North Pacific and North America within 5-10 days. Using a new El Niño Precipitation Index (ENPI) to track these changes, researchers found that El Niño–like or La Niña–like precipitation patterns on subseasonal timescales (as short as several days) can lead to corresponding shifts in atmospheric pressure in the midlatitudes. This suggests the possibility that the overall seasonal impacts of ENSO are built from these shorter, frequent events and that tracking tropical convection in the equatorial Pacific could improve weather forecasting for the midlatitudes by offering insight into potential changes up to two weeks in advance.

The research by Goss et al. (2021) explores how disruptions in the Arctic polar vortex, especially during winter, influence weather patterns across the Northern Hemisphere. It focuses on two types of events: Sudden Stratospheric Warming (SSW) events, which disrupt the polar vortex, often lead to changes in the jet stream that bring colder weather to the subarctic Northern Hemisphere, while Strong Polar Vortex (SPV) events tend to have the opposite effect. Using reanalysis data and results from a 202-year GCM integration, Goss and colleagues found that these two types of events were associated with different frequencies of three preferred regimes of the North Atlantic jet. In particular, SPVs were associated with increased frequency of a northern jet regime, while SPVs were associated with an increased frequency of the central and southern regimes, both consistent with observed weather impacts. These findings provide new insights into the stratosphere-troposphere relationship and can improve medium-range weather forecasts, helping predict how stratospheric changes might impact weather in North America and Europe, and improving predictability for events such as midlatitude cold air outbreaks.

Goss, M., S. Lee, S. B. Feldstein, and N. S. Diffenbaugh, 2018: Can ENSO-like convection force an ENSO-like extratropical response on subseasonal time scales? *J. Clim.*, 31, 8339–8349, https://doi.org/10.1175/jcli-d-17-0771.1.

Goss, M., E. A. Lindgren, A. Sheshadri, and N. S. Diffenbaugh, 2021: The Atlantic jet response to stratospheric events: A regime perspective. *J. Geophys. Res.*, 126, https://doi.org/10.1029/2020jd033358.

Subproject 3.4: Understanding adaptation in climate impacts analyses

Activity on this subproject has ceased due to funding cuts imposed by DOE.

Program Element IV

Subproject 4.1: Planned research community engagement activities

2017 (Year 1)

We have held a major PI meeting at Stanford University in December 2016, numerous individual project and cross project meetings, and participated in the annual IAMC meeting in Beijing on December 5‑7, 2016. Weyant participated as a Scientific Advisory Board Meeting in the final meeting of the European ADVANCE project meeting in Brussels on October 24‑25, 2016 and the third meeting of the European “Climate and Development Linkages” (CD‑LINKS) project in Beijing on December 1‑3, 2016. Fisher-Vanden coordinated research activities with the E.U. PESETA project. Finally, we have coordinated our work with related research being conducted at the major U.S. integrated modeling centers and several non‑U.S. based centers.

2018 (Year 2)

A PI and outreach meeting in Snowmass, CO (July 2017) included presentations by closely‑related (U.S. and international) projects and an innovative set of cross‑project discussions on common challenges and opportunities for future collaboration. Weyant participated in planning the annual IAMC meeting in Recife, Brazil (December 2017) and the 4th European “Climate and Development Linkages” (CD‑LINKS) meeting in Potsdam (May 2017).

2019 (Year 3)

A PI and outreach meeting held in Snowmass, CO (July 2018) included presentations by closely-related (U.S. and international) projects and an innovative set of cross-project discussions on common challenges and opportunities for future collaboration. Weyant participated in planning the annual IAMC meeting in Seville, Spain (December 2017) and the

6th European “Climate and Development Linkages” (CD-LINKS) meeting in Rio De Janeiro, Brazil (March 2019). The Cooperative Research Agreement (CRA) also sponsored participation of 15-20 PIs, postdocs, and graduate students for the BER EESM PI meeting (November 2018).

2020 (Year 4)
(1) The CRA held a PCHES annual PI meeting with participation of approximately 50 PIs, postdocs, and graduate students (Penn State, May 2019). This meeting also included PI collaborators from other MSD sponsored projects. (2) An MSD program PI and outreach meeting held in Snowmass, CO (June 2019) included presentations by closely-related (U.S. and international) projects and an innovative set of cross-project discussions on common challenges and opportunities for future collaboration. A major objective of this meeting was to learn about the launch of the new MSD Community of Practice. (3) Weyant and Fisher-Vanden participated the 12th IAMC meeting in Tsukuba, Japan (December 2019) and the 1st and 2nd meetings of the European ENGAGE meetings in Vienna (September 2019) and on-line (March 2020). This group includes several European MSD-type projects.

2023 (Year 7)
The Groundwater and Society Workshop, held at Pennsylvania State University on May 8-10, 2024, was organized by the University of New Hampshire and the Pennsylvania State University. By evaluating the existing status of connected human-groundwater systems, motivating advancements driven by human-related problems, and promoting transdisciplinary collaborations, the workshop aimed to stimulate research on the multi-sector dynamics of groundwater use. The workshop brought together 43 researchers from 17 institutions, primarily at the early career stage, and was organized into plenary presentations and active breakout sessions. Experts in groundwater modeling, environmental economics, and social sciences proposed and led five working sessions: (1) Defining sustainable groundwater use; (2) Groundwater and global change; (3) Understanding the potential impacts of lithium mining on groundwater resources and the economy; (4) Groundwater and trade; and (5) Model to management: what are the pathways for science to become policy? Following the session discussions, eight papers were launched, with abstracts and manuscript development plans presented on the last day of the workshop. These manuscripts will be included in the special issue "Focus on Groundwater and Society: Sustainably Managing an "Invisible" Resource" in Environmental Research Letters (ERL), with the January 31, 2025 submission deadline. Feedback was collected post-workshop where we learned the workshop met its goals but that engaging with researchers studying governance and institutions would be a good future direction for similar workshops. The Program on Coupled Human and Earth Systems (PCHES-FRAME) provided funding for this event.

Outreach Workshops: 2017-2024

The original project proposal included a plan to hold annual summer community outreach workshops from 2017-2021 to communicate results from the project team to researchers from other MSD and other relevant research communities. However, this plan was interrupted, delayed and recast by the Covid-19 pandemic which made it impossible to hold this type of workshop in person in 2020, 20021 and 2022. Annual in-person workshops were organized and conducted in the summers of 2017, 2018, 2019, 2023 and 2024. In 2020, 2021, and 2022 initial agenda planning as well as preliminary contracting for lodging and workshop services were negotiated, but eventually abandoned as public health regulations in various jurisdictions made it impossible or risky to continue with implementation of the preliminary plans. This workshop process was supplemented by several on-line activities, which took place during the years when in person meetings were impossible or inadvisable.

The five in-person meetings that were conducted were: (1) "Modeling Integrated Energy-Water-Land Systems Dynamics" on July 18-20, 2017; (2) "Analyses of Multi-Sector Energy and Environmental Dynamics," on July 18-20, 2018; (3) "Multi-Sector Dynamics (MSD)" on July 16-19, 2019; (4) "Uncertainty Characterization & Quantification in MSD Research" on June 26-29, 2023; and "Coastal and Urban System Impacts and Extremes in MSD Research" on June 24-27, 2024. Agendas and slides for most of the presentations made at these workshops are available at: https://emf.stanford.edu/all-events.

During 2020, PI John Weyant helped plan and conduct a four part webinar meeting on "Multi-Sectoral Urban Interactions: Fundamental Science Needs to Inform Pathways to More Resilient Communities in a Changing Climate" for the U.S. Global Change Research Program. That program included half day long online sessions during November of 2020, which included presentations and participation by many of our team members, leaders from the other MSD teams, as well as project leads from teams supported by other USGCRP agencies working on related research topics. This led to the publication of a workshop report in early 2021 (Vallario, Arnold and Weyant, 2021): Vallario, Bob, Jeffrey Arnold, and John Weyant (2020). "Coastal Integrated Hydro-Terrestrial Modeling A Multi-Agency Invited Workshop," U.S. Global Change Research Program, 2021 (https://eesm.science.energy.gov/system/files/C-IHTM_Workshop_Report_Nov2020.pdf).

During 2021, Weyant and his administrative team provided support to another MSD team led by Andy Jones and LBNL and Christa Brelsford at ORNL who organized and conducted an online meeting on July 21-23 entitled "Multi-Sectoral Urban Interactions: Fundamental Science Needs to Inform Pathways to More Resilient Communities in a Changing Climate.". The workshop resulted in the publication of the report: "Multi-Sectoral Urban Interactions: Fundamental Science Needs to Inform Pathways to More Resilient Communities in a Changing Climate," (https://multisectordynamics.org/wp-content/uploads/2021/10/Brelsford_Jones_Urban_Workshop_Report_2021.pdf)

During 2022, it was decided to take the initial program and logistics planning that had been completed and roll it over into the planning of the 2023 in person workshop which seemed much more likely to be possible at that time.

Annual Research Outreach meetings were held at Penn State University, and continued virtually during the COVID-19 pandemic. These meetings brought together the entire PCHES-FRAME team—including senior personnel, students, postdocs, and technical staff—as well as invited experts from the broader MSD community and DOE representatives. Because the project team is both geographically dispersed and highly integrated, these gatherings provided valuable opportunities to share research progress, generate new ideas, strengthen existing relationships, and welcome new members. External experts offered critical feedback and suggestions, and each meeting included dedicated time for in-depth discussion of their insights. Meeting dates:

- May 21-22, 2018 (at Penn State)
- May 15-16, 2019 (at Penn State)
- June 1, 8, 15, 22, 2020 (virtual)
- September 19 and 26, 2022 (virtual)
- May 9-10, 2023 (at Penn State)

Members of the PCHES-FRAME project have actively contributed to projects within the broader EESM community, driving advancements in modeling and analysis. For instance, Mort Webster's team collaborated with the IM3 project to improve hydroelectric plant representation in the PSM. Researchers at JGCRI—including Robert Link, Kate Calvin, and colleagues—have worked with Reed and Keller on ensemble-based exploratory analysis of SSPs in GCAM, resulting in new analytical tools, improved code testing, and enhanced data analytics. Calvin has also partnered with Fisher-Vanden and Frolking on the development of integrated water-crop-land use-economic models. In addition, Jared Carbone (Colorado School of Mines) has collaborated with Douglass Wrenn and Karen Fisher-Vanden on a location choice model, leveraging synergies with the IM3 project's population/migration modeling. Finally, insights from research published in the paper Srikrishnan & Keller (2021) on agent-based modeling have informed model development for the ICoM project.

Project members Klaus Keller and Vivek Srikrishnan have also contributed to the following vision documents, papers, and reports by the MultiSector Dynamics Community of Practice (MSD-CoP):

- Reed, P. M., Hadjimichael, A., Moss, R. H., Monier, E., Alba, S., Brelsford, C., Burleyson, C., Cohen, S., Dyreson, A., Gold, D., Gupta, R., **Keller, K**., Konar, M., Macknick, J., Morris, J., **Srikrishnan, V.**, Voisin, N., & Yoon, J. (2022). MultiSector Dynamics: Scientific Challenges and a Research Vision for 2030, A Community of Practice Supported by the United States Department of Energy's Office of Science. Zenodo. https://doi.org/10.5281/zenodo.6144309
- Monier, E., Reed, P.M., Vernon, C.R., Hadjimichael, A., Brelsford, C.M., Burleyson, C.B., Dyreson, A.R., Fletcher, S.M., Giang, A., Gupta, R.S., Jackson, N.D., Jones, A.D., Lamontagne, J.R., McCollum, D.L., Morris, J.F., Moss, R.H., Peng, W., Saari, R.K., **Srikrishnan, V**., Szinai, J.K., Yoon, J. (2024) MultiSector Dynamics: 2023 Inaugural Workshop Report. MSD-LIVE Data Repository. doi:10.57931/2371710.
- Reed, P.M., Hadjimichael, A., Malek, K., Karimi, T., Vernon, C.R., **Srikrishnan, V**., Gupta, R.S., Gold, D.F., Lee, B., **Keller, K**., Thurber, T.B, & Rice, J.S. (2022). Addressing Uncertainty in Multisector Dynamics Research [Book]. Zenodo. https://doi.org/10.5281/zenodo.6110623".
- Reed P., Hadjimichael A., Moss R., Brelsford C., Burleyson C., Cohen S., Dyreson A., Gold D., Gupta R., **Keller K.**, Konar M., Monier E., Morris J., **Srikrishnan V.**, Voisin N., Yoon J.: Modeling MultiSector Dynamics to Inform Adaptive Pathways (2022). Earth's Future, 10, e2021EF00262, http://dx.doi.org/10.1029/2021EF002621
- Yoon J., Romero-Lankao P., Yang E., Klassert C., Urban N., Kaiser K., **Keller K.**, Yarlagadda B., Voisin N., Reed P., and Moss R.: A Typology for Characterizing Human Action in MultiSector Dynamics Models (2022). Earth's Future 10, e2021EF002641 http://dx.doi.org/10.1029/2021EF002641

Project member contribution to MSD-CoP research in form of presentations:

- **Keller, Klaus**: Realizing synergies between academic researchers, stakeholders, and decisionmakers. Invited discussant. Energy Modeling Forum Meeting. Snowmass (CO). June 25 (2024)
- Urban, N., Yoon J., Romero-Lankao P., Klassert C., Reed P., Yang E., Flores A., Kaiser K., Voisin N., and **Keller K.**: New Typology for Representing Human Decision Making in MultiSector Dynamics (MSD) Models. Talk at the 2020 AGU fall meeting. Virtual. December 11 (2020)
- Patrick P., Vernon C., and **Keller K.:** Challenges, & Opportunities for Coupled Uncertainty Analysis and Model Diagnostics in MultiSector Dynamics Research Invited keynote presentation. Energy Modeling Forum Meeting. Snowmass (CO). June 26 (2023)
- Yoon, J., Urban N., Romero-Lankao P., Klassert C., Yang E., Reed P., Kaiser K., Voisin N., Moss R., **Keller K.**, Yarlagadda B., and **Srikrishnan V**.: A Typology for Representing Human Actors in MultiSector Dynamics Models. Poster at the Fall AGU meeting. New Orleans (LA). December 13 (2021).

Project member contribution to MSD-CoP research in form of co-leadership included:

- **Klaus Keller** as a Session Co-Chair for the AGU Union Session: Modeling MultiSector Dynamics to Understand Adaptive Pathways. AGU Fall Meeting 2021
- **Klaus Keller** as a Session-Co-Chair (with Nathalie Voisin) of AGU Union Session: Modeling MultiSector Dynamics to Inform Adaptive Pathways. Virtual Session, December 2020
- 2021 – present: **Klaus Keller** is a Co-Chair of the Scientific Steering Group of the MultiSector Dynamics Community of Practice
- **Klaus Keller** as a Co-organizer of the Energy Modeling Forum Meeting Week 2: Uncertainty Characterization & Quantification in Multisector Dynamics Research, Snowmass (CO). June 24-27 (2024)

SYNTHESIS, INTEGRATION, AND OUTREACH

This element was embedded into the Program Element 4.1

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[1]MANUSCRIPTS IN PREPARATION

Alipour, A. Roth S., Ye, Sharma B., Zuidema S., Grogan D., Nicholas R., Keller K. Characterizing Parameter Uncertainty on Water Balance Model Soil Moisture Estimates over US Agricultural Lands.

Avila T., Lafferty D., Stover M., Guerrero S., Sue Wing I., and Sriver R. Historical vs future wildfire risk in the western US.

Cisneros-Pineda A., Haqiqi I., Liu J. Zuidema S., Grogan D. Nonlinear Crop Losses Due to Excess Soil Moisture and the Role of Subsurface Drainage.

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Daenzer K., Pandara-Valappil, F., Frolking S., Grogan D., Nucciarone J., Calvin, K., Fisher-Vanden K., Lammers R. How does crop production adapt with groundwater restrictions in the West?

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Haacker E., Knappett, P., Bitterman P., Iavorivska, L., Pena Rodriguez S., Kirchhoff, C. Perspective on usability of groundwater models for decision support.

Horing J. and Azevedo. Survey on stakeholder understanding about and concern about wildfires related to electric utility operations

Lafferty D., Grogan D., Alipour A., Zuidema S., Haqiqi I., Sriver R., Keller K. Combined climate and hydrologic uncertainties shape projections of future soil moisture extremes.

[1]The work conducted through the PCHES-FRAME provided a foundation that allowed for its extension through the PCHES-ADAPT project. As PCHES-ADAPT is still ongoing, the resulting work remains in preparation.

Lammers R., Grogan D., Zuidema S., Frolking S., Wollheim. Requirements for Successful Model Coupling in Interdisciplinary Research.

Liu J., Ayres A., Moyo T., Pakhtigian E., Valappil F. Water Resource Impacts of Lithium Mining Expansion in the Western U.S.

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Merrick J., Weyant J., Ye H.. Applications of a Framework of Choosing The Resolution of Normative Models.

Olmstead S., Plough J., Wrenn D. The role of flood risk characterization in evaluating property market impacts *(In review)*.

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Perla J., Fisher-Vanden K., Sue Wing I., Webster M., Lammers R., and Kumar V. Climate Change-Induced Stressors and Power System Resiliency.

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