Sectoral Interactions, Compounding Influences and Stressors, and Complex Systems: Understanding Tipping Points and Non-Linear Dynamics

Renewal Request for Cooperative Agreement: DE-FG02-94ER61937

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Abstract

Within the scope of our Cooperative Agreement, we propose to utilize a multi-system, multi-sector modeling framework that includes land use, water supply and use, energy resources, multi-scale socioeconomics and Earth systems to explore potential tipping points and transition states for regional to sub-regional scales, exploring the dynamics and potential new states that may emerge, as well as the driving forces contributing most significantly at the appropriate scales. The goal of this work is to understand how the convergence of human and natural systems, and their interactions, both influence and are influenced by multi-scale economics. We will investigate the scope, specificity, model forms, details, and data requirements for meaningful understanding of dynamics spanning scales. We will also explore methods and acquire insights that have the potential to be transferred and extended to other regions. We will focus on connections within and between two sub-regions of the United States: (1) the lower Midwest, and (2) the central Gulf Coast. Both of these target sub-regions are susceptible to various common types of individual and/or compound extreme events, including flooding, heat waves, and drought, and are likely to experience changes in population, economic activity, and transformation of energy, water, and land-using sectors. Additionally, the Midwest may experience severe snow/ice storms, while the Gulf region is highly exposed to the risk of tropical storms and hurricanes.

The research includes three overarching tasks: (1) multi-stressor risk triage, which quantifies the risk of multiple environmental and human stressors and influences, identifying vulnerable built and natural systems; (2) understanding instabilities and tipping points; and (3) understanding the typology of response options. To explore these complex interactions, we will focus our research on compounding influences and stressors in the target regions on: (1) water flow and quality, (2) coasts and (3) energy, and the resulting implications for multi-sector dynamics. The general objectives of the research are to understand: (1) the forces and patterns that affect economic and infrastructure development across and within regions; (2) the characteristics of interacting natural, managed, and built environments and human processes that lead to stabilities, instabilities, and tipping points in economic and infrastructure development; and (3) how foresight could increase system resilience to future forces, stressors, and disturbances (both natural and as a result of economic and infrastructure development). Based on our assessment of structure, function, and evolution of interactions in physical, natural, and socioeconomic systems addressed above, we will identify extractable insights of relevance to other regions.

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Project Description

1. STATE OF CURRENT PROGRAM AND VISION FOR FUTURE

1.1 Strengths of the Joint Program

The MIT Joint Program on the Science and Policy of Global Change has focused on a balanced approach for the continual development and numerical experimentation within a multi-system multi-sectoral modeling framework and analysis system over the course of 25 years. This balanced approach places equal emphasis on modeling and linking the various co-evolving components of: (a) physical systems (including the physical dynamics and chemical processes of the atmosphere and ocean, the biochemistry and ecosystem dynamics of land and ocean, hydrology and land-surface processes, and physical resources); and (b) human systems (including economic markets, energy, agriculture, land-use change, population dynamics, and infrastructure). Another signature focus of the program has been to use a risk-based approach to quantifying uncertain effects of future environmental and socioeconomic change.

As research has progressed, it has become clear that the interaction among various human activities and the natural resources involves interaction among systems at multiple time and geographical scales. **Figure 1** illustrates the broad elements of this complex "systems of systems" that is the research vision for future modeling by the MIT Joint Program. The goal of this development is to: (1) understand the forces and patterns (research foci; outer ring in Fig. 1) that are driving evolution of water, energy, and land resources; coasts, the built environment, urban structure, and material flows; and atmospheric composition and links to economic sectors (physical and socio-economic systems; second and third ring, Fig. 1); (2) examine stabilities and instabilities in these systems, and their interactions, to find potential tipping points at multiple scales (inner ring, Fig. 1); and (3) examine how different approaches to representing foresight affects the co-evolution of these systems and their resilience and vulnerabilities to provide extractable insights.

1.2 Project Scope and Vision

The scope of our Cooperative Agreement has had an emphasis on: (1) continuing development of our global integrated modeling system, with a focus on energy-water-land-atmosphere interactions; (2) better quantification of uncertain responses of the Earth system at scales relevant to decision-making under uncertainty; and (3) focused efforts on the interactions within the U.S. to develop understanding of vulnerability to global environmental change and tools that can assist in adaptation to these changes.

Within and consistent with the scope of our Cooperative Agreement, we will continue to strengthen our understanding of how primary interactions among water, land, and energy systems, and corresponding development may both influence, and be influenced by, economic activity at regional and sub-regional scales (or, more generally at multiple scales). Emphasis will be on long-term changes in stressors and influences (the latter can be positive or negative), concentrating on weather patterns and extremes, population/demographic shifts, and existing infrastructure and its future reconfiguration within a range of typological landscapes, from urban to rural and accompanying gradients. Specifically, the general objectives of this work are to examine the following major science questions:

1. **Forces and Patterns.** What combination of factors, varying by geography, contribute to salient ***patterns of economic and infrastructure development in trans-regional, regional, and sub-regional evolutions****,* including interactions and interdependencies among natural and built environments and human processes and systems?
2. **Stabilities and Instabilities.** What characteristics of interacting natural and built environments and human processes lead to ***stabilities*****,** ***instabilities, and tipping points*** in

economic and infrastructure development across systems, sectors, and scales, and what role do strong interdependencies, feedbacks, influences, and stressors play?

3. **Foresight**. How might long-term economic and infrastructure development patterns, stabilities, instabilities, and systems resilience ***evolve*** within multi-sector, multi-scale landscapes as a result of ***future forces, stressors, and disturbances (natural and as a result of human activity),*** and what pathways, characteristics, and risk profiles may emerge from ***both gradual and abrupt transitions***?

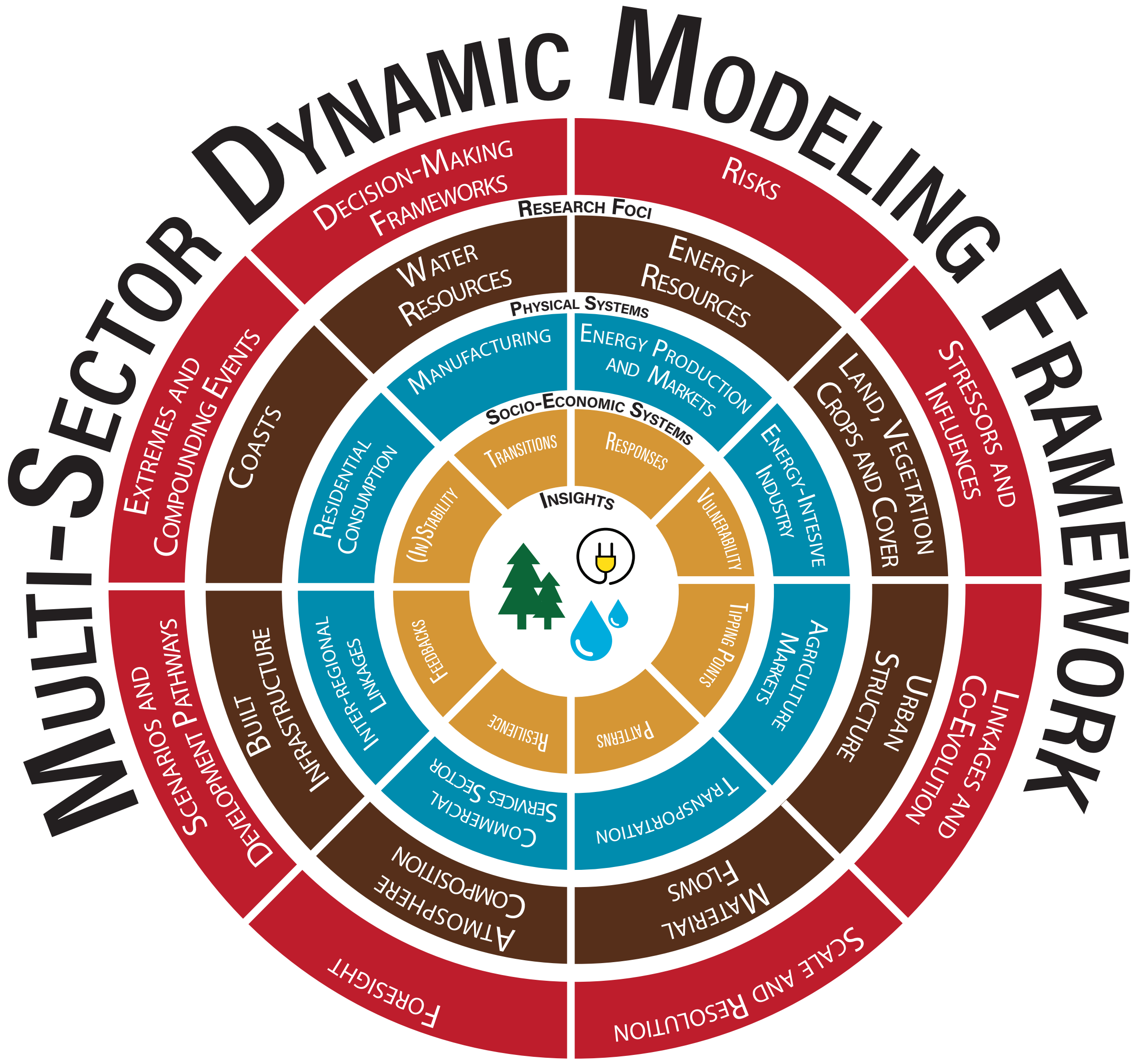

Figure 1. Schematic of the MIT multi-system multi-sector dynamic modeling framework.

2. INTRODUCTION

Deeper understanding of multiple influences and stressors on regional and sub-regional material and resource flows, socioeconomic activities and trans-regional networks is crucial for continuing prosperity. Our nation has a strong record of dealing with various challenges to its productivity, economic activity, and general populace, with challenges ranging from natural disasters to national security threats. In large part, this resilience derives from a pro-active stance and symbiosis among federal, state, and local governments, academia, and the private sector to identify potential threats, assess vulnerabilities to those threats, and devise strategies to lower the risks and preserve operational capacity and economic activity. Extreme events become disasters when they push the system beyond the conditions for which it was planned—a tipping point. Several recent regional extreme events (2017 hurricanes Harvey and Maria, 2018 hurricanes Florence and Michael, 2017 and 2018 drought and wildfires in California, and 2019 flooding of the Missouri and Mississippi Rivers) in addition to less intense but repeated and/or compounding events have caused significant disruptions and damage. These events highlight the fact that some areas of the country were largely unprepared and/or the development and co-evolution of critical resource systems failed to consider important precursory indicators trending toward a tipping point.

Given these considerations, what happens when the convergence and complexity of potential influences and stressors fall outside of normal short- to mid-term planning horizons or the capabilities of typical sector-specific or linear models, or fall outside of the historical record or simple extrapolation of historical trends? For example, economic development and trade, infrastructures and networks, land use and land cover, urban and coastal systems, natural resource development, and highly interactive sectors such as energy, water, and agriculture can all be subject to various long-term, potentially disruptive influences and stressors, which could change their trajectories. The inherent dynamics can exceed the resilience of the system, leading to non-linear behaviors and transitions to fundamentally new states. These influences and stressors can be gradual, abrupt, or both, and include changes in weather patterns and extremes (floods, droughts, heat waves, tropical cyclones, tornadoes, and snow and ice storms), sea-level rise and inundation, other forms of hydrologic shifts impacting both surface or ground water supplies, water quality issues such as hypoxia and salinity intrusion, and frequency and extent of wildfires and wildfire propagation. Long-term anthropogenic influences and stressors might include population/ demographic shifts, structural changes in regional, sub-regional and trans-regional economies and markets, technology advances, and changing institutions and governance.

For this study, our **overarching questions** are:

- ***Could changes in the severity, frequency, and intervals of extreme and/or compounding events significantly exceed the resilience of the coupled system and/or alter the trajectories of regional and sub-regional multi-sector dynamics and economic activity?***
- ***What insights can be gained from a focus on these events, such as coastal and inland flooding from tropical storms, extreme heat, ice storms and droughts, accompanied by significant changes involving water, energy, land use, populations, and the built environment?***

3. PROPOSED RESEARCH AREAS

We propose to utilize a multi-system, multi-sector modeling framework (Fig. 1) that includes land use, water supply and use, energy resources, multi-scale socioeconomics and Earth systems to explore potential tipping points and transition states for regional to sub-regional scales, exploring the dynamics and potential new states that may emerge, as well as the driving forces contributing most significantly at the appropriate scales. The goal of this work is to understand how the convergence of human and natural systems and their interactions both influence and are influenced by multi-scale economics. Our intent is to investigate the scope, specificity, model forms, details, and data requirements for meaningful understanding of dynamics spanning scales. We also seek to explore methods and acquire insights that have the potential to be transferred and extended to other regions.

We will focus on connections within and between two sub-regions of the United States, as depicted in **Figure 2** by the red- and blue-shaded areas: (1) the lower Midwest and; (2) the central Gulf Coast. The shading in the Fig. 2 defines only approximately the geographic extent

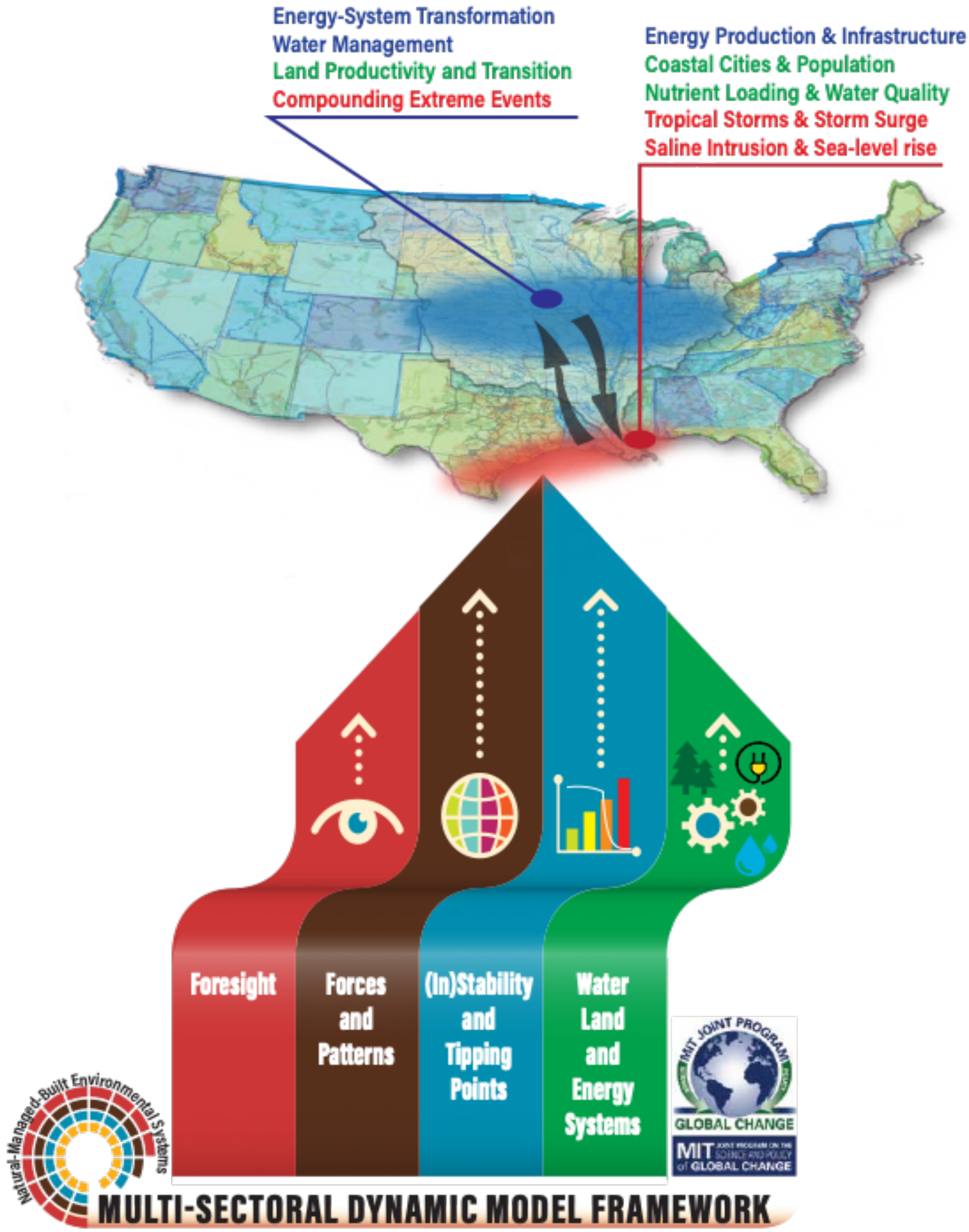

Figure 2. Schematic depicting the overarching research framework that covers the interlinked, multi-sectoral dynamics in and between the natural and human systems. Our key sub-regions of focus are highlighted by the blue- and red-shaded regions, and are chosen due to their complex and co-evolving upstream and downstream connections across the energy and river management systems. Within each sub-region, key infrastructure (blue text), influencers (green text), and stressors (red text) will be considered within our multi-sector dynamic modeling framework.

of these regions because different scales are relevant for different systems, and the geographical scale covered will need to vary. For example, river flooding or sediment loading in the Gulf depend on the entire Mississippi River drainage basin, and the land-use activities within it, while demand for crops and river transport will depend mainly on demand from export markets. We chose these sub-regions because both are susceptible to various common types of individual and/or compound extreme events, including flooding, heat waves, and drought, and are likely to experience changes in population, economic activity, and transformation of energy, water, and land-using sectors. Additionally, the Midwest may experience severe snow/ice storms, while the Gulf region is highly exposed to the risk of tropical storms and hurricanes.

In 2019, the Midwest has seen extreme cold, snow, flooding and low-pressure cyclonic events. Over the coming century, the frequency, intensity, and duration of these compounding events are expected to change (e.g. Dominguez et al., 2012; Kao and Ganguly, 2011; Kharin et al., 2013). Such changes could have dramatic ecological, economic, and sociological consequences (Field et al., 2012). In addition to the co-evolution and co-functioning of land management, energy infrastructure, and water resource systems across these landscapes, the two sub-regions are also distinguished by their connection via water pathways and infrastructure along the Mississippi River system.

We will focus on two key interconnections between the sub-regions: (1) the Mississippi River, which connects the regions as a transportation system and via water supply and quality, and (2) energy flows. The Mississippi River's transportation infrastructure consists of many ports and functions to transport commodities via barges, which is an extremely efficient mode of transport. Agricultural commodities grown in the Midwest, such as corn and wheat, are transported downstream, and from the Gulf Coast are shipped to other parts of the country and the globe. Fertilizers, many of which are produced in facilities along the Gulf Coast, are shipped upstream to Midwest ports, and then to farms. This transportation system relies on dependable water levels of the river. Natural systems, agricultural practices, land-use and infrastructure decisions, population, and extreme weather events all influence water levels. Moreover, droughts and floods can severely stress river management and operations and thereby cause major disruptions. These influences and stressors, along with energy systems, also impact the quality of the water, which will affect millions of people who rely on the Mississippi River for water supply, and a fishing industry that depends on coastal water quality. In terms of energy flows between the sub-regions, the current structure of the connection consists of energy (such as gasoline and LNG), being transported from the Gulf Coast to the Midwest, via pipelines and barges. Energy supply, energy demand (population and GDP), the river and other energy transportation systems, natural systems and extreme events affect these energy flows.

We will investigate the sectoral interactions and compounding influences and stressors of these complex systems, and explore how they might co-evolve. For example, the river transportation system could grow increasingly unstable due to increasing risk of extreme weather events, growing water demands for irrigation and municipal use, land-use change and energy infrastructure decisions that affect water flow. At the same time, energy transformations across the regions could result in increased demand for fuels produced at facilities along the Gulf Coast (e.g. refined oil and LNG) under development paths that continue to rely on fuels, or could potentially reverse energy flows between the sub-regions if development moves toward more renewables, such as wind resources in the Midwest. We will identify and contrast rapid and slow growth and transformations across sub-regions and resource systems, noting that these changes are not necessarily commensurate or complementary to one another, and many critical pieces of infrastructure are approaching their expected lifespans. Moreover, environmental and human stressors as well as compounding and intensifying extreme events are accelerating damage and decay to these systems, which may lead to widespread, premature failures. These interlinked phenomena may operate and appear stable under contemporary conditions, yet changing and co-evolving stressors, states, and structures may lead to instabilities that have salient features, and yet are also predictable against the range of plausible outcomes in an uncertain future.

To identify and advance predictability capacity for these potential "tipping points" we must employ a numerical experimentation approach that can capture a wide range of complexities. Our approach is to use an extensive probabilistic joint-distribution Monte Carlo sampling procedure that explores a wide range of plausible future outcomes. We will apply a multi-system multi-sector dynamic model that comprehensively treats interactions among economic sectors and physical systems, including energy resources, land use and land-use change, and water resources. This linked system will enable evaluation of how risks and events in one part of the system propagate within and between other systems. For example, how extreme precipitation upstream propagates downstream to affect communities and infrastructure over the Mississippi River basin (Fig. 2). We can investigate how coastal storm surges and increased rainfall inland might combine to worsen flooding. We can track socioeconomic linkages through trade, interdependence of sectors for supply chains, and reconfiguration of infrastructure. We will apply our Earth-system modeling methods to characterize the change in the risk of extremes, drawing on new large ensemble simulations of our Earth-system model combined with hybrid techniques to downscale these projections to the needed spatial granularity. We will also utilize our analogue method for characterizing changes in extremes, such as tropical and extra-tropical storms and extreme heat and ice events, by relating them to changes in the larger-scale Earth-system processes that are more reliably simulated in global circulation models.

4. RESEARCH TASKS

The research includes three overarching tasks: (1) multi-stressor risk triage, (2) understanding instabilities and tipping points, and (3) understanding the typology of response options applied to three interacting systems (coasts, energy, and water) within the target regions. (see **Table 1**). The multi-stressor risk triage (Task 1) quantifies the risk of multiple environmental and human stressors and influences, identifying vulnerable built and natural systems. Research needed to understand instabilities and tipping points (Task 2) requires a broad conceptual framework that includes: (a) identifying the current structure and function of targeted economic sectors and physical systems; (b) completing integration of human and physical system model components; (c) selecting, from large probability-based ensembles, multiple scenarios of economic and infrastructure development that lead to different end-states; (d) quantifying stressors and influences; (e) evaluating the vulnerability of energy, water and coastal systems to multiple stressors across the selected scenario end-states; and (f) evaluating transition paths where development strategies account for accumulating changes in stressors under different decision frameworks, including myopic decision-making, perfect foresight and decision-making under uncertainty (implemented via approximate dynamic programming). Finally, in Task 3, we will apply this conceptual framework to selected target regions and systems with the goal of identifying extractable insights and response typologies that could be applicable to other regions.

TASK 1. Multi-Stressor Risk Triage

The methodology used here will be an adaption of the toolkits originally developed by Strzepek et al. (2011, 2013) that assessed environmental risk on current and potential World Bank infrastructure portfolios. The analyses' original conception provided a computationally efficient assessment of environmental risks over river basins of the world and used monthly meteorological variables as well as selected hydrological indicators. We plan to expand our approach to include socioeconomic variables, such as population demographics, economic development, energy

Table 1. Summary of Research Tasks

- **TASK 1. Multi-Stressor Risk Triage**
- **TASK 2. Understanding Instabilities and Tipping Points**
    - *Subtask 2.0.1 Collect data on existing built infrastructure and resources at risk in the region*
    - *Subtask 2.0.2 Select scenarios for development in the regions with a range of end-states*
    - *Subtask 2.0.3 Complete integration of natural, physical and economic system model components*
    - **Task 2.1 Water Flow and Quality**
        - *Subtask 2.1.1 Assess changes in frequency of extreme weather events*
        - *Subtask 2.1.2 Assess availability, quality, and temperature of water and riverine resources*
        - *Subtask 2.1.3 Evaluate implications of stressors for key systems, sectors and dynamic interactions*
        - *Subtask 2.1.4 Develop decision-making under uncertainty framework to explore response strategies to flood risk*
    - **Task 2.2 Coasts**
        - *Subtask 2.2.1 Quantify various stressors relevant to coastal development*
        - *Subtask 2.2.2 Construct metrics of damages*
        - *Subtask 2.2.3 Develop decision-making under uncertainty framework to explore response strategies to combined storm surge and inland flood risk under different assumptions about foresight*
    - **Task 2.3 Energy**
        - *Subtask 2.3.1 Assess changes to wind resources*
        - *Subtask 2.3.2 Assess changes in extreme heat*
        - *Subtask 2.3.3 Run different possible wind resource profiles through regional multi-sector dynamic model linked to a detailed electric power sector model*
        - *Subtask 2.3.4 Create an understanding of impacts of separate and combined stressors*
        - *Subtask 2.3.5 Explore energy transition decisions under different decision frameworks*
- **TASK 3. Understanding the Typology of Response Options**

production and infrastructure, land-use change, and others. Among the selected natural and physical indicators, we will include the following: maximum and mean surface-air temperature as well as precipitation, potential evapotranspiration, climate-moisture index, annual mean runoff, basin yield, annual high flow, annual low flow, groundwater (baseflow), and a reference crop water deficit metric. Expansion of our methodology to a multi-sectoral approach that includes land use, water supply and use, energy resources, and multi-scale socioeconomics and Earth systems will provide an initial quantification of co-evolution of human-driven and nature-driven stressors.

We have recently added two important aspects to this analysis suite (see **Figure 3**) that brings quantitative details to the total range of uncertainty (composite of the interquartile and maximum outlier range) as well as the skewness of extreme values (a normalized composite of the net number of outliers above or below the distribution median). Further, we are able to implement this method across a variety of landscapes (i.e. not confined to river basin geometries as in the World Bank implementation). Our hybrid downscale approach (Schlosser et al., 2012) combines the large ensembles from our global Earth-system model with the representative response patterns of regional environmental changes derived from all participating Earth-system models within the Coupled Model Intercomparison Projects (CMIPs). In this way, we will construct large ensembles (thousands of members) of all the atmospheric variables needed to drive and create the meta-ensemble of triage indicators. Similar ensembles will be assembled for population change, land use, resource demand, and sectoral change utilizing the full distribution of socio-economic projections from our probabilistic human-Earth multi-dynamic and sector prediction framework, augmented with a similar ensemble of projections of our multi-sector, regional model of economic activity.

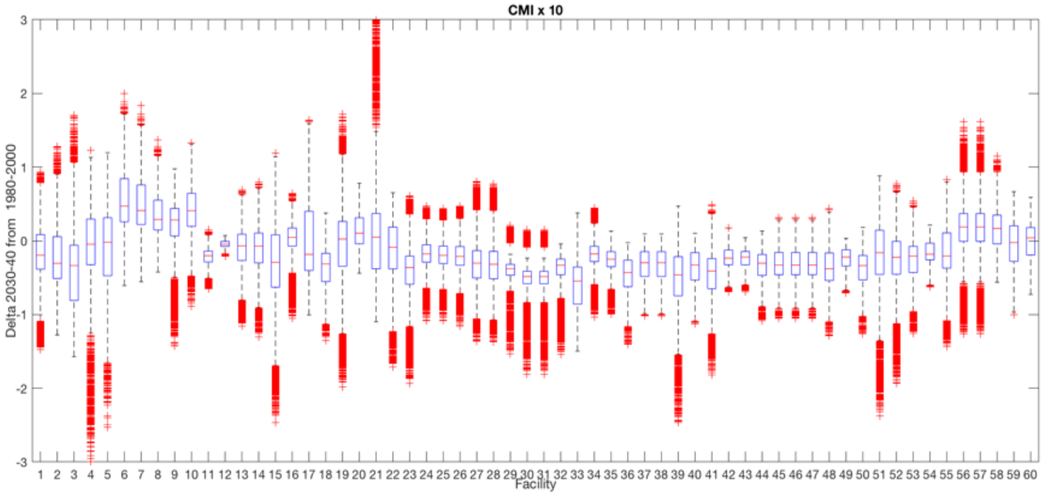

Figure 3. Illustrative example of the distribution of outcomes from the proposed triage assessment. Each of the whisker plots represents an outcome for a particular grid (or location). Shown here are the results for changes in the climate-moisture index (CMI) by mid-century – based on atmospheric driver data from the MIT Earth System Model ensemble projections. Given the large ensemble that we are able to create, we can assess the total range of outcomes as well as the skewness in the extreme/outlier values (denoted by the red cross hairs) – see text for details.

The triage has the ability to screen selected landscapes and infrastructure for their vulnerability to stressors and extremes. A total multi-stress risk index will be determined from a (weighted) combination of all the indicators deemed important across each of the sub-regions that will be based on their relevance to the natural and human environmental systems' co-evolution. The default weighting is to treat each of the indicators equally when creating the single aggregate value. However, this may not be appropriate for areas that are more prone to flooding, for which the annual high flow value would be given additional weight, and similarly for agricultural locations that are more sensitive to drought, in which case potential evapotranspiration and crop water deficit would be the more relevant indicators. Our weighting will consider these geographic distinctions based on data collection and surveys constructed from subtasks 2.1.1-2.1.3.

The simulated ensemble of economic development paths will provide a range of end-states of energy, population, economic activity and land use, without consideration of environmental stressors. From this database we will select diverse scenarios to explore the compounding impacts of both environmental stressors and human-driven influences for multiple sectors and systems (discussed below under Task 2).

TASK 2. Understanding Instabilities and Tipping Points

Using our multi-system multi-sector dynamic framework, we will explore how compounding influences and stressors affect patterns of economic and infrastructure development, stability of the systems, and complex non-linear interactions and feedbacks among systems. As developed in Task 1, these influences and stressors will include gradual changes, extreme events, and changing frequency of the extremes. As previously noted, extreme events represent a key trigger to tipping points and instabilities in co-evolving systems. For example, in many places along the Mississippi River, levees have enabled development of populated areas that were commonly prone to floods, but that are now considered at low risk. However, under changing climatic conditions and a concurrent increase in risk of extreme precipitation events, these developed areas could become unstable. Response strategies will need to consider tradeoffs of increasing the height of levees with the potential risk that poses for channeling higher water flows/levels to natural and built environments downstream. The sub-regions of our focus also experience changes in population and its demographics, water quantity and quality issues, land-use change, and expanding requirements for energy production and infrastructure as driven by demand within and outside the sub-regions. These socioeconomic influences and stressors, if not adequately addressed, potentially add to instability and increase vulnerability of the connected sectors.

We intend to apply recent advances in the predictability of changes in extreme/compounding weather, climate, and socioeconomic stressors. The method employs an enhanced, machine-learning based analogue approach that is flexible and transferable to any location as well as different types of extreme events of interest. The analogue method relies on determining the "telltale signs" at the large meteorological atmosphere-scale for the occurrence of an extreme event at the local scale. The power of this method is that we can detect different extreme and compounding events in which there is a distinct, discernable combination of larger-scale conditions associated with the (observed) occurrence of local events. The method has been shown to improve the accuracy and consensus in modeled historical variations as well as projections of future changes in extreme events (Gao et al., 2014; Gao and Schlosser, 2018). The successful application of this method for different extreme events across various regions of continental U.S. has also demonstrated its robustness and transferability (Gao et al., 2014, 2017). We will also explore how the impacts of such events are compounded by socio-economic changes.

To explore these complex interactions, we will focus our research on compounding influences and stressors in the target regions on: **(1) water flow and quality, (2) coasts** and **(3) energy**, and the resulting implications for multi-sector dynamics. To do so, we will first complete the following subtasks:

Subtask 2.0.1 - Collect data on existing built infrastructure and resources at risk in the sub-regions. To investigate potential vulnerabilities and instabilities, it is important to first understand the key assets in the sub-regions. Such assets include built infrastructure (e.g. cities, levees, ports, energy facilities, etc.), as well as physical resources (e.g. important watersheds, ecosystems, energy resources, etc.). Collecting and mapping this data will identify key assets and areas to focus on when exploring how compounding influences and stressors might impact vulnerabilities, instabilities and tipping points in the region, and will inform how evolving risks might impact different systems and sectors.

Subtask 2.0.2 - Select scenarios for development in the regions with a range of end-states. From our large ensembles constructed in Task 1, we will select multiple scenarios of development that lead to different end-states of energy, population, economic sector activity, and land use. For example, we will include scenarios that reconfigure the energy infrastructure rapidly to clean technology sources, those that continue to rely on the current energy mix, those that expand the use of traditional energy technologies, and scenarios of gradual transformation. We will augment these scenarios with different assumptions about infrastructure development along the Mississippi River to explore how different evolutions of infrastructure could affect multiple sectors.

Subtask 2.0.3 - Complete integration of natural, physical and economic system model components. To be able to explore the implications of stressors on various sectors, we will complete the integration of natural, physical and economic system model components. We will employ our extensive expertise in linking models of socio-economic, population dynamics and energy (e.g. Rausch and Mowers, 2012; Chen et al., 2016; Tapia-Ahumada et al., 2015), crops and land use (e.g. Gurgel et al., 2016; Blanc, 2017a,b); water flow and quality (e.g. Schlosser et al., 2014; Strzepek et al., 2013; Ledvina et al., 2018; Winchester et al., 2018); terrestrial ecosystems (e.g. Kicklighter et al., 2012; Gurgel et al., 2011); and atmospheric chemistry, ocean and land dynamics (e.g. Sokolov et al., 2018a). We will focus on completing pathways for water and environmental impacts, such as irrigation, agricultural productivity, land use, flood/drought damage, extreme heat and ice storm damages, transportation disruptions, thermal cooling availability, and municipal water supply.

Building on these three tasks, for each of the three systems (water, coasts and energy), we will then quantify relevant stressors and influences, evaluate their vulnerability across scenarios, and explore response strategies under different decision frameworks.

Task 2.1 Water Flow and Quality

To study water flow and quality, we will use our high-resolution water resource model along with our water quality model (Boehlert et al., 2015; Strzepek et al., 2015a,b). These models take in information from our models of economic activity, population dynamics, energy, crop, land use and the physical Earth system. In turn, the water models provide projections of water flow and water quality (e.g. water temperature, pollution level, etc.). These depend on: (a) weather and climate (precipitation, temperature, evapotranspiration and extreme events), which in turn depend on human activities and natural systems; (b) water demand from agriculture (i.e. irrigation) as well as municipal, industrial and energy uses, which in turn depend on climate, economic activity, energy, population, etc.; (c) the use of fertilizers for agriculture; (d) land use and natural systems; and (e) infrastructure (e.g. levees, urban development, etc.). The resulting water flow impacts infrastructure, including the river transportation system of ports and levees as well as energy infrastructure and buildings, agriculture, economic activity, populations, and ecosystems. Water quality affects populations, ecosystems, economic activity, and the energy sector. We will capture these interactions in our models and explore them under a wide range of scenarios, including scenarios of different economic and infrastructure development and population trajectories for the region, such as more or higher levees or different urban development. We will investigate how the frequency of droughts and floods may change over time, with a particular focus on the implications for river transportation infrastructure (ports, levees) and the economy, and potential tipping points (for example, areas that are not currently at flood risk, but may become so in the future). We will explore how development upstream may have impacts downstream. We will also explore decision-making around flood risk, including how decisions might differ if based on local impacts vs. impacts on the system as a whole. Independent local decisions could lead to an unstable system, while considering the whole system could make the system more stable.

Subtask 2.1.1 - Assess changes in frequency of extreme weather events. Based on the risk triage assessment in Task 1, we will identify the “hotspot” locations that show a salient vulnerability to extremes and stressors. We will then employ the analogue method described above to quantify the occurrences of various damaging, and possibly, compound events and their future changes that pose a salient threat to the water, land, and energy systems of identified “hotspots.” The extreme events include flooding, heat waves, drought, and winter snow/ice storms in the lower Midwest as well as flooding, heat waves/drought and tropical storms in the central Gulf Coast. We will compile a variety of daily, quality-controlled, long-term observational data sets to quantify the historical occurrence of different extreme events in our target regions. We will employ one of the third-generation reanalysis products – the Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2, Gelaro et al., 2017), to construct the large-scale atmospheric variables for the analogue method. To quantify the future occurrences of various damaging compound events and their changes, we will draw from the latest model simulations from the international CMIP Phase 6 (Eyring et al., 2016). We aim to strengthen the consensus of projected trends in these events, bracketed within primary sources of uncertainty, and thereby provide a fortified scientific basis for future resilience.

Subtask 2.1.2 - Assess availability, quality, and temperature of water and riverine resources. Our multi-sector model framework employs a parsimonious linked water-systems model that has been used to evaluate the impacts of human and Earth-system changes on water availability and quality, globally (e.g. Schlosser et al., 2014), in large developing regions (e.g. Fant et al., 2016c; Gao et al., 2018b) and over the contiguous U.S. (e.g. Blanc et al., 2014, 2017; Boehlert et al., 2015; Strzepek et al., 2015a,b). With the existing model framework and the capability to resolve the U.S. river network into over 2,119 basins (**Figure 4**), we will assess inter-basin impacts as well as upstream/downstream linkages between our sub-regions of interest. Based on our selection of scenarios delivered from our probabilistic, multi-sector model framework (Task 1 and subtask 2.0.2), we will construct a meta-ensemble of simulations that will assess the concurrent range of outcomes in water resource availability and quality. From these, we will assess a variety of impacts across our water-coasts-energy system of systems focus. Examples would include: cooling capacity of thermal power plants (via hydro-climatologic variability and change as well as riverine development) and downstream effects on water quality and aquatic ecosystem health; river nutrient loading and downstream water availability as a result of widespread, upstream transformations in agricultural management and the environment; riverine transport capacity (to/from coastal ports) as a result of co-evolving transformations in the hydro-climatic landscape as well as riverine management and development; as well as flood and drought risks that result from co-evolving transformations within and across the natural, managed, and built environments as determined by the scenarios we will develop.

Subtask 2.1.3 - Evaluate implications of stressors for key systems, sectors and dynamic interactions. Under the selected scenarios, we will explore how the effects of various stressors, especially floods and droughts, affect the evolution of key systems, sectors and interactions, potentially leading to different states of systems. For example, floods and droughts can cause major disruptions to the river transportation system, especially if they impact key infrastructure (e.g. ports). Cities, agriculture, land use and ecosystems are also affected by these events. As another example, changes to water quality can place stress on populations reliant on the river for drinking water, as well as on energy infrastructure reliant on the river for thermal cooling. Such changes can affect the regional economy.

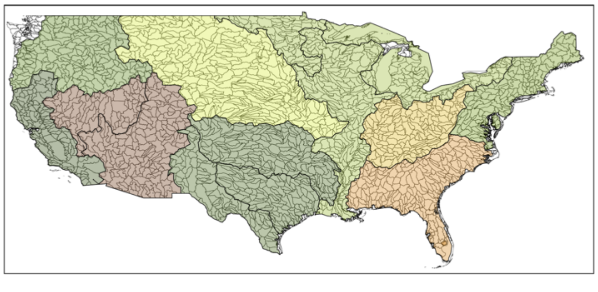

Figure 4. Depiction of the basin-level detail of water resources model framework employed by the proposed research. The lighter contours outline the 2,119 basins resolved by the model system. Heavier contours denote larger basins of the U.S. used in the global implementation of the model.

Subtask 2.1.4 - Develop decision-making under uncertainty framework to explore response strategies to flood risk. We will develop a decision-making under uncertainty framework focused on response strategies (e.g. levee building, relocation, etc.) to flood risk. In particular, we will explore how decisions made upstream may have negative impacts downstream. For example, in response to flood risk, an upstream city may decide to build a levee, which in turn would channel higher water-flows downstream, increasing the flood risk downstream. This could even create tipping points in which downstream locations that were not previously at risk for flooding become at risk. We would also consider other adaptive strategies such as the decision to transform riverine development and settlements with "setback" levees (extensively used internationally but as yet not widely adopted along U.S. river systems – and particularly not on the Mississippi River). We will also explore how decisions might differ if based on local flood risk and impacts vs. flood risk and impacts on the system as a whole. Independent local decisions could lead to an unstable system, while considering the whole system could make the system more stable.

Task 2.2 Coasts

We will explore changing risks to coastal built and natural systems along the Gulf Coast. Coastal developments are subject to several influences and stressors, including tropical storms, inland flooding, sea-level rise, subsidence, population, economic activity, and infrastructure. We will quantify risk of flooding of a coastal city, such as New Orleans, including the joint risk of coastal inundation caused by storm surge (potentially combined with sea-level rise and subsidence) and urban flooding caused by intense inland rainfall. We will also consider the role of changing population dynamics, economic activity and infrastructure decisions. We will build on earlier subtasks, which will have identified key infrastructure and resource assets, including those on the coast (subtask 2.0.1), assessed long-term changes in extreme precipitation events (subtask 2.1.1), and completed the modeling system integration necessary to evaluate coastal flooding driven by inland precipitation (subtasks 2.0.3 and 2.1.2). To that, we will add quantification of coastal inundation due to hurricanes and storm surge. We have access to physics-based hurricane simulations for the Gulf Coast region developed at MIT (see below). The storm risk information from those simulations, which includes changes in storm frequency and intensity over time, will then inform storm surge and coastal inundation risk. We will investigate the compounding risk of coastal surge combined with inland flooding. We will then use information about the assets at risk and data from previous flooding events to construct metrics of costs/damages associated with such risk, which can be used in decision-making frameworks. We will develop a decision-making framework focused on response strategies for flood risk in a coastal city. We will then explore how decisions may change as additional risks are taken into account, as well as how decisions may change under a myopic framework that accounts for current conditions vs. a decision-making under uncertainty framework that takes account of future directions.

Subtask 2.2.1 - Quantify various stressors relevant to coastal development. We will identify a coastal city of interest, such as New Orleans, and the key influences and stressors affecting it. We will focus on the joint risk of coastal inundation caused by storm surge (potentially combined with sea-level rise and subsidence) and urban flooding caused by intense inland rainfall, along with consideration of changing population dynamics, economic activity and infrastructure decisions. We will compile storm risk information from physics-based hurricane simulations for the Gulf Coast region developed by an MIT group led by Prof. Kerry Emanuel (Emanuel et al., 2006, 2008; Neumann et al., 2015). Emanuel's approach includes estimation of how coastal risk (e.g. from surge, wind, and rain) evolve with changing environmental and climatic conditions (e.g., Emanuel et al., 2008; Lin and Emanuel, 2016; Emanuel, 2017). We will investigate if surge risk analysis for this region also already exists. If not, we will translate the storm risk into surge risk based on a surge model, such as ADCIRC (Luettich and Westerink, 2012) or a simpler statistical surge model. We will also investigate the possibility of accounting for additional risks related to sea-level rise and subsidence, depending on the availability of existing data and research. Consideration of population, economic and infrastructure factors will come from our large probability-based ensemble of scenarios (Task 1).

Subtask 2.2.2 - Construct metrics of damages. We will use information about the coastal assets at risk (identified in Task 2.1.2) and data from previous flooding events to construct metrics of costs/damages associated with coastal floods. These metrics will also factor in how the physical risks are compounded by socio-economic changes. The metrics will then be used in decision-making frameworks.

Subtask 2.2.3 - Develop decision-making under uncertainty framework to explore response strategies to combined storm surge and inland flood risk under different assumptions about foresight. We will investigate decisions related to response strategies for flood risk in a coastal city, and then explore how decisions may change under a myopic framework that accounts for current conditions vs. a decision-making under uncertainty framework (implemented via approximate dynamic programming, e.g. Morris et al., 2018a) that takes account of future directions. In other words, how does foresight change the response strategy? In addition, we will explore how decisions made under uncertainty may change as additional risks are taken into account, for example storm surge risk alone vs. the combine risk of storm surge and inland flooding.

Task 2.3 Energy

Our study of energy flows will explore several scenarios for energy transformations in the regions, including the scenarios that reconfigure the energy infrastructure rapidly to clean technology sources, those that continue to rely on the current energy mix, those that expand the use of traditional energy technologies, and scenarios of gradual transformation. Both traditional and advanced energy technologies are subject to influence from multiple stressors. We will investigate forces and patterns of impacts on changing wind resources, stream temperatures for thermal cooling, and operations under extreme heat and icing/heavy snow conditions. Population growth and economic expansion will create additional demands on energy infrastructure. We will explore how co-evolution of multiple influences and stressors could impact electricity capacity/generation and investment decisions on new capacity depending on the nature of the energy transition in these regions.

Subtask 2.3.1 - Assess changes to wind resources. We will employ a hybrid approach that combines the probabilistic rigor of our large ensemble projections of global climate trends with regional patterns of potential change in wind (and power density) as estimated by the CMIP climate models. This approach was pioneered by our previous analysis (e.g. Gunturu and Schlosser, 2012, 2015; Hallgren et al., 2014; Fant et al., 2016a,b) that was developed to study wind power over southern Africa (see **Figure 5**). These studies combined machine learning, similarity theory, and adjustments based on near-surface atmospheric stability to establish emerging trend patterns. The resultant statistically-based model represents the relationship of global mean temperature to local changes in wind speed and power density. In this way, risk-based estimates of wind power density changes will be constructed by applying global temperature change probabilistic distributions produced from ensembles (~400 members) simulated by our global modeling framework.

Multiple scenarios will be considered that are based on our latest suite of projections. These distributions of outcomes (i.e. changes in wind power) can be displayed graphically (e.g. Fig. 5). From these, we can identify regions at high risk to strong changes, and address how these risks change under a variety of climate outcomes and transition pathways. These distributions can also be binned across a range of values (e.g. percent change) or judged/quantified of exceeding a certain threshold (i.e. cut-in or cut-out windspeed) in order to quantify the likelihood of a change in a critical aspect of wind-power operations.

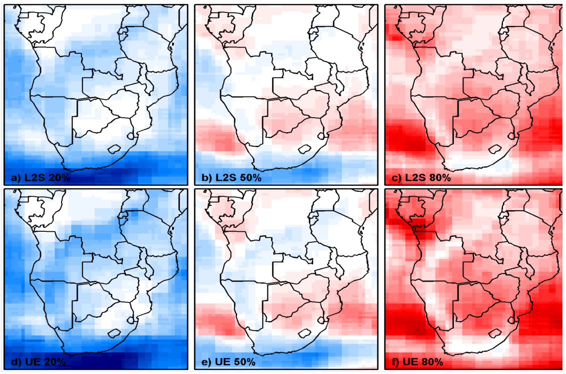

Figure 5. Results from our prior study (Fant et al., 2016b) show examples of the risk-based outputs anticipated under the proposed research. The panels of maps convey the 10th, 50th, and 90th percentile of change in wind power, averaged for June-August, with darker shades of red/blue indicating stronger increases/decreases in wind power density. These results provide geographic aspects of risk that can also be conveyed for a given location. The results are shown for a strong mitigation and an unconstrained emissions scenarios. In the proposed work, this will be updated with our most recent scenarios (from subtask 2.0.2) and expanded to include the most recent climate information (i.e. CMIP5 and CMIP6) with sub-regional highlights.

Subtask 2.3.2 - Assess changes in extreme heat. We will employ methods similar to those described in subtask 2.1.1 to assess the specific risks and tipping points (i.e. failures of critical pieces and/or junctures in the energy system) that result from extreme heat events. Under the scenarios we develop (i.e. Task 1 and subtask 2.0.2), we will use our analogue method to project changes in excessive heat event occurrence across our two sub-regions of interest. Under each scenario, we will determine the change in occurrence of a particular severity of heat wave.

Subtask 2.3.3 - Run different possible wind resource profiles through regional multi-sector dynamic model linked to a detailed electric power sector model. We will use information on the changes in wind resources developed in subtask 2.3.2 and convert it to inputs for our multi-sector dynamic model. For this task, we will link our model to the Regional Energy Deployment System (ReEDS) model developed at National Renewable Energy Laboratory (Cohen et al., 2018). It will allow us to explore electricity capacity planning and dispatch at high spatial resolution that will include issues related to integration of renewable energy to the grid, technology innovation, operational constraints, and maintaining and expanding the generation and transmission infrastructure.

Subtask 2.3.4 - Create an understanding of impacts of separate and combined stressors. Within our multi-sector dynamic model, we will assess how the multiple stresses and influences interact and how they either multiply or ameliorate an individual stress. Based on different transition paths and end-states determined in subtask 2.3.1, we will create an impact analysis of the interactive physical, natural and socioeconomic systems that will provide a deeper understanding of factors influencing the evolution of energy systems and flows.

Subtask 2.3.5 - Explore energy transition decisions under different decision frameworks. We will explore decisions related to energy (e.g. generation capacity investments, thermal cooling investments, transmission infrastructure investments, etc.) under different decision frameworks, including myopic decision-making, perfect foresight and decision-making under uncertainty (implemented via approximate dynamic programming). This comparison will provide insight into how decisions may change under different assumptions about foresight. We will also explore how decisions made under uncertainty may change depending on which risks are included. For example, wind capacity investments with and without accounting for the added risk of changing wind resources, or investments in alternative thermal cooling technologies (e.g. dry cooling vs. river cooling) with and without accounting for changing river temperature.

TASK 3. Understanding the Typology of Response Options

Tasks 1 and 2 focus on specific regions, resources, and types of infrastructure. Under Task 3, we will produce a document summarizing findings across the two regional case studies of water flow and quality, coasts, and energy as they relate to the overall science objectives of the research (Abstract and Section 1.2), which are to understand: (1) the ***forces and patterns*** that affect economic and infrastructure development across and within regions; (2) the characteristics of interacting natural and built environments and human processes that lead to ***stabilities, instabilities, and tipping points*** in economic and infrastructure development; and (3) how ***foresight*** could increase system resilience to future forces, stressors, and disturbances (both natural and as a result of economic and infrastructure development).

Based on our assessment of structure, function, and evolution of interactions in physical, natural, and socioeconomic systems addressed above, we will identify extractable insights of potential relevance to other regions, and identify a typology of response options. We will be able to see if there is a typology of response options that emerges in similar circumstances in the two regions and three resource areas (water, energy, and coasts). However, these regions, while linked, are quite different. For example, the Gulf Coast region will be affected directly by sea-level rise, changing strength and frequency of tropical storms, and possible subsidence, while these events will have limited direct impact on the lower Midwest. However, there may be generalizable insights on the role of risk assessment and infrastructure development pathways that lead to more or less development in areas highly vulnerable to extreme events.

Our working hypotheses include:

- Uncertainty quantification and risk assessment can lead to more stable and resilient development pathways.
- The scale of decision-making contributes to the stability of systems, with independent optimal local decisions potentially adding instability to larger systems while optimal system-level decisions could create greater stability.
- The level of foresight factored into decision-making affects the resulting stability and resilience of systems, with decision-making under uncertainty frameworks performing better than myopic or perfect foresight decision frameworks.
- Considering regional, sectoral and system connections results in more resilient response strategies.
- Considering risks jointly with their compounding influences and stressors, rather than in isolation, results in more resilient response strategies.

To determine whether these hypothesized lessons and insights are actually generalizable to other regions would require application of the approach in other regions—i.e. some out-of-sample tests that are beyond the scope of this project. As Tasks 1 and 2 proceed, we will be able to address this final Task 3 in increasing breadth and depth.

5. CONNECTIONS TO MULTI-SECTOR DYNAMICS COMMUNITY

We will organize annual workshops, hosted at MIT, to gather input from and communicate our current research activities and findings to, other top-level research groups in the Multi-Sector Dynamics (MSD) community. We will invite group representatives from the Integrated Multi-sector Multi-scale Modeling (IM3) effort organized by Pacific Northwest National Laboratory in Richland, Washington (PNNL-WA), Integrated Human-Earth System Dynamics (IHESD) effort organized by PNNL in Bethesda, Maryland (PNNL-MD), and the Program on Coupled Human Earth Systems (PCHES) organized at the Pennsylvania State University. We will also reach out to individuals in the MSD community who are working on related topics. The workshops will allow us to identify useful areas of collaboration, to disseminate our knowledge obtained in this project, and use the input from other groups.

6. PERSONNEL AND MANAGEMENT PLAN

The Co-Principal Investigators for this proposal are Prof. Ronald Prinn, Dr. John Reilly, Dr. Adam Schlosser and Dr. Sergey Paltsev. They are responsible for the overall direction and management of the research. They are accompanied in the proposed research by a team of highly qualified specialists that includes Dr. Jennifer Morris (socioeconomic aspects, multi-sectoral dynamics, and decision-making under uncertainty), Dr. Xiang Gao (hydrology and land surface processes), a research scientist (RS, to be appointed) with expertise in land use, energy and built infrastructure, and Dr. Andrei Sokolov (ocean and atmospheric dynamics, atmospheric chemistry). Dr. Schlosser will lead the research tasks related to multi-stressor risk triage and non-linear dynamics of tipping points. Dr. Paltsev will lead the research tasks related to forces and patterns of economic and infrastructure development. Project management will benefit from significant leverage upon the substantial supporting infrastructure of the MIT Joint Program on the Science and Policy of Global Change and the MIT Center for Global Change Science.

The expected timeline for the research tasks is given in **Table 2**.

Table 2. Timeline for Research Tasks

Task, *Subtask*	**Personnel Responsible for Task**	**Year 1**	**Year 2**	**Year 3**
1. MULTI-STRESSOR RISK TRIAGE	Schlosser, Gao, Paltsev, Morris & Prinn	X	X	
2. UNDERSTANDING INSTABILITIES AND TIPPING POINTS				
2.0.1 Collect data on existing built infrastructure and resources at risk in the region	Morris, Gao, Schlosser & Paltsev	X		
2.0.2 Select scenarios for development in the regions with a range of end-states	Sokolov & Morris	X	X	
2.0.3 Complete integration of natural, physical and economic system model components	Prinn, Reilly, Paltsev, Schlosser & RS*	X		
2.1 Water Flow and Quality				
2.1.1 Assess changes in frequency of extreme weather events	Gao & Schlosser		X	X
2.1.2 Assess availability, quality, and temperature of water and riverine resources	Schlosser & Gao	X	X	X
2.1.3 Evaluate implications of stressors for key systems, sectors and dynamic interactions	Paltsev, Morris & RS		X	X
2.1.4 Develop decision-making under uncertainty frame-work to explore response strategies to flood risk	Morris, Sokolov & Schlosser		X	X

Task, *Subtask*	**Personnel Responsible for Task**	**Year 1**	**Year 2**	**Year 3**
2.2 Coasts				
2.2.1 Quantify various stressors relevant to coastal development	Morris & Schlosser	X	X	X
2.2.2 Construct metrics of damages	Paltsev & Morris		X	X
2.2.3 Develop decision-making under uncertainty framework to explore response strategies to combined storm surge and inland flood risk under different assumptions about foresight	Morris, Schlosser, Gao & RS		X	X
2.3 Energy				
2.3.1 Assess changes to wind resources	Schlosser	X	X	
2.3.2 Assess changes in extreme heat	Gao & Schlosser	X	X	
2.3.3 Run different possible wind resource profiles through regional multi-sector dynamic model linked to a detailed electric power sector model	Paltsev & Schlosser		X	X
2.3.4 Create an understanding of impacts of separate and combined stressors	Paltsev, Schlosser, Morris & RS		X	X
2.3.5 Explore energy transition decisions under different decision frameworks	Morris, Reilly & Paltsev			X
3. UNDERSTANDING THE TYPOLOGY OF RESPONSE OPTIONS	Prinn, Reilly, Paltsev & Schlosser			X

* RS = Research Scientist (to be appointed)

Appendix 1: Biographical Sketches

RONALD G. PRINN

TEPCO Professor of Atmospheric Science, Dept. of Earth, Atmospheric & Planetary Sciences
Massachusetts Institute of Technology, Bldg. 54-1312, Cambridge, MA 02139
Phone: 617-253-2452, Email: rprinn@mit.edu, Website: http://mit.edu/rprinn/

Education and Training

University of Auckland, New Zealand, Chemistry, and Pure and Applied Math., B.Sc., 1967
University of Auckland, Chemistry (with first class honors), M.Sc., 1968
Massachusetts Institute of Technology, Chemistry, Sc.D., 1971

Research and Professional Experience

1993-present: *TEPCO Professor* of Atmospheric Science, Department of Earth, Atmospheric and Planetary Sciences, MIT. General research interests involve the chemistry, dynamics and physics of the atmospheres and climates of the Earth and other planets, and the interactions among science, economics and technology that guide sound policy. Serves as PI on a range of projects in atmospheric chemistry, biogeochemistry, climate science, and integrated assessment of science and policy regarding climate change and air pollution.

1998-2003: *Head*, Department of Earth, Atmospheric, and Planetary Sciences, MIT. Leads all academic and administrative functions of the department including its vision, budget, organization, hiring, and conduct of all faculty, staff and students.

1991-present: *Co-Director*, MIT Joint Program on the Science and Policy of Global Change (JPSPGC). Founding Co-Director of research program of integrated earth system modeling including the link of earth system and human system components to study the human and natural contributions to global environmental change, its implications for society and economies, and the role of technology in mitigating and adapting to global change. Responsibilities: management and oversight of all research, finances, and personnel.

1990-present: *Director*, MIT Center for Global Change Science
Founding Director of a major Research Center to facilitate large projects to address fundamental questions about the earth system, with a goal of improving the ability to predict changes in the global environment. Projects include AGAGE and JPSPGC. Responsibilities: management and oversight of all research, finances, and personnel.

1981: *Visiting Associate Professor*, California Institute of Technology, Division of Geological & Planetary Sciences

1971-1992: *Professor* (*Assistant*, 1971; *Associate*, 1976; *Full*, 1982), MIT

Publications (10 most closely related to proposed project; see full list at: http://mit.edu/rprinn/)

Prinn, R. G., R.F. Weiss, J. Arduini, T. Arnold, H.L. DeWitt, P.J. Fraser, A.L. Ganesan, J. Gasore, C.M. Harth, O. Hermansen, J. Kim, P.B. Krummel, S. Li, Z. M. Loh, C.R. Lunder, M. Maione, A.J. Manning, B.R. Miller, B. Mitrevski, J. Mühle, S. O'Doherty, S. Park, S. Reimann, M. Rigby, T. Saito, P. K. Salameh, R. Schmidt,P. G. Simmonds, L.P. Steele, M.K. Vollmer, R.H. Wang, B. Yao, Y. Yokouchi, D. Young, and L. Zhou: History of chemically and radiatively important atmospheric gases from the Advanced Global Atmospheric Gases Experiment (AGAGE), *Earth Syst. Sci. Data,* 10: 985-1018, doi: 10.5194/essd-10-985-2018, 2018.

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1.2 CAM-chem (CAM4): MOZART-4 vs. Reduced Hydrocarbon vs. Super-Fast Chemistry. *Geoscientific Model Development,* 11(10), 4155-4174, doi: 10.5194/gmd-2018-16, 2018.

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Sokolov, A., Kicklighter, D., Schlosser, A., Wang, C., Monier, E., Brown-Steiner, B., Prinn, R., Forest, C., Gao, X., Libardoni, A. and Eastham, S., Description and Evaluation of the MIT Earth System Model (MESM). *Journal of Advances in Modeling Earth Systems*, 10(8), 1759-1789, doi: 10.1029/2018MS001277, 2018.

Tian, H., J. Melillo, A. Michalak, P. Ciais, P. Canadell, P. Friedlingstein, E. Saikawa, S. Wofsy, K. Gurney, L. Bruhwiler, E. Dlugokencky, S. A. Sitch, M. Saunois, P. Bousquet, R. Prinn, S. Pan, B. Zhang, G. Chen, B. Poulter, C. Schwalm, J. Yang, D. Huntzinger, and C. Lu, The terrestrial biosphere as a net source of greenhouse gases to the atmosphere, *Nature* 531: 225-228, doi: 10.1038/nature16946, 2016

Prinn, R. G., Development and application of earth system models, *Proceedings of the National Academy of Sciences* 110: 3673-3680, 2013, doi: 10.1073/pnas.1107470109, 2012

Webster, M.A., A.P. Sokolov, J.M. Reilly, C.E. Forest, S. Paltsev. A. Schlosser, C. Wang, D. Kicklighter, M. Sarofim, J. Melillo, R.G. Prinn, H.D. Jacoby, Analysis of climate policy targets under uncertainty, *Climatic Change* 112:569-583, doi: 10.1007/s10584-011-0260-0, 2012.

Cohen, J.B., and R.G. Prinn, Development of a fast, urban chemistry metamodel for inclusion in global models, *Atmos. Chem. Phys*., 11, 7629-7656, doi:10.5194/acp-11-7629-2011, 2011.

Prinn, R., S. Paltsev, A. Sokolov, M. Sarofim, J. Reilly, H. Jacoby, Scenarios with MIT Integrated Global Systems Model: Significant global warming regardless of different approaches, *Climatic Change*, 104:515-537, doi: 10.1007/s10584-009-9792-y, 2011.

Synergistic Activities (Five Examples)

1. Principal Investigator and leader, Advanced Global Atmospheric Gases Experiment (AGAGE) and its predecessors (ALE, GAGE) in which the rates of increase of the concentrations of the trace gases involved in the greenhouse effect and ozone depletion have been measured continuously over the globe since 1978.
2. Pioneering the use of inverse methods, which use the above measurements and 3-dimensional models to determine trace gas emissions and understand atmospheric chemical processes.
3. Developed with colleagues the first comprehensive global 3-D dynamical-chemical-radiative model of the ozone layer and applied it to elucidating the effects of supersonic aircraft on ozone.
4. Developed with colleagues a unique integrated global system model coupling models of economics, climate physics and chemistry, and terrestrial ecosystems, and applied it to assessment of uncertainty in climate predictions and analysis of climate policies.
5. Made significant contributions to the development of national and international scientific research programs in global change (International Global Atmospheric Chemistry Program, International Geosphere-Biosphere Program).

JOHN M. REILLY

Co-Director, MIT Joint Program on the Science and Policy of Global Change
Senior Lecturer, Sloan School of Management, Massachusetts Institute of Technology (MIT)
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jreilly@mit.edu

Education and Training:
University of Wisconsin, Madison, Economics and Political Science, B.S. 1976
University of Pennsylvania, Philadelphia, Economics, M.S. 1979
University of Pennsylvania, Philadelphia, Economics, Ph.D. 1983

Research and Professional Experience:
Co-Director, MIT Joint Program on the Science and Policy of Global Change, 2010-present

Oversee and manage a program of integrated earth system modeling including the link of earth system and human system components to study the human and natural contributions to global environmental change, its implications for society and the economy, and the role of technology in mitigating and adapting to global change. Responsible for primary interaction with a consortia of industrial sponsors that support the Program.

Senior Lecturer, Sloan School of Management, MIT, 2007-present
Senior Research Scientist, Laboratory for Energy and the Environment, MIT, 2003-2007
Principal Research Scientist, Laboratory for Energy and the Environment, MIT, 1998-2003
Associate Director for Research, Joint Program on the Science & Policy of Global Change, MIT, 1998-2010
Acting Director, Resource Economics Division, and Deputy Director for Research, Economic Research Service, U.S. Department of Agriculture, Washington, DC. 1986-1998

Served as a staff economist, Section Leader, Branch Chief, Deputy Director, and Acting Division Director of a Division 100+ staff with responsibility for economic analysis and research on agricultural resources, environment and technology including water and land resources, biotechnology, climate change, and water quality.

Visiting Scientist, Center for Energy and Environmental Policy Research, MIT, 1992-1993
Economist, Pacific Northwest Lab., Battelle Memorial Institute, Washington, DC, 2/1985-9/1986
Economist, Institute for Energy Analysis, Oak Ridge Assoc. Universities, TN, 1/1980-2/1985
Economist, Office of the Secretary, U.S. Dept. of Transportation, Washington, DC, 5/1979-9/1979
Economist, Energy Information Administration, U.S. DOE, Washington, DC, 5/1978-9/1978

Publications (10 most closely related to proposed project):

Reilly, J.M. and J.M. Melillo, 2016: Climate and Land: Tradeoffs and Opportunities, *Geoinformatics and Geostatistics: An Overview*, 4(1): 1000135 (doi:10.4172/2327-4581.1000135)

Chen, Y.-H.H., S. Paltsev, J.M. Reilly, J.F. Morris and M.H. Babiker, 2016. Long-term economic modeling for climate change assessment, *Economic Modelling* 52(Part B): 867–883. (2016).

Winchester, N. and J.M. Reilly, 2015. The feasibility, costs, and environmental implications of large-scale biomass energy*, Energy Economics* **51**: 188-203

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Reilly, J., P.H. Stone, C.E. Forest, M.D. Webster, H.D. Jacoby, and R.G. Prinn, 2001: Uncertainty and Climate Change Assessments. *Science*, **293**: 430-433.

Synergistic Activities:

1) US EPA Science Advisory Board, Panel on Biogenic Carbon Emissions (2013-2015)
2) National Research Council, Committee on the Effects of Provisions in the Internal Revenue Code on Greenhouse Gas Emissions (2011-2013)
3) US Carbon Cycle Science Steering Group (2003-2006)
4) US Climate Change Science Program, Lead Author, Synthesis & Assessment Product 2.1 (2005-2007)
5) National Research Council, Committee on Global Change Research (2000-2002)

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Education and Training

University of Colorado, Boulder, Economics, Ph.D., 2001
Belarusian State University, Minsk, Belarus, Radiophysics and Electronics, Diploma, 1989

Research and Professional Experience:

2014 - present: *Senior Research Scientist*, MIT (research in energy and climate economics and policy, integrated assessment, research program management);
2008 - 2014: *Principal Research Scientist*, MIT (energy-economic modeling, integrated assessment, economic research management);
2002 - 2008: *Research Scientist*, MIT (energy-economic modeling, integrated assessment);
1997 - 2002: *Instructor*, *Teaching Assistant*, *Research Assistant*, Economics Dept., U. Colorado, Boulder (teaching courses in microeconomics, international finance, economic forecasting and macroeconomics; energy economics research);
1998 - 1999: *Actuarial Modeling Expert*, Int'l Management & Communications Corp., Arlington, VA (analyzing population dynamics and pension benefits);
1995 - 1997: *Executive Director*, Program in Economics and Management of Technology in Belarus, The Economics Institute, Boulder, CO (directing educational program);
1991 - 1993: *Scientific Worker*, Belarussian State University, Minsk, Belarus (research in correlation analysis of random signals).

Publications (10 most closely related to proposed project)

Monier, E., S. Paltsev, A. Sokolov, H. Chen, X. Gao, Q. Ejaz, E. Couzo, C. Schlosser, S. Dutkiewicz, C. Fant, J. Scott, D. Kicklighter, J. Morris, H. Jacoby, R. Prinn, and M. Haigh, 2018: Toward a consistent modeling framework to assess multi-sectoral climate impacts, *Nature Communications*, 9, 660.

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Schlosser, A., K. Strzepek, X. Gao, C. Fant, E. Blanc, S. Paltsev, H. Jacoby, J. Reilly, and A. Gueneau, 2014: The future of global water stress: An integrated assessment, *Earth's Future*, 2(8), 341-361.

Paltsev, S., 2017: Energy Scenarios: The Value and Limits of Scenario Analysis, *WIRE Wiley Interdisciplinary Reviews: Energy and Environment*, 6, e242.

Staples, M., H. Olcay, R. Malina, P. Trivedi, M. Pearlson, K. Strzepek, S. Paltsev, C. Wollersheim and S. Barrett, 2013: Water consumption footprint and land requirements of large-scale alternative diesel and jet fuel production, *Environmental Science and Technology*, 47(21), 12557-12565.

Reilly, J., J. Melillo, Y. Cai, D. Kicklighter, A. Gurgel, S. Paltsev, T. Cronin, A. Sokolov and A. Schlosser, 2012: Using land to mitigate climate change: hitting the target, recognizing the tradeoffs. *Environmental Science and Technology*, 40(11), 5672-5679.

Paltsev, S., 2016: The Complicated Geopolitics of Renewable Energy, *Bulletin of the Atomic Scientists*, 72(6), 390-395.

Paltsev, S., V. Karplus, H. Chen, I. Karkatsouli, J. Reilly, and H. Jacoby, 2015: Regulatory control of vehicle and power plant emissions: How effective and at what cost? *Climate Policy*, 15(4), 438-457.

Gurgel, A., T. Cronin, J. Reilly, S. Paltsev, D. Kicklighter, and J. Melillo, 2011: Food, Fuel, Forests, and the Pricing of Ecosystem Services, *American Journal of Agricultural Economics*, 93(2), 342-348.

Melillo, J.M., J. Reilly, D.W. Kicklighter, A. Gurgel, T. Cronin, S. Paltsev, B. Felzer, X. Wang, A. Sokolov and C.A. Schlosser, 2009: Indirect emissions from biofuels: How important? *Science*, 356: 1397-1399.

Synergistic Activities (Five examples)

1) Advisory Board Member, Global Trade Analysis Project (GTAP), 2006-present.
2) Economy-Wide Modeling Panel, Science Advisory Board, U.S. Environmental Protection Agency (EPA), 2015-2017.
3) Lead Author, Fifth Assessment Report (AR5), Working Group III, Intergovernmental Panel on Climate Change (IPCC), 2011- 2014.
4) Advising the Government of Poland on Energy-Economic Modeling Frameworks for Climate Policy Analysis, The World Bank, 2012.
5) Advising the Ministry of Water and Environment of Uganda on Contribution of Water Resource Development and Environmental Management to Uganda's Economy, 2015-2016.

C. ADAM SCHLOSSER

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Education and Training:
University of Massachusetts, Amherst, Physics, B.S. 1989
University of Maryland, College Park, Meteorology, M.S., 1992
University of Maryland, College Park, Meteorology, Ph.D., 1995

Research and Professional Experience:

10/2013 - present: *Senior Research Scientist*, Center for Global Change Science (CGCS), and *Deputy Director*, Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology: Conduct, facilitate, and oversee independent research on prediction of climate and environmental changes. Oversee science research elements and staff of the MIT Joint Program. Coordinate research for integrated assessments with the Program's Co-Directors and Deputy Director on economics, and develop strategic plans for research and staffing levels, Integrated Global System Model (IGSM) framework development, analysis tools, and operation of high-performance computational resources.

7/2008 – 10/2013: *Principal Research Scientist*, Center for Global Change Science, and *Assistant Director for Science Research*, MIT Joint Program on the Science and Policy of Global Change: Conduct independent research on climate and environmental changes, with a particular focus to better understand the natural mechanisms of the global land systems. Assist in oversight and execution of Joint Program research, with a emphasis on climate (change) prediction and its limits – and also includes the relevant and required aspects of the Integrated Global System Model (IGSM) framework development, analysis tools, and operation of high-performance computational resources.

11/2003 – 7/2008: *Research Scientist*, MIT Joint Program: Develop land-system model framework within the MIT integrated assessment model.

8/2001 – 11/2003: *Associate Research Scientist/Scientific Coordinator*, NASA/GSFC: Coordinate NASA Energy- and Water-cycle Study (NEWS) Program; conduct independent research in collaboration with NEWS scientists.

10/1997 – 8/2001: *Research Scientist,* Center for Ocean-Land-Atmosphere Studies: Conduct Land-Climate model development and predictability research toward improved climate prediction.

9/1995 – 7/1997: *UCAR Visiting Scientist*, Geophysical Fluid Dynamics Lab: Conduct experiments with the GFDL climate model to assess soil-moisture persistence and coupled land-climate predictability. Lead evaluation of Global Soil Wetness Project Phase 2.

9/1990 – 9/95: *Graduate/Faculty Research Assistant*, Dept. of Meteorology, U. of Maryland: Observational studies, model development, and multi-model comparison of land models used in climate prediction. Co-lead PILPS2d land-model comparison for Russian catchments.

Publications (10 most closely related to proposed project):

Gao X. and C.A. Schlosser, 2019: Mid-Western U.S. Heavy Summer-Precipitation in Regional and Global Climate Models: The Impact on Model Skill and Consensus Through an Analogue Lens, *Climate Dynamics*, 52(3-4): 1569-1582, doi: 10.1007/s00382-018-4209-0.

Gao X., C. A. Schlosser, and E. Morgan, 2018: Potential Impacts of Climate Warming and Changing Heat Waves on the Electric Grid: A Case Study for a Large Power Transformer (LPT) in the Northeast United States, *Climatic Change*, 147(1-2): 107-118, doi: 10.1007/s10584-017-2114-x.

Gao, X., C.A. Schlosser, C. Fant and K. Strzepek, 2018: The Impact of Climate Change Policy on the Risk of Water Stress in Southern and Eastern Asia. *Environmental Research Letters*, 13(6):4039 (doi: 10.1088/1748-9326/aaca9e).

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Schlosser, C. A., X. Gao, K. Strzepek, A. Sokolov, C. E. Forest, S. Awadalla, and W. Farmer, 2013: Quantifying the likelihood of regional climate change: A hybridized approach, *J. Climate*, doi: 10.1175/JCLI-D-11-00730.1

Synergistic Activities (Five examples):

1. Integrated Assessment Model Consortium: Member and Representative for MIT
2. Committee on Hydrology, American Meteorological Society: Member (2007 – 2012)
3. NASA Energy- and Water-Cycle Study: Science and Integration Committee (2001-2010)
4. USGCRP/CCRI/CCSP Interagency Working Group for the Global Water Cycle
5. NRC Committee on Hydrological Sciences (COHS): Panelist Predictability Working Group

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Monier, E., S. Paltsev, A. Sokolov, H. Chen, X. Gao, Q. Ejaz, E. Couzo, A. Schlosser, S. Dutkiewicz, C. Fant, J. Scott, D. Kicklighter, J. Morris, H. Jacoby, R. Prinn, M. Haigh, 2018, Toward a consistent modeling framework to assess multi-sectoral climate impacts, *Nature Communications*, 9: 660 (doi:10.1038/s41467-018-02984-9).

Morris, J., V. Srikrishnan, M. Webster and J. Reilly (2018a): Hedging Strategies: Electricity Investment Decisions under Policy Uncertainty. *Energy Journal*, 39(1), doi: 10.5547/01956574.39.1.jmor (https://www.iaee.org/en/publications/ejarticle.aspx?id=3028).

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Appendix 4: Facilities and Other Resources

Computer: The MIT Center for Global Change Science (through its Joint Program on the Science and Policy of Global Change) has a networked computer cluster that provides computational, analytical, and data-storage needs. In its current configuration it is a 60 compute-node compute cluster, linked via a low-latency infiniband network (a mix of dual quad-core, dual hex-core, and dual octo-core Intel Nehalem and Sandy Bridge-based units). This represents approximately 700 total physical cores. This Linux-based computing system was built for model simulations, data analyses, and storage of large data sets and will be a significant resource available to this project. The cluster also operates a cross-mounted, infiniband-networked suite of fileserver units with a present capacity approximately 1000 TB RAID6 disk storage. The cluster has 20 TB of total “home space” for general usage, source code, plots and figures, model builds, etc., with quotas of 300 GB per user, in addition to disk storage on fileservers. Storage is backed up automatically with up to daily frequency (offsite) and protected from disk failure via a RAID array. All computational resources for this project are housed in the Massachusetts Green High-Performance Computing Center (MGHPCC) (http://www.mghpcc.org), a data center dedicated to research computing. The MGHPCC is operated by MIT in collaboration with Boston University, Harvard University, Northeastern University and the University of Massachusetts. This facility is in Holyoke, MA and is connected by high-speed bandwidth to the MIT campus in Cambridge, MA. The MIT Joint Program, together with MGHPCC, provides hardware and maintenance support for the computational cluster.

Facilities/Office Space and Other Resources: Office space is provided by the MIT Center for Global Change Science (CGCS) and the Department of Earth, Atmospheric and Planetary Sciences (EAPS). The currently available office space and facilities are sufficient for project personnel and are anticipated to be available for the duration of the proposed effort. Administrative and secretarial support at MIT is provided through the CGCS and EAPS. Combined project support staff from these shared activities consists of approximately three full-time personnel.

Appendix 6: Data Management Plan

Our proposed project will produce both software and simulation results. This plan describes the management and distribution of both types of data. Key findings and conclusions of our research have been and will continue to be published in the peer-reviewed literature. Within these publications, we strive to provide descriptions of the experimental structure and model description, as well as all data sourced and values of parameters used in model runs. We will adhere to the scientific standard that readers should be able to replicate the results based on the materials in the article and available to them in the referenced sources. In more technically involved and comprehensive model development and evaluation, we can produce a Joint Program report available on our website (http://globalchange.mit.edu), which may subsequently be referenced in peer-reviewed publication as supporting literature. Each of these Joint Program Reports will include instructions and/or contact information for accessing the data that were used to produce each of the presented figures, among other details. In many cases, identical figures (or a subset), are shown in manuscript(s) submitted for peer-review publications – and we will make reference to the companion Joint Program Report as to instructions for accessing the data analyzed. In cases where new or follow-on information to our technical report is required, we may augment these instructions accordingly within a peer-reviewed manuscript. Additionally, the MIT Joint Program also maintains a Technical Note series for the primary purpose of documenting detailed methodological developments that are of interest mainly to the technical audience, and we will disseminate any data and/or source code information as warranted.

COMPUTER SOFTWARE

Software versions are considered developmental (i.e. not ready for public release) until they produce final simulations that are analyzed and documented through a peer-reviewed journal article or technical report. Developmental versions are only available to project members and approved collaborators. Upon publication of the of scientific results using simulations with the "developmental software", source versions of codes used to produce the simulations (open-source versions) can be made available via an open-source license on GitHub (https://github.com/) as a "Public Project." The researchers at MIT currently maintain a GitHub portal in conjunction with its integrated assessment model development (http://github.com/mit-jp/igsm), and therefore subsequent versions that include the proposed model developments and enhanced coupling will build upon the corresponding version branches. We will use the tagging feature in the *git* version control system so that the precise code base is retrievable. The software will be available for use under the license, but without support or consulting services beyond what is provided on the GitHub site. Open-source versions of the code will be maintained for a minimum of five years from the date of release.

SIMULATION OUTPUT

Through the course of this proposed research, we will be producing large amounts of data. Overall, our approach to data management is to provide efficient hardware platforms for staff scientists' analyses, redundancy of stored data against hardware failure, and long-term security and accessibility of data storage for archival and dissemination to interested researchers from the community-at-large. The MIT Joint Program maintains an in-house compute cluster with RAID protected disk-storage (total capacity of over 1 Petabyte) as well as off-site backup storage capabilities. The cluster also allows for smaller scale (i.e. 100s of Gb) data-transfer requests for any interested collaborator or member of the scientific community to make use of any data that we generate (via password authorization transfer protocols such as bbcp and ssftp as well as secure web-browser driven downloads.

All simulation output generated by the project and used in peer-reviewed journal articles and other openly distributed technical publications will be archived, maintained and curated for ten years from the release of the publication, or when the DOE project ends, whichever is sooner. Data appearing directly in publications will also be made available through the aforementioned transfer protocols. These data sets will be machine-readable in the self-describing netCDF format (http://www.unidata.ucar.edu/software/netcdf/), which is broadly accepted good-practice standard utilized in the weather and climate science research communities. For graphical display of our model results, we will provide shapefile formats and/or instructions that can reproduce figures from the netCDF data files directly, either of which can be readily processed by a number of software packages available to the community-at-large (and used amongst the Joint Program research staff). As such, this will allow for critical data elements to be readily available for the public domain and research community that are interested in using this data to further evaluate and/or confirm our model results as well as conduct broader research and application assessments. To the extent possible, we will also respond to requests from interested users who may require subsets of our data (to improve data-transfer efficiency) as well as provide software scripts that we have developed to aid in their analyses.

TRANSFER AND SHARING OF DATA, SOURCECODE, AND EXPERIMENTS

Each researcher at MIT owns a “public” subdirectory in their computer account that can be seen and downloaded via a web page browser. This has been used as a primary form of data and sourcecode transfer for our researchers with their collaborators (as well as “by request” inquiries). This form of data transfer can nominally handle data files and bundles in the 10s of GBs. Every MIT researcher and faculty member is also provided a free Dropbox account - and so under similar collaborative circumstances, this software is used to create shared folders for sourcecode and data transfer. These means of data transfer have proven effective and secure and will be of primary collaborative use in both the aforementioned software, simulation, and analysis activities. It should also be noted that many of the experimental simulations proposed will not be analyzed to the fullest extent – particularly if we find in our preliminary assessments that the model is insensitive to a particular modification or parameter value. In this case, a full description of the results will likely not be included in published work. However, it is quite possible that these simulations contain other results that could be useful to other researchers at a later date, and therefore, all model simulations merit storage. For all of the experimental simulations proposed herein, documentation will be maintained specifying the date, time, parameters, and model changes within the experiment along with any relevant run-time comments.

Appendix 7: Report of Progress under Existing Award (12/2016–5/2019)

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7.1 Introduction

The MIT Joint Program on the Science and Policy of Global Change has over the course of more than 25 years developed a multi-system multi-sectoral modeling and analyses framework for study of co-evolving components and critical drivers of physical systems and human systems. This facility provides a test-bed to: (1) investigate complex interactions among economic sectors, changing technologies, and the evolving land/freshwater/atmosphere/ocean systems of the Earth; (2) develop and apply methods for examining uncertainty in economic and Earth system projections and their implications for human systems; and (3) better understand complex, multi-sector dynamics to develop extractable insights on: (1) the forces and patterns that are driving evolution of water, energy, and land resources; coasts, the built environment, urban structure, and material flows; and atmospheric composition; (2) stabilities and instabilities in these systems, and their interactions, to find potential tipping points at multiple scales; and (3) how different approaches to representing foresight affects the co-evolution of these systems and their resilience and vulnerabilities.

Beginning in 1994, the DOE Office of Science, Office of Biological and Environmental Research, Climate and Environmental Sciences Division has provided support for this effort under Award DE-FG02-94ER61937. Progress along the way has been summarized in annual reports and progress reports attached to renewal proposals. The most recent award was an extension for the period December 15, 2016 to December 14, 2019.

The emphasis of the current award has been on: (1) continuing development of the MIT global integrated modeling system framework, with a focus on energy-water-land-atmosphere interactions; (2) better characterization of uncertain responses of the Earth system at scales relevant to decision-making under uncertainty; and (3) focusing efforts on interactions within the U.S. to develop understanding of vulnerability to global environmental change and tools that can assist in adaptation to these changes.

This Appendix covers progress under the award from 12/15/2016 to 5/30/2019. We report highlights of efforts to enhance the modeling structure to investigate interactions among water, land, and energy systems, and how these systems are influenced by and influence economic activity at multiple scales. **Citations in this Appendix that appear in bold font indicate publications issued during the report period**, coauthored by MIT project personnel who are engaged in the DOE-sponsored work.

7.2. Multi-System Multi-Sector Model Development

The approach of the MIT Joint Program to global change issues has been to develop a capability for comprehensive analysis applying computer models that provide reasonable representations of human drivers and Earth system response and their interactions, but that remain computationally suitable to make it possible to simulate large scenario ensembles, and for uncertainty quantification. The modeling framework is composed of an Earth system model, an economic model of human activity, and a growing set of more detailed auxiliary models that represent the complex physical processes (e.g. river basins, land use and land cover, stocks and flows of physical energy resources, and the built environment that modify or interact with these natural resources) through which the earth system and economic sectors are coupled. Model development efforts have focused on improvements necessary to evaluate energy-water-land-atmosphere interactions. A major focus is the linkages between the Earth system and economic activity through water, land, renewable energy resources, weather extremes, and atmospheric chemistry. The aim is to enhance these linkages in the global model, but with increased fidelity within the U.S. and the complex interactions among these systems. A version of the economic activity component of the global model, built on state-level data for the U.S., allows a capability for better characterizing trade-offs between renewable energy and other energy resources, along with linkages to water and land, and a focus on sub-national economic activities and interactions with physical systems. Similarly, we have improved the geographic resolution of water, land, and energy resource characterization.

The global modeling framework consists includes components that represent human activity (**Chen *et al.,* 2016**) and the Earth system (**Sokolov *et al.,* 2018a**). Global economic activity is resolved for large countries and regions, as represented by models that project changes in human activities and their effects on Earth systems, including emissions of pollutants and radiatively-active substances and changes in land use and land cover. Earth system modules that are linked with the human activities model simulate the atmosphere, ocean, land and ecosystem responses to human activities and emissions (**Monier et al., 2018**). This modeling framework is used to assess consequences and risks of environmental change (including modules for detailed representation of water, land and energy use, coastal infrastructure, demography, urbanization, and urban air chemistry). The Earth system modules contain: the global land system that includes vegetation, hydrology and biogeochemistry as affected by human activity, environmental change and feedbacks on climate and atmospheric composition; the circulation and biogeochemistry of the ocean and its interactions with the atmosphere, marine ecosystems, and physical and biological oceanic responses to climate change; and the circulation and chemistry of the atmosphere, including its role in radiative forcing and interactions with the land and ocean that determine climate change impacts. Progress on model development during the report period is described below.

- **Global economic model.** New modules and enhancements added to the MIT global economic model include: (1) a land-use module now accounts for the economic incentives behind land-use change and the accompanied CO_2 emissions or uptake; (2) a household transportation module improves the analysis of automobile fuel efficiency requirements; (3) the power sector module was updated with more low-carbon generation options and a refined approach to calculate electricity costs and the assessment of generation technologies (**Morris et al., 2018, 2019**). The improved model has disaggregation in sectors critical for evaluating land-use change and now includes 8 crops, 3 livestock types, 2 bioenergy options, pasture, forestry and lumber, 4 sectors of building materials that compete with lumber and a construction and dwellings sector. These additional details facilitate a more complete evaluation of how changes in agriculture and forestry may affect land-use change and how environmental change and response strategies could lead to substitution among different goods throughout the economy, including building construction, with further impacts on land use.

- **State/region economic model of the U.S.** The benchmark database for the state/region economic model was updated and rebalanced. The default regional aggregation is 12 U.S. regions, but it is now set up to run with 30 regions. The backstop technology costs were updated and a detailed representation of private passenger vehicle transport was added. We calibrated the model to sectoral carbon emissions and electricity generation to improve representation of the historical years. We also initiated a major reworking of the U.S. model to take advantage of a new open-source database developed from US Bureau of Economic Analysis data. In collaboration with NREL, the updated U.S. model has been linked to an updated ReEDS (v.2.0) with improved representation of water use in thermoelectric cooling. In addition, we advanced development of an hourly electricity model in collaboration with the MIT Energy Initiative, and initiated its linkage with our U.S. economic model. Advancements to EleMod include updating the costs and existing capacities of technologies and the representation of electricity transmission connections between its 12 regions, including hourly profiles of wind and solar resources of different classes, and representing hydropower (both run-of-river and pumped hydro).
- **Atmospheric chemistry model.** Development of a computationally efficient atmospheric chemistry component of the Earth system model involved an evaluation of utilizing simplified chemical mechanisms within the model configuration. We compared the accuracy of three chemistry packages of different levels of complexity and found close agreement in simulated ozone chemistry (**Brown-Steiner et al., 2018a**). In a related study, using simulated and observed surface ozone data within the U.S. over a 25-year span, we analyzed how the magnitude of the variability of the data due to meteorology depended on the spatial or temporal scale over which the data were averaged (**Brown-Steiner et al., 2018b**).
- **Representing crops.** We developed two flexible and computationally efficient approaches to represent crops in the Earth system model, a key step in developing more refined models of land use change in response to environmental change. First, emulators of existing crop models were developed using the AgMIP archive of crop model simulations (**Blanc, 2017a**). This statistical emulator approach provides an efficient framework to run large ensemble of simulations of future crop yields under different climate projections, while reproducing the behavior of various crop models and for multiple crop types. The second approach relies on agro-climate indices that are relevant to land stakeholders and represent key climate stressors and land management processes that control crop yield.
- **Nitrogen availability for ecosystems.** One area of development of the MIT Earth system model is to improve the representation of soil thermal dynamics and nitrogen dynamics by upgrading the existing terrestrial ecosystem model. We compared two versions of the ecosystem model to evaluate how permafrost thaw and nitrogen deposition and fixation may increase the nitrogen availability and thus potentially increase carbon sequestration in nitrogen-limited ecosystems (**Kicklighter et al., 2019**).
- **Extreme event detection.** The performance of an algorithm for detecting heavy precipitation events was determined to be independent of the model resolution and even better than that of precipitation simulated from regional circulation models (**Gao and Schlosser, 2018)**. The algorithm thus presents a robust and economic way to assess extreme precipitation

frequency across a broad range of global circulation models and multiple climate change scenarios with minimal computational requirements.

7.3. Uncertainty Quantification and Risk-Based Approach

We continued efforts that expand our unique modeling and analytic capabilities to assess current and future risks in the land-water-energy nexus, and better characterize uncertain responses of the Earth system at scales relevant to decision-making under uncertainty. A set of uncertainty studies elucidated: key uncertainties in economic growth, development, and technology deployment across economic sectors; predictability of hydrologic response to environmental change, especially as it affects power generation (hydroelectricity, power plant cooling); and land-use change, and its links to water, energy, and changing consumption patterns. The modeling framework provides linkages among the coevolving critical drivers of Earth system and socioeconomic changes, and serves as a platform for uncertainty quantification and sensitivity studies that support risk-based analysis.

- **Projecting uncertain Earth system evolution.** A calibration exercise using the MIT Earth system model with updated climate forcing over the period 1860-2010 was completed (**Libardoni et al., 2018a,b**). We compared the performance of the model with that of more computationally intensive models and showed that the MIT model effectively simulates changes in the observed climate system since the mid-19th century and the main features of the present-day climate system (**Sokolov et al., 2018a**). The model was used to produce a 400-member ensemble of climate simulations, applying two emissions scenarios produced by the MIT economic model that are designed to stabilize the system. We calculated regional distributions of surface temperature change using a statistical downscaling approach based on the geographical patterns obtained from simulations of 34 CMIP5 models, and estimated probability distributions of surface temperature change for different regions of the world. (**Sokolov et al., 2018b**).
- **Projecting extreme events.** A new analogue technique applied to projections of extreme precipitation events investigated the change in frequency of heavy precipitation (**Gao et al., 2017**). The new algorithm produces more precise projections by pinpointing telltale large-scale atmospheric patterns associated with the occurrence of smaller-scale events such as moisture convection and topography.
- **Uncertainty in runoff-response.** We analyzed runoff-responses across the climate/Earth-system models of the CMIP5 in conjunction with our water-impact/risk assessment of the contiguous U.S. An analytical framework was constructed to describe changes in runoff contributed by changes in atmospheric forcing (i.e. precipitation, meltwater) and changes in process-level characteristics of runoff (as depicted in the models). Using the CMIP5 scenarios we assessed the portion of the runoff response that excludes the direct response from changes in precipitation (and meltwater) to ascertain the shift in response due to shifts in the process-level, "local" (i.e. gridpoint) hydrologic functioning. The analyses identified regions where a considerable runoff change is attributable to process-level controls.
- **Projections of U.S. regional water stress.** Water availability for irrigation in the U.S. and the impact of earth system changes on water resources and irrigated crop yields was assessed (**Blanc et al., 2017**). In follow-up work, we assessed the trends in managed water stress in simulations from our *2018 Outlook* scenario with spatial downscaling updated with CMIP5 regional information. The socio-economic drivers from the *Outlook* scenario were used to drive the water-demand sectors. Regional findings included a stronger increase in water stress in the

hydro-climate changes in the southern U.S. The central tendency of the simulated response in the Northeast U.S. depicts the largest relative increase in water stress, largely attributable to growth in population and the economic drivers of water demand (**Reilly et al., 2018**).

- **Risk assessment of large power transformers.** We completed a study using data from the North American Regional Climate Change Assessment Project that compares our extreme analogue method's results between NARCCAP and the CMIP models (**Gao and Schlosser, 2018**). We found no salient improvement in the skill or consensus of projected trends in extreme-event occurrences. Based on our preliminary assessment of heat stress on large power transformers (LPTs) in the Northeast U.S. (**Gao et al., 2018a**), our follow-on analysis considers cold-season events (ice and snow) and how these events may change and impact key transmission lines. Additional LPT sites to consider have been selected and we have begun assessment and calibration of the analogue patterns.

7.4. Applications

An overarching goal of our research is to provide a foundation for adaptation that recognizes the range of possible global change outcomes over the next few decades and is cognizant of other changes in the system that may add or relieve stress created by global environmental change. Our analysis of multi-sector dynamics within the U.S. recognizes linkages to the rest of the world through trade and global environmental change. The modeling framework has been applied to U.S. energy-water-land-atmosphere interactions and to a more resolved look at the potential vulnerability and environmental implications of alternative renewable energy systems at scale.

- **Testing the more disaggregated economic model.** We completed simulations of a new version of the global economic model with multiple crops and livestock types that include land-use change driven by economic development, trade, and environmental change (**Chen et al., 2016; Gurgel et al., 2016**). To test the sensitivity of land-use projections to environmental change, we used results of our emulator model of AGMIP Globally Gridded Crop Models to project future yields (**Blanc, 2017a**), as well as estimates of yield changes reviewed in the IPCC AR5 based mostly on site-level crop models simulated for a variety of crops and locations globally (**Blanc, 2017b**).
- **Irrigated land expansion potential.** We developed a new emulator for assessments of regional and global water, land, energy and economy interactions (**Ledvina et al., 2018**). Using data on the value of production on irrigated and rain-fed cropland for 140 regions and 8 crop sectors in the GTAP database, we estimated the value of irrigated and rain-fed crop production using production quantities and prices. To represent the potential of irrigated land areas to expand, we used irrigable land supply curves for 126 water regions globally, based on water availability and the costs of irrigation infrastructure from a detailed water resource model.
- **Regional impacts on crop yields**. Building on prior work, we expanded a toolset of crop-yield emulators that enable computationally efficient assessment of environmental impacts on crop yields (**Blanc, 2018**). With a crop-yield emulator that "trains" a statistical model to make reasonably accurate predictions based on the output of multiple process-based models, the emulators were extended to consider rain-fed maize, rice, soybean and wheat yields at the national or regional level for a range of temperature and precipitation conditions.
- **Empirical crop model using agro-climate indices.** A new and novel empirical crop model was developed to provide agro-climate indices for maize with information on the frequency and duration of key drivers of crop productivity (i.e. heat stress, dry days, frost days). These agro-

climate indices were computed over the contiguous U.S. at the county level for a large ensemble of climate simulations (2 RCP scenarios and 32 CMIP5 models) statistically downscaled at 6 km resolution for the historical period and 21st century (**Monier et al., 2016**).

• **Marine ecosystem response.** The MIT Earth system model framework was used to drive a unique marine ecosystem model that incorporates explicit treatment of light reflected from the ocean's surface, which allows the model to capture a signal that is currently monitored by satellites (**Dutkiewicz et al., 2019**).

• **Wind power density estimates.** The experimental framework to pursue the predictability assessment for wind and solar resources was refined based on the recent acquisition of an updated version of the Modern-Era Reanalysis for Research and Applications (MERRA2). We investigated whether MERRA2 provides distinctly different patterns of wind power density resource and intermittency to see whether our target areas for this study should be altered.

• **Implications of the US shale gas boom.** We investigated the implications of the U.S. shale gas boom in a modeling exercise that estimated the supply responses of coal-fired and gas-fired generations based on U.S. state-level data. We find that across a wide range of model settings that if gas prices would have remained at 2007 levels in 2011, economy-wide emissions would have been lower (**Chen et al., 2019**). A look at energy forecasts and the value and limits of energy scenario analyses is reported in **Paltsev (2016)**.

7.5. Community Engagement

The Joint Program participates widely with other modeling groups, in technical workshops and collaborative applications. We were involved in numerous inter-model comparison studies involving our global economic model, regional energy models, an agricultural model, and our global systems modeling framework as a whole.

• **Multi-sector dynamics community.** We are collaborating with the Joint Global Change Research Institute of the Pacific Northwest National Laboratory through staff visits and a scenario-based modeling intercomparison exercise focused on the economic and Earth system models used in the MIT global system modeling framework and PNNL's GCAM. In addition, we co-convened an AGU Fall Meeting session in 2018 on "Coupled natural-human systems and global environmental change: innovative interdisciplinary approaches." We participated in the Energy Modeling Forums 32 and 34, and the Integrated Assessment Model Development, Diagnostics and Inter-Model Comparisons (PIAMDDI) organized by the EMF. We participated in the Snowmass summer workshops organized by Stanford University and engaged in a series of discussions and presentations on multi-sectoral dynamics in energy-water-land interactions.

• **Broader community collaborations**. We have ongoing collaborations with researchers at the Marine Biological Laboratory, NREL, NCAR, and with faculty at U.S. universities (U.C. Davis, Penn State, Emory, Lehigh, Auburn, Boston, Purdue, Tufts, N.C. State, Maine Maritime Academy, Wisconsin, Harvard School of Public Health, Colorado State, Alaska, Rhode Island, Michigan Tech), Canadian universities (Waterloo, British Columbia, HEC Montreal), European universities (ETH-Zurich, Cambridge, Stockholm, Leuven), a Brazilian university (U. Federal de Viçosa), the University of Hong Kong and Tsinghua University in China.

• **Data sharing.** We have continued to produce and expand a broad suite of models/outputs, data products, and tools of use to the broader research community. Our high-performance computing cluster underwent an expansion funded under this award, which allowed us to expand the connectivity of our data archive and fileserver network and provide a data portal service for access to key model output and data products to better serve the community-at-large. We archive the model outputs of published studies and have provided the data upon request. Data produced during our participation in the U.S. Climate Change Impacts and Risk Analysis (CIRA) project have been disseminated to a number of research groups. We have also made available to the scientific community-at-large our global system modeling framework simulation ensembles (~6,800 members) of key climate variables, and multi-decade products on daily wind power density. And detailed data from our *2018 Food, Water, Energy and Climate Outlook* are available as a spreadsheet on the Joint Program's website (https://globalchange.mit.edu/outlook2018).

- **Model sharing.** The source code of various models and model components within our global system modeling framework have been made publicly available. An ensemble of statistical tools for emulating crops yields from global gridded crop models has been made available (**Blanc, 2017a**). The code for the MIT Earth system model (**Sokolov et al., 2018a**) and MIT economic model (**Chen et al., 2016**) are publicly available with open source software licenses for non-commercial research and educational purposes (http://globalchange.mit.edu/research/research-tools/earth-system-model; https://globalchange.mit.edu/research/research-tools/human-system-model/download). Key data-processing scripts maintained on the MIT Joint Program GitHub repository are also made accessible by request, providing an efficient framework to share code.

- **Conference/Workshop Participation/Presentations (selected examples)**

1. Blanc: "Estimating the impact of crop diversity on agricultural productivity in South Africa", NBER Conference on Understanding Productivity Growth in Agriculture, Cambridge MA, May 2017.
2. Blanc: "After the Storm: Faster, Easier, More Accurate Crop Damage Assessment" and "A simpler, faster way to assess environmental impacts on crop yields." MIT Agriculture Workshop, Cambridge, MA, Nov 2018.
3. Blanc: "Global Gridded Crop Model Emulators within the MIT-IGSM". DOE Principal Investigator meeting, Potomac MD, Nov 2018
4. Brown-Steiner: "Air quality uncertainties pertaining to choice of chemical mechanisms of different levels," AAAS Annual Meeting, Boston MA, February 2017
5. Brown-Steiner: "Using superfast chemistry to emulate MOZART within the CESM CAM-Chem: Strengths, weaknesses, and possibilities," CESM Chemistry Climate Working Group Meeting, Boulder, CO, March 2017
6. Brown-Steiner: "Leveraging Mechanism Simplicity and Strategic Averaging to Identify Signals from Highly Heterogeneous Spatial and Temporal Ozone Data," American Geophysical Union (AGU) Fall Meeting, Dec. 2017
7. Chen: "Transparency in the Paris Agreement," 20th Annual Conference on Global Economic Analysis, Purdue University, West Lafayette, IN, June 2017
8. Chen: "What would the US economy and emissions look like without shale gas", 21st Annual Conference on Global Economic Analysis (GTAP), Cartagena, Colombia, June 2018
9. Forest, Libardoni, Sokolov, Monier: "Improving constraints on climate system properties with additional data and new statistical sampling methods," AGU Fall Meeting, New Orleans, LA, Dec. 2017
10. Gao: Panelist for "Adaptation and Resiliency Programs at Electric Utilities," Environmental Business Council Program Series, Westborough, MA, Feb 2018

11. Gao: Discussant on “Environmental Impacts of Scaling-up Energy,” MIT Joint Program Workshop on Energy at Scale, Cambridge, MA, USA. Jun 2018
12. Gao: “Mid-western US Heavy Summer-precipitation Regional and Global Climate Models: The impact of Downscaling on Model Skill,” DOE PI meeting, Potomac, MD, Nov 2018
13. Gao: “Confronting Future Risks of Water Stress in the United States with Climate Mitigation.” AGU Fall Meeting, Washington DC. Dec 2018.
14. Gurgel: “Economic Impacts of Bioelectricity from Forest Biomass when Forest Producers have Comparative Advantage: the case of Brazil.” 21st Annual GTAP Conference on Global Economic Analysis, Cartagena, Colombia, June, 2018
15. Monier: invited participant at the JpGU-AGU Joint Meeting and the National Institute for Agro-Environmental Sciences of the Japan National Agriculture and Food Research Organization in Chiba, Japan, May 2017.
16. Monier, Paltsev, Sokolov, Fant, Chen, Gao, Schlosser, et al., “A paradigm shift toward a consistent modeling framework to assess climate impacts.” AGU Fall Meeting Dec 2017
17. Monier: Session convener and Chair, AGU Fall Meeting 2017, “Integrated Assessment Models and their Applications to Global Change Research”
18. Monier: Session convener, AGU Fall Meeting 2018, “Coupled human-natural systems and global environmental change: Innovative interdisciplinary approaches”
19. Monier: participant, DOE’s Program on Coupled Human and Earth Systems (PCHES) Research Outreach Meeting, Penn State U., May 2018
20. Monier: “Details of Modeling Key Water-Land: Land-Water Interactions,” and panelist on “Earth System Trends and Forcings,” Energy Modeling Forum, Workshop on Analyses of Multi-Sector Energy and Environmental Dynamics, Snowmass, CO, Jul 2018.
21. Monier: “High-resolution agro-climate empirical modeling of crop yield,” and panelist on “Climate Risks to Agriculture,” MIT Joint Program Agriculture Workshop, Cambridge, MA, Nov 2018
22. Monier: “Scenario Research and Development,” DOE Climate and Earth System Modeling PI Meeting, Potomac, MD, Nov 2018.
23. Morris: Participant, PNNL/JGCRI GCAM Community Modeling Meeting, College Park, MD, USA. Oct 2018.
24. Morris: “Economic and Energy Uncertainty Quantification,” DOE Modeling PIs Meeting, Potomac, MD, Nov 2018.
25. Morris: “Uncertainty in Coupled Human-Earth Systems and the Cost of Meeting 2°C and 1.5°C,” AGU Fall Meeting, Dec 2018
26. Paltsev: “Representing Carbon Capture and Storage in the MIT EPPA Model”, DOE Office of Fossil Energy’s Energy-Economic Modeling Workshop, Washington, DC, April 2017
27. Paltsev: Bioenergy with carbon capture and storage: key issues and major challenges”, GTAP Conference on Global Economic Analysis, West Lafayette, IN, June 2017
28. Paltsev: “Projecting Energy and Climate for the 21st Century”, Stockholm Environment Institute, July 2017
29. Paltsev: “Projecting Energy and Climate for the 21st Century: MIT Joint Program Outlook”, International Institute for Applied Systems Analysis, Laxenburg, Austria, February 2017
30. Paltsev: participant, Energy Modeling Forum, Analyses of Multi-Sector Energy and Environmental Dynamics Workshop, Snowmass Colorado, July 2018

31. Paltsev: "Pathways to Paris: Technology and Policy Options for Latin America and ASEAN," and Panelist on "Hard to Decarbonize Sectors," COP-24, Katowice, Poland. Dec 2018
32. Prinn: "Climate Change Risks and the Challenge of Avoiding 2°C Warming," The Bose Institute Centenary Invited Lecture, The Bose Institute, Kolkata, India, August 2017
33. Prinn: "The Dangers of Climate Change and the Task of Avoiding 2°C Warming," The Indian Institute of Science Education and Research, Kolkata, India, August 2017.
34. Prinn: "Climate Change: Science, Forecasts, Risks & Responses", University of Texas Energy Institute Board, Austin, TX, April 2018
35. Reilly: Participant, "Modelling Tools to Inform National Sustainable Development Policies for the 2030 Agenda" UNDESA (ICTP) high-level meeting, Trieste, Italy, June 2017
36. Reilly: "Contributions of GTAP to Modeling Natural Resources and the Environment," 25th Annual Global Economic Modeling Conference, Purdue U., June 2017
37. Reilly, Schlosser, Yuan, et al.: "Modeling Renewable Electricity, Water and Renewable Resources," Meeting with Union of Concerned Scientists to share model advances and developments on water, renewable resources, and electricity, Cambridge, MA, June 2017
38. Reilly: "Climate Change, Agriculture, Water, and Food Security: What we know and don't know," Agriculture Research Workshop sponsored by the MIT Abdul Latif Jameel, Water and Food Systems (J-WAFS) Lab, Dedham, MA, May 2018
39. Reilly: Participant, National Academy of Sciences, Engineering, and Medicine, Gulf Research Program, Gulf Region Cooperative Meeting on the integration of economic models with models of biophysical systems, Arlington, VA, Jun 2018
40. Reilly: "The MIT Integrated Global Systems Model: Multi-Sectoral Dynamics and Energy-Water-Land Interactions", Snowmass Workshop on Analyses of Multi-Sector Energy and Environmental Dynamics, Snowmass, CO, July 2018.
41. Reilly: "Incorporating Irrigated Land into an Economic Model", Snowmass Workshop, July 2018.
42. Reilly: "A Roadmap for Decarbonization and Climate Stabilization: Low-Carbon Technology Pathways and the Energy System," MITEI Annual Research Conference: Energy Intelligence, Cambridge, MA, Oct 2018
43. Reilly: "The MIT Joint Program Models of Multisectoral Dynamics," DOE Principal Investigator Meeting, Potomac, MD, Nov 2018
44. Reilly: "Profile and Trends of the Northeastern United States Market" Quebec Government annual Quebec Mines Congress, Quebec City, Quebec, Canada, Nov 2018.
45. Reilly: Participant, DOE's Program on Coupled Human and Earth Systems (PCHES) Research Outreach Meeting, Penn State, May 2019
46. Schlosser: Participant, DOE Biological and Environmental Research Advisory Committee Grand Challenges II workshop, Rockville, MD, March 2017
47. Schlosser: invited lecturer for short-course symposium on "Climate Change and HealthCare" at the Massachusetts General Hospital Center for Biomedical Imaging, Boston, MA, March 9 – April 18, 2017
48. Schlosser: "Resiliency of the Nation's Power Grid: Assessing Risks of Premature Failure of Large Power Transformers Under Climate Warming and Increased Heat Waves," AGU Fall Meeting, Dec 2017

49. Schlosser: Session convener and Co-Chair, AGU Fall Meeting 2017, "Integrated Human-Earth Systems Modeling for Vulnerability and Risk, Dec 2017
50. Schlosser: Chair, and presentations "Modeling, Limits to Prediction, and Projecting Risk from Change," and "Mitigation and Adaptation Amidst Changes in Water-Energy-Food Nexus," MIT Joint Program Workshop on Water Resource Risks: Integrated Approaches to Support Actions, Cambridge, MA, Dec 2017
51. Schlosser: "Potential Impacts of Climate Warming and Increased Summer Heat Stress on the Electric Grid: A Study for a Large Power Transformer in the Northeast US". Environmental Business Council Program on "Adaptation and Resiliency for Electrical Utilities", Westborough, MA, Feb 2018
52. Schlosser: "Climate-Energy Nexus: Risk, Resiliency, and Recourse". MIT Center for Energy and Environmental Policy Research Workshop, Cambridge, MA, May 2018
53. Schlosser: "Details of Modeling Key Energy-Water-Land Interactions," Energy Modeling Forum, Analyses of Multi-Sector Energy and Environmental Dynamics Workshop, Snowmass Colorado, July 2018
54. Schlosser: "Confronting Global Water Risks into an Unprecedented Era: Successes and Challenges with Risk- Based, Multi-Sector Prediction," Earth and Environmental System Modeling PI Meeting, Potomac, MD, Nov 2018
55. Schlosser: Agriculture as a Contributor to Global Change and Climate Risks and Agriculture. MIT Joint Program Agriculture Workshop, Cambridge, MA, Nov 2018
56. Sokolov: "Probabilistic Estimates of Climate Impacts of the Paris Agreement and Contributions from Different Countries," AGU Fall Meeting, Dec 2017
57. Sokolov: "Evaluation of transient response of climate system based on the distribution of climate system parameters constrained by observed climate change," EGU General Assembly, Vienna, Austria, April 2018
58. Sokolov: "Uncertainty in the Regional Surface Warming under 2^{o}C and 1.5^{o}C Scenarios,"_AGU Fall Meeting, Dec 2018
59. Wang: "Climate Effects of Aerosol-Cloud-Precipitation Interaction," Pacific Northwest National Laboratory, Richland, WA, Jan 2018
60. Wang: "Forecasting the occurrence of adverse environmental and weather events using deep learning algorithm," First Fudan International Workshop on Atmospheric Science Frontiers, Fudan University, Shanghai, China, Jan 2018
61. Winchester, and Ledvina "The Impact of Oil Prices on Bioenergy, Emissions and Land Use," 20th Annual Conference on Global Economic Analysis, W. Lafayette, IN, June 2017
62. Winchester: Session Chair, "Bioenergy and emissions," Global Trade Analysis Project (GTAP) Annual Conference, Cartagena, Colombia. Jun 2018
63. Winchester: "The economic and emissions benefits of engineered wood products in a low-carbon future," Wood Week, Santiago, Chile, Aug 2018
64. Winchester: "Food-energy-water interactions and emissions from land-use change," MIT Water Workshop, Cambridge, MA, Sep 2018