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Research Program

Coastal Integrated Hydro-Terrestrial Modeling

A Multi-Agency Invited Workshop

November 2020

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EXECUTIVE SUMMARY

This report describes the results of the November 2020 Coastal Integrated Hydro-Terrestrial Modeling (C-IHTM) workshop series. Organized around five sessions held over five days, the workshop series focused on the challenges of modeling and evaluating coastal landscapes of co-evolving human and natural systems subject to influences and stressors, including extreme weather events, sea level rise, natural and anthropogenic disturbances, and other impacts from climate change. The effort was jointly planned and undertaken by the federal interagency C-IHTM Coordinating Group within the U.S. Global Change Research Program (USGCRP) and the MultiSector Dynamics (MSD) research community. The five-day virtual workshop included robust participation from a wide range of science and engineering research communities.

Modeling the interaction and co-evolution of human and natural systems at our Nation's coasts requires consideration of myriad interacting human systems and processes, including water, land, and energy systems; infrastructure; population/demographics; business and economic sectors and sectoral interdependencies; socioeconomics (more broadly); and natural processes and systems, ranging from coastal hydrology and shoreline morphology to environmental systems and services. Acting on these often strongly interconnected systems are influences and stressors that shape the individual and coupled human and natural systems' responses. Examples include forces such as droughts, floods, heat waves, wildfires, technology advances, changing markets (regional and international), and institutional/ governance factors, several of which are likely to become more pronounced in years to come. Understanding such changing effects as they cascade and ripple through the integrated coast (see figure E.1), and accompanying non-linear dynamics and tipping points, is a major scientific challenge and a topic of significant interest for communities charged with managing coastal regions and resources. Understanding the current state of coastal modeling science, and envisioning paths forward to tackle these and related modeling needs, were of highest interest for the workshop participants.

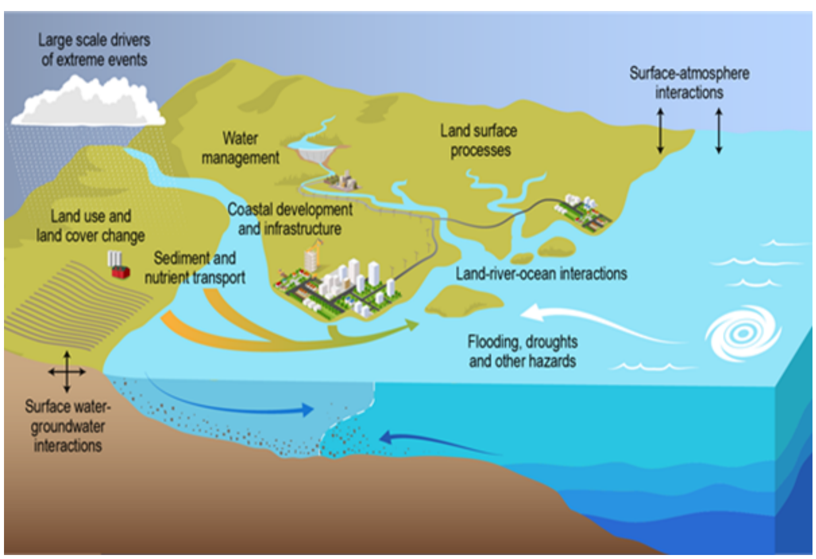

Figure E.1 *Courtesy of PNNL 2019. The complex interactions between natural and human systems and stressors that occur along the coasts.*

The workshop provided further evidence of the needs and interests shared among many communities of researchers and coastal managers for including cross-sectoral, cross-system, and cross-scale interactions within integrated modeling frameworks. Accompanying findings are summarized in more detail below, organized by major topic:

1) **Open science – concepts, methods, and enabling tools**
   Adopting open science principles is necessary to fully achieve all the goals of C-IHTM, reduce barriers to entry, gain economies of scale, and avoid duplication of effort. The modeling community will need to foster a culture and develop procedures that address concerns regarding the misuse of open data or code, potential loss of a researcher's competitive advantage within the community, and the absence of universally available tools for capturing detailed components of complex C-IHTM multi-model workflows. Numerous potential paths forward have been identified with examples that include embedding more software engineers into modeling projects and encouraging contributions to the interoperability standards for software ecosystems of the Open Modeling Foundation.

2) **Use cases – regions and topics**
   Use cases, both geographically and/or topically based, hold significant potential to advance C-IHTM and associated collaborations. Moving beyond concepts, the discipline required to undertake such collaborations for modeling applications forces convergence in capabilities as well as in solutions to identified impediments. A use case in this context is a set of one or more experiments with the purpose of exploring and evaluating science questions. In total, 38 use cases are identified with topics of common interest that include compound stressors/events, energy transitions, land use and land cover change, population change and development patterns, economic dynamics, extreme events, water supply and demand, and water quality.

3) **Integrated modeling frameworks**
   There is a compelling demand for agile, integrated modeling frameworks that can connect various systems, processes, stressors, and influences. Such integrated frameworks are not only essential for representing the coupled systems interactions and dynamics, but in facilitating the incorporation of interagency/inter-community domain expertise and appropriate component models within a broader collaborative environment. Challenges exist in areas such as the integration and coherence of data that feed the component models, uncertainty quantification that spans diverse domains (some with unique methods and conventions), and lack of well-established metrics for diagnostics and evaluation of integrated frameworks with a diverse set of components spanning multiple domains. Notably, storylines are emerging as powerful tools for organizing context-relevant integrated modeling frameworks, and opportunities exist through the potential development of a comprehensive catalog of models and tools, strengthened stakeholder engagement and, reinforcing a highly cross-cutting idea, the pursuit of shared use cases.

4) **Linking communities of practice**
   Connecting and leveraging existing communities of practice (CoPs) offers considerable benefits for C-IHTM. For this effort, the term community of practice means a group of individuals who share an interest in a topic or objective and work together to learn from one another's work. Many potentially relevant CoPs were identified, with four that were the subject of more detailed discussion and focused attention: MultiSector Dynamics, Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI), Coastal Coupling, and Community Surface Dynamics Modeling System (CSDMS). The need for a meta-analysis of existing, relevant CoPs was highlighted, with further details to include a

survey and analysis of the topical focus; membership; other aspects of the CoPs to identify overlaps, gaps, and opportunities; an effort to combine the meta-analysis with a mapping exercise to identify geographical overlaps and collaborations; and assessment of the CoPs' structure and function to identify best practices for using CoPs.

Synthesis and Potential Paths Forward

The emergent themes from the four topical workshop sessions can be organized into two general sets of questions and topics with many points of overlap: 1) coastal models and computational methods and frameworks and 2) applications of those models and frameworks to actual coasts. For models and methods, examples include teleconnections, integrated modeling frameworks, testing, evaluation, and benchmarking, and how to balance computing resources across multi-member ensembles and models with small grid-spacing or other high resolutions. For applications, examples include water scarcity, coastal retreat, and water quality.

The deep connections across the theme elements, and more generally between the models and their applications, were recognized in the discussion of possible paths forward for the community of people in the workshop, including 1) advancing targeted workshops tied to and spanning communities such as the C-IHTM and the MSD Working Group; 2) developing a descriptive inventory of models and modeling approaches, including active areas of research, resolution requirements for processes/questions and methods for sensitivity analysis; 3) identifying important parameters and sensitivity to those parameters; and 4) model intercomparisons focused on parameters and uncertainties.

Following the workshop, and during the preparation of this report, the C-IHTM Coordinating Group has since undertaken and/or developed plans for the following:

1) Consolidate interests around three major teams: Modeling and Modeling Frameworks; Data and Observations; and Use Cases, each co-led by representatives from 2–3 agencies.
2) Select two use case regions (from a broader set of eight) as an initial focus for the application and testing of convergence and collaboration in C-IHTM.
3) Develop a hierarchy of questions that can help frame the interests and questions motivating each agency while revealing the potential connections linking research-to-operations-to-research (R2O2R) opportunities spanning the many agencies and agency members of C-IHTM.
4) Advance a collective catalog (aka inventory) characterizing the relevant models, data systems, and tools and, where possible, linking back to the hierarchy of questions.
5) Build collaborative modeling experiments in the two use case regions selected.

The nature and pace of these C-IHTM Coordinating Group activities following the workshop substantiate its value, directionally and motivationally, strengthening the conceptual foundations and insights for inter-community actions and collaborations in C-IHTM.

1. INTRODUCTION

The extensive U.S. coastline faces many unique challenges as a result of climate change and other global changes. Rising sea levels threaten vulnerable coastal infrastructure and communities, increased storm activities are causing enormous losses of life and property, and culturally and economically relevant coastal biodiversity is threatened by patterns of land use and climate change.

Hurricane Dorian pictured over the southeastern United States on Sept. 5, 2019. Expanding populations and increasing development concentrated at the Nation's coasts, combined with changing and compounding stressors, such as more intense coastal storms, pose challenges for coastal communities and for current and future planning. Source: NOAA/Regional and Mesoscale Meteorology Branch.

These threats are compounded by the expansion of coastal cities and poorly understood population dynamics that draw certain people to them while pushing others inland. Coastal states already represent over 80% of U.S. GDP, with shore-adjacent counties alone representing over 40%. People are concentrated at the coasts in roughly similar proportions. [1]

With so much economic and social activity concentrated at the coasts, it is imperative that federal agencies are able to accurately understand current coastal conditions and processes, as well as how they will change in the future. Diverse agency mission needs have driven a rich and extensive base of discrete data, modeling, and analysis capabilities. While useful for their intended purposes, these capabilities do not fully address the range of complex interactions and interdependencies of the highly coupled coastal system, nor provide insights into the structure, function, and potential evolution of these complex landscapes consisting of interactive land, water, air, environment and,

[1] Fleming, E., J. Payne, W. Sweet, M. Craghan, J. Haines, J.F. Hart, H. Stiller, and A. Sutton-Grier, 2018: Coastal Effects. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 322–352. doi: 10.7930/NCA4.2018.CH8

importantly, human components. Improving the coordination and synthesis of such knowledge, understanding, and predictive modeling capabilities will strengthen the national capacity to explore complex coastal issues/problems and their potential multisector, multiscale solutions.

Current opportunities for improved collaboration are, in part, motivated by a number of recent developments:

1. The recent completion of a major interagency workshop on Integrated Hydro-Terrestrial Modeling (IHTM) in September 2019 (co-led by NSF, USGS, and DOE with attendance from many more agencies) lays the foundation and identifies candidate paths forward for a more directed effort in interagency, integrated hydro-terrestrial modeling in coastal regions.[2]

2. Recent new investments in IHTM frameworks at the national laboratories, universities, and elsewhere have advanced open source, interoperable capabilities (from workflow to enabling software) that already draw on some representative interagency model components. Preliminary geographies that are the subject of those capabilities also appear to be shared areas of interest among various agencies.

3. Computationally intensive, high-resolution climate simulations and advanced scaling techniques provide new and important capabilities, along with new developments in model evaluation techniques and metrics of model performance.

4. Existing and newly formed communities of practice (CoPs) can be leveraged for more integrated modeling of coasts, with an emphasis on linking natural and human systems (both infrastructure and socioeconomic) under a broad range of compounding stressors and influences.

5. Advances in the discrete modeling capabilities at various agencies have progressed to the point where they are not only ready for coupling, but there is growing recognition of the need for coupling to encompass broader influences, contexts, and systems and sectoral interactions and dynamics. The September 2019 IHTM Workshop reflects that growing interagency realization and interest.

To that end, in mid-2019, the U.S. Global Change Research Program (USGCRP) identified the coasts as a focus area for the organization's activities, starting a new Coastal Focus Group a few months later. To better leverage interagency capabilities and the strong network of USGCRP agency scientists, coastal IHTM (C-IHTM) was identified as a priority under USGCRP's new Coastal Focus Group, now the Coasts Interagency Group. An interagency C-IHTM Coordinating Group under the USGCRP umbrella formed in the spring of 2020, and the group's first major undertaking was to plan a C-IHTM Workshop, which took place virtually over five Mondays in November 2020 (see Appendix B for workshop agenda).

IHTM is a new concept that may aid researchers and the government in understanding and responding to the threat of coastal hazards. As was discussed in a September 2019 interagency workshop, IHTM aims to integrate and combine models at different scales to create a more robust modeling ecosystem that can better represent complex system dynamics and feedbacks. A robust IHTM framework would encapsulate biological, hydrological, and climatic systems as well as

[2] Community Coordinating Group on Integrated Hydro-Terrestrial Modeling (2020), "Integrated Hydro-Terrestrial Modeling: Development of a National Capability," report of an interagency workshop held September 4-6, 2019 with support from the National Science Foundation, the U.S. Department of Energy, and the U.S. Geological Survey, https://doi.org/10.25584/09102020/1659275

anthropogenic dynamics such as population, migration, and land use changes. The ability of IHTM to represent complex system dynamics makes it particularly useful for studying the unique multifaceted problems facing the coasts.

Importantly, the C-IHTM Workshop was co-organized and attended by many active members of the MultiSector Dynamics (MSD) community, a collective of university- and national lab-based researchers who work on the modeling of coupled human and natural systems. In recognition of the crosscutting and interdisciplinary nature of coastal modeling challenges, the workshop also included invited researchers from academia and government with specific, relevant expertise who were not already working on MSD projects, to speak about current advances in integrated modeling. These guests included representatives from sister communities such as the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI), the Community Surface Dynamics Modeling System (CSDMS), and the NOAA Coastal Coupling CoP (see Appendix C for a list of workshop participants). The invited speakers provided opportunities to build connections between workshop participants and outside networks and gave participants a chance to learn about novel coastal modeling approaches that they can apply to their own work.

The workshop was organized around five themes focused on the coasts, each of which received a dedicated session over successive weeks that was co-led by federal and MSD partners:

1. Open science – concepts, methods, and enabling tools (Chapter 2)
2. Use cases – regions and topics (Chapter 3)
3. Integrated modeling frameworks (Chapter 4)
4. Linking communities of practice (Chapter 5)
5. Synthesis and potential paths forward (Chapter 6)

This sequential structure was used to facilitate action-oriented discussions that built off the September 2019 IHTM workshop to begin charting a concrete path forward. The C-IHTM workshop was thus intended as a means for improving coordination within and across federal agencies and our academic colleagues. It also set out to define priority topics and geographies that motivate the federal and academic communities, as well as to elucidate how to achieve those capabilities in a coastal setting.

After the workshop, the federal C-IHTM Coordinating Group organized into smaller work teams of federal agency representatives to advance interagency interests and enhance communication with the MSD community. Both communities are fundamentally committed to the concepts that can advance improved collaboration and innovation and, separately, have begun specific activities for further exploratory planning in the near- and long-term. USGCRP continues to provide a forum for the C-IHTM Coordinating Group to carry out their discussions and planning, and the group anticipates collaborations with other USGCRP entities as well.

This workshop report outlines the key objectives, discussions, and potential outcomes of each of the five workshop sessions. The report summarizes the discussions in the workshop and concludes with key next steps for the Federal Government and academic community.

2. OPEN SCIENCE – CONCEPTS, METHODS, AND ENABLING TOOLS

2.1 Motivation, Objectives, and Organization

The Integrated Hydro-Terrestrial Modeling (IHTM) Workshop Report summarized the need and opportunity to leverage existing capabilities to develop a more seamless national hydro-terrestrial modeling capability. The first session of the Coastal-IHTM (C-IHTM) Workshop started where the IHTM workshop and report left off in terms of recommendations for how to use an Open Science by Design[3][4] approach to C-IHTM. The underlying premise of open science is that conducting research openly will ultimately lead to better science. This is accomplished both by enhancing the reproducibility and extensibility of basic and applied research and by accelerating productivity through leveraging shared knowledge and resources.

As subsequent sessions of the C-IHTM workshop established, there is an amazing wealth of expertise, data, and models relevant to C-IHTM. Those resources are scattered across a multitude of agencies and domains. A recurring theme throughout the workshop was that it can be hard to fully grasp the breadth of data and models that already exist within siloed research communities. The goal of adopting an open science approach to C-IHTM is to break down those silos by making information and resources easier to find and reuse. Open science can also facilitate the transferability of data and models across the research-to-operations-to-research (R2O2R) development cycle.

The goal of this first session of the C-IHTM workshop was to highlight the potential for open science to transform coastal research. This builds on the vision established by the IHTM workshop to develop “An integrated water community committed to open science by design that collaborates across agencies and academia, identifies common goals, leverages expertise and resources, shares data and research, and co-develops models.” A session on open science naturally came first because, as the NASEM and DOE reports highlighted, open science must be incorporated from the very beginning of a project for it to reach its full potential.

The session was designed and led by individuals from three federal agencies. We chose to focus on two central themes: 1) model coupling and interoperability and 2) facilitating reproducibility and extensibility across the research lifecycle. These themes were established in four technical presentations in the plenary session and were then expanded upon in four corresponding breakout sessions. Those breakout session reports form the basis for this summary document.

2.2 Discussion and Insights

The major themes of our session were captured by the four plenary talks. The main points of those talks and relevant ideas from their corresponding breakout sessions are summarized below. The

[3] National Academies of Sciences, Engineering, and Medicine. 2018. Open Science by Design: Realizing a Vision for 21st Century Research. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/25116

[4] U.S. DOE. 2019. Open Watershed Science by Design: Leveraging Distributed Research Networks to Understand Watershed Systems Workshop Report, DOE/SC-0200, U.S. Department of Energy Office of Science. https://doesbr.org/openwatersheds/

talks were prefaced by an introduction to the goals of the session and an overview of open science themes from the IHTM workshop by David Lesmes from the United States Geological Survey (USGS).

2.2.1 Reproducibility and Extensibility

The first talk of this session was delivered by Casey Burleyson from the DOE's Pacific Northwest National Laboratory (PNNL). The main point of this talk was that adopting open science principles is necessary to fully achieve all the goals of C-IHTM. The talk outlined how open science works by reducing barriers to entry, gaining economies of scale, and avoiding duplication of effort. The breakout session associated with this theme repeatedly highlighted the explosion of collaboration within research communities, such as the Community Surface Dynamics Modeling System (CSDMS), where open science plays a central role.

While generally accepted as a net benefit, there are several common obstacles to fully implementing open science principles. These include the need for a culture shift to overcome common concerns related to the potential for others to misuse open data or code, implicit obligations to support open data or code, and the potential loss of a researcher's competitive advantage within the community. Another major obstacle is the absence of universally available tools for capturing all of the detailed components of complex C-IHTM multi-model workflows.

Other specific topics of conversation and outcomes focused on this first theme included the following:

1. Training and expertise are a rate-limiting constraint to making data and models open. Any push towards open science in the context of C-IHTM should be accompanied by an expansion of training and provision of common tools (e.g., GitHub, open data repositories, etc.) that facilitate interoperability.
2. Early career researchers were repeatedly highlighted as gateways to open science as they have the most to gain by broader collaboration.
3. Because Federal agencies are increasingly requiring Data Management Plans (DMPs) and Software Productivity and Sustainability Plans (SPSPs) in research proposals, and this requirement has helped to advance open science goals, the proposed DMPs and SPSPs should be carefully reviewed by domain experts as part of the peer review process and should be a part of subsequent annual project reports in order to encourage compliance.

2.2.2 Benchmarking and Model Evaluation

The second talk in our session, delivered by Chris Massey of the U.S. Army Corps of Engineers (USACE), focused on how open science can be used to build trust in models as they are benchmarked and evaluated. The main points of this talk were first to provide a set of common guidelines defining the process of benchmarking; second to define common terms relative to benchmarking, such as verification, validation, calibration, and uncertainty; and third to address best practices for implementing benchmarking in an open science environment.

The conversation started with examples of common practices for verification and validation for coastal hydrodynamic models under a variety of conditions, including extreme events such as hurricanes. From event-based benchmarking, the discussion extended to the utilization of long-term (>40 years) continuous monitoring datasets, such as those provided by the Coastal and Hydraulics Laboratories Field Research Facility located on the Atlantic coast at Duck, NC.

The discussion then moved into the overall process of benchmarking, with emphasis on how best to describe and document a benchmark case, including its applicability and accuracy, and how those might adapt when considering systems of systems, instead of just a single model. Methods for distributing or publishing the benchmark in an open science way were discussed along with what is required for reproducibility, such as including metadata standards and version numbering of software. By following the basic guidelines for defining, describing, and documenting the benchmark cases, with attention paid to making them reproducible and readily available, open science benchmark cases will serve as a mechanism for fairly evaluating models and building trust in their use for future applications.

2.2.3 Model Interoperability

Chris Vernon of PNNL gave the third plenary talk in our session. His talk focused on model interoperability and how open-source software can benefit both the original researcher and downstream users. The main points of this talk were to show the benefits of building open source, interoperable software from a component-based perspective and to define what being open source actually entails beyond the common perception. The conversation started by describing what software interoperability is philosophically and how developing with interoperability in mind can promote open collaboration, increase reusability, and ensure that research efforts can communicate across agencies on a common platform to increase efficiency and capitalize on investments. The presentation also discussed the importance of developing standards to support interoperability and a need for common ontologies and highlighted emerging efforts to do so, such as the Open Modeling Foundation (OMF).

The discussion progressed to a comparison of two large and all open-source projects from the MultiSector Dynamics (MSD) community: the Global Change Intersectoral Modeling System (GCIMS) and the Integrated Multisector Multiscale Modeling (IM3) projects. The GCIMS project was used to demonstrate how interoperability can be achieved in a system of autonomous systems having multiple sector and scale representations that were built to interact to support a single model, GCAM, by design through the use of emulators and reduced-form models with comparable footprints. As a contrast, the IM3 project prioritizes coupling best-in-class, physics- and process-based models, which are generally not designed to be interoperable. The modeling software for IM3 includes varying levels of complexity and a variety of languages and computational requirements. Though the requirements and strategies for each project vary, the ability to use all open-source software and standardized components promote an interoperable effort enabling both projects to benefit from their individual development activities.

The following are highlights from the breakout session:

- There was a common theme showing a need to embed staff with software engineering expertise into research teams to support integrated software development, with a focus on interoperability from planning throughout the life cycle of the experiment.
- Group members relayed that successes in interoperability have been achieved through providing educational resources that demystify the use of software and standards. Others

suggested that success in interoperability also occurs when modeling software transitions from proprietary to open source, most often arising from a desire to collaborate. This transition expands the user base that can provide review and feedback, thereby improving the software and the resulting capacity for interoperability.

- The group plans to offer a contribution to interoperability standards that are currently under development/review for the OMF and other open-source efforts from the perspective of multi-model software ecosystems.

2.2.4 Granularity in Model Coupling and Interoperability

The final plenary talk was delivered by Ethan Coon of the DOE's Oak Ridge National Laboratory (ORNL). Ethan provided an historical overview of model coupling and highlighted several current approaches that have enhanced the flexibility and reusability of model coupling approaches. This talk was intended as a forward-looking view of task-based coupling strategies, which couple composable, reusable model components as opposed to entire models. Model components are written as stateless functions, and coordination across model components is controlled by a centralized data manager. Advantages of coupling at this granularity include better code reuse across modeling teams, the opportunity to take advantage of next-generation computing architectures, simpler and better testing, and increased understanding of model structure uncertainty. A disadvantage of this approach is the relative difficulty of working with existing legacy code in these types of frameworks.

The discussion following the talk consisted of a large group of attendees interested in discussing future technologies in coupled models. The group first considered the question, "What actions related to model interoperability could be taken now by individual codes to ensure better interoperability in common modeling platforms?" Key discussion focused on documenting code, including using standard ontologies for variable names and providing detailed and up-to-date documentation of inputs and outputs of a given model, and leveraging libraries and tools wherever possible to simplify interfaces. The largest discussion came around the granularity of code. Participants stressed the need to refactor existing codes into smaller, more model agnostic components. Opportunities enabled by such efforts were seen both within a code community (allowing new community members to more quickly change code by having smaller code components to understand) and across communities (allowing better and deeper coupling of models).

Next, the group focused on the question, "What specific topics could be described now that might usefully drive continued model development?" The group identified several low-hanging fruits in this area, including shared ontologies and file structures for the community and common community metrics and benchmarks for comparing models and understanding the effects of model structural change. Longer-term goals included better coupling of human and physical models and dynamic (living document) references for models and model components, creating a shared reference for the community of practice.

2.3 Opportunities and Potential Paths Forward

In total, this first session of the C-IHTM workshop outlined several actionable steps that the community could undertake as it applies open science principles to C-IHTM:

- Include open science goals and approaches from the beginning of any new C-IHTM collaborative effort. This would include enhancing the review procedures for project DMPs and SPSPs and providing community-based training and tools to projects.
- Embed more software engineers into modeling projects, where they can help domain scientists understand modern software engineering practices and avoid common mistakes that limit the integration of models across teams and agencies.
- Encourage contributions to the interoperability standards for multi-model software ecosystems that are currently under development and review for the OMF.
- Adopt and contribute to existing infrastructures that could assist with modeling software interoperability across agencies (e.g., CSDMS, etc.).
- Develop reproducible benchmark cases for different model processes to enable a common standard by which to evaluate models and build confidence in their use.
- Adopt an ontology and, where possible, common file formats to enable transfer of baseline knowledge across modeling communities and enable coupling infrastructures.
- Encourage refactoring of existing code bases into smaller process-based components that facilitate richer coupling strategies across models.

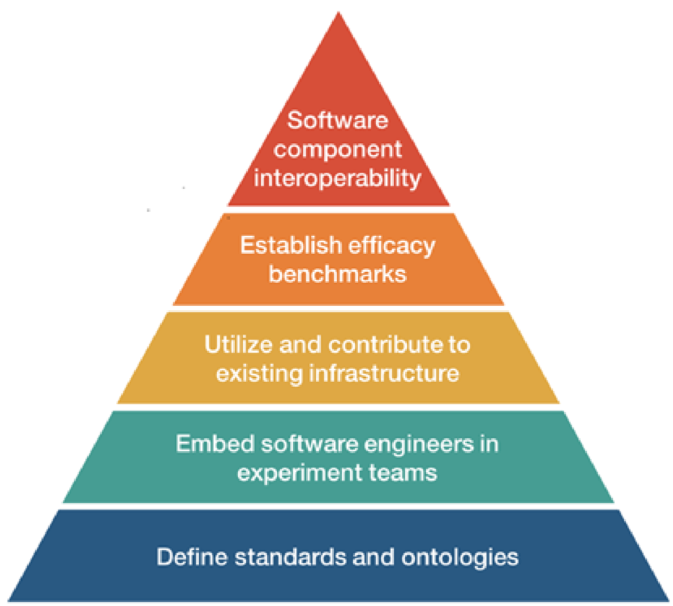

Figure 2.3 *Progressing towards the Open Science by Design mission with opportunities and potential paths forward to establish fully open-source and interoperable cross-agency modeling capabilities that support findability, accessibility, interoperability, and reusability (FAIR) principles being adopted through well-defined standards and ontologies.*

3. USE CASES – REGIONS AND TOPICS

3.1 Motivation, Objectives, and Organization

The second session of the C-IHTM Workshop focused on use cases to stimulate discussion of multi-agency, multi-scale integrated modeling efforts that both illustrate major C-IHTM themes and raise potential opportunities for new collaborations. The main goal of the session was to identify specific use cases for interagency and intercommunity collaboration for enhancing our collective modeling capabilities in domain/region/methodological spaces associated with coupled human–natural systems. A use case in this context is a set of one or more experiments with the purpose of exploring and evaluating science questions.

The session began with four plenary presentations that highlighted examples of regional/topical use cases that build and apply multi-sector modeling capabilities. Facilitated parallel breakout sessions then explored attributes of good use cases and brainstormed use cases that could be pursued in future multi-agency collaborations that bring together existing capabilities across groups, expand on those capabilities, and help to close research gaps. The breakout groups then reported on use cases that emerged as being particularly promising for collaborations.

3.2 Discussions and Insights

3.2.1 What Makes a Good Use Case?

Each breakout group began by discussing the characteristics of good use cases. We agreed that good use cases could be geographic (e.g., focus on a particular region), topical (e.g., focus on a specific research theme or dynamic), or a combination of both (e.g., drought in the West). There was also broad consensus that good use cases should

- involve complex interactions among multiple systems, sectors, and scales;
- address the needs of real-world stakeholders and be able to inform actions;
- address key scientific research gaps and science questions; and
- demonstrate the value of interagency collaboration and leveraging capabilities jointly.

In addition to these four widely agreed upon characteristics, discussions also suggested that use cases should be likely to provide generalizable insights, highlight systems undergoing change, and use open science and FAIR data principles. Groups also discussed the value of considering low-hanging fruit—smaller subsets of use cases based on work already being done that could be connected and synthesized—rather than attempting to advance an entirely new, large, and independent use case.

3.2.2 Value of Collaboration on Use Cases

All integrated modeling efforts are constrained by geographic, temporal, or thematic boundaries; ignore potentially impactful exogenous factors; fail to fully quantify model sensitivities and uncertainties; and suffer from data limitations leading to an over-simplification of processes and feedbacks. Attempts to address these model limitations increase model complexity, reduce transparency, and increase uncertainties and the range of outcomes, which further confounds interpretation of results by decision-makers. For these reasons, addressing model limitations often falls within the realm of fundamental scientific research and supporting agencies, such as the DOE. In contrast, agencies with a mandate for developing applied models and research (e.g., EPA, USGS, NOAA, USACE) focus their attention on informing stakeholder questions with models constrained by additional simplifying assumptions or run for smaller geographic domains or shorter time scales.

Clearly, these differences present an opportunity for greater collaboration among agencies and communities of practice developing integrated modeling systems to answer fundamental science questions and those developing models to inform management decisions. Successful collaboration requires identification of the critical limitations of applied modeling efforts and identification of the components of fundamental scientific research that may inform or resolve those limitations, and vice versa (i.e., research-to-operations and operations-to-research (R2O2R)).

3.2.3 Plenary Presentations

Four plenary presentations were used to highlight examples of regional/topical use cases and limitations that are ripe areas for collaboration. The first two presentations represented agency projects (USGS and EPA) with an applied focus and more narrow scope, while the second two (PNNL and MIT) represented projects more focused on fundamental research with broader scopes funded by the MultiSector Dynamics program within the DOE Office of Science.

1) **Modeling the Effects of Land-Use Planning and Land Conservation on Water Quality in the Chesapeake Bay Watershed (USGS)**

   The Chesapeake Bay Land Change Model (CBLCM) is an open-source pseudo-cellular automata land change model tailored for loose coupling with watershed models and estimates land use conditions in the year 2025 and other future years. The CBLCM simulates infill and redevelopment, residential and commercial development, forest and farmland conversion to development, and growth served by sewer or septic wastewater treatment. It simulates a range of plausible future scenarios and produces over 100 stochastic iterations for each scenario to quantify spatial uncertainties. This use case involves multiple models (e.g., airshed, watershed, and estuarine water quality) developed by multiple federal agencies and used to inform decisions. The models in this system are continually evolving based on changing needs of decision-makers and new science and data.

   The modeling does have some limitations that could benefit from collaboration. Urban growth simulation is constrained by county-scale population projections, and gives no consideration to alternative projections or shifts in domestic or international migration trends. Changes in crops, timber harvests, and farm animals are informed solely by recent trends, not by economic factors affecting markets and commodity prices. Rare disruptive events such as hurricanes, severe drought, or global pandemics are ignored. Knowledge on how fine-scale landscape features affect hydrology, sediment movement, stream temperature, and nutrient transformations is limited. Lastly, the potential co-benefits of Best Management Practices for reducing greenhouse gas emissions and runoff and moderating stream temperature are poorly understood.

2) **Simulating Locally Relevant Development Patterns Consistent with Global Climate Change Scenarios: Loose Coupling of ICLUS and UrbanSim (EPA)**

   EPA's Integrated Climate and Land Use Scenarios (ICLUS) produces projections of population, land use, and impervious surfaces by incorporating scenarios and storylines from the IPCC and producing spatially explicit information for assessing activities at the regional, state, and county levels. ICLUS is being applied to finer spatial scales by linking its population projections to the open-source UrbanSim model that incorporates planned changes to transportation infrastructure, sidewalk-scale geographic accessibility, commercial and residential real estate markets, employment, and household location choices. Working with officials from the Land of Sky region in North Carolina, the ICLUS-UrbanSim suite will produce census block-level results relevant to local planning decisions.

   Applying this suite of models to coastal areas presents unique and persistent challenges. The role of sea level rise in population and land use dynamics is understood in a general way (i.e., storm surge will discourage development and drive out-migration from coasts). However, we lack the spatially and thematically detailed data to model those responses at useful spatial scales. More information is needed on human responses to stressors like sea level rise at the household and community levels. Moreover, uncertainty regarding the feasibility and likelihood of various adaptation responses (e.g., coastal armoring) that would alter patterns of development and migration further hampers detailed simulations in these areas.

3) **Integrated Coastal Modeling (ICoM) Experiment (PNNL-led with many participating institutions)**

   The long-term vision of the Integrated Coastal Modeling (ICoM) project is to develop predictive understanding of the land–river–estuary–ocean continuum and interactions with human integrated systems, including long-term changes, tipping points, and shocks. Many models are being used across ICoM to address the long-term vision, and these models often have different process representation and resolution. ICoM is developing model intercomparison experiments to understand how different modeling approaches compare in their ability to characterize coastal extreme events and the subsequent coastal urban environment risk through storyline and climatological experiments in the mid-Atlantic region.

   These experiments will be enhanced through coordination with other researchers, agencies, communities, and stakeholder interest groups in the mid-Atlantic region by considering additional tools and data to evaluate coastal–ocean process representation. In addition, these collaborations will improve local-scale representation of human systems, including decisions impacting land use/land cover change, water management, and other coastal region adaptation plans.

4) **An Integrated Framework for Modeling Multi-System Dynamics: the Mississippi River Basin (MIT)**

   The DOE MSD project led by MIT focuses on the Mississippi River Basin, specifically the lower Midwest and the Gulf Coast, and teleconnections between the two. The project asks whether compounding human and natural influences and stressors (i.e., changes in extreme events, water, energy, land use, populations, economic activity, and the built environment) could exceed the resilience of coupled systems and alter regional multi-sector dynamics. It also seeks to explore how risks and events in one part of the river basin system may propagate (e.g., how agricultural management decisions might affect water quality, ecosystems, and fisheries downstream).

The team is developing a multi-system modeling framework that includes key natural and socio- economic systems across scales (global to local) and takes a mid- to long-term view while also tying back to near-term decisions. At local scales, the project seeks to leverage data, tools and stakeholder connections of other agencies and communities (e.g., the high-resolution modeling for land use change, water quality and population by USGS and EPA). In turn, MIT modeling could inform high-resolution tools and local decisions by providing projections of influences that are typically either outside the scope of localized applied research or simplified in assumptions about boundary conditions or exogenous factors (e.g., global agricultural markets, commodity prices, economic growth, energy transitions, demand for land and water, and extreme events).

3.2.4 Synthesis of Use Case Brainstorming

Each breakout group brainstormed potential use cases that connect fundamental and applied research questions and modeling frameworks and included the multiple elements of good use cases discussed above. Use cases that were suggested covered complex interactions among multiple systems, sectors, and scales. In total, 38 use cases were suggested (see Table A.1 in Appendix A). The topics and dynamics of highest interest within and across those use cases were the following:

- Compound events (e.g., storm surge plus inland flooding)
- Energy/energy transitions
- Land use/land cover change
- Population change/development patterns
- Economic dynamics
- Extreme events (flooding, drought, storm source, sea level rise, wildfires, extreme heat)
- Water supply/demand
- Water quality (nutrient loading, hypoxia, saline intrusion)

Real-world stakeholder needs were also a key part of the suggested case studies. Top needs addressed in use cases included **resource management** (land/agriculture, water, energy, ecosystems, fisheries); **adaptation and resilience**; **human responses**; and **equity**.

The use case suggestions also addressed key scientific research needs and gaps in which interagency/group collaboration would be essential to leverage needed capabilities. In terms of geography, use case suggestions ranged from the Mississippi River Basin/Gulf Coast, to the Mid-Atlantic (Delaware River, Chesapeake Bay) and West Coast. The use cases focused on the following broad topic areas:

- **Landscape evolution:** the co-evolution of human and natural systems and corresponding stressors and influences, including population and economic dynamics, energy transitions, land use/land cover change, urban development, water quantity (flood, drought), water quality (agricultural runoff, hypoxia), resource management, regional teleconnections, adaptation, resilience, and extreme events.
- **Climate change and compound extreme events:** hurricanes, storm surge, flooding, sea level rise, saline intrusion, subsidence, drought, extreme heat, fires, etc.
- **Coastal and water management decisions:** infrastructure development decisions (levees, ports, etc.), migration/retreat, water management (e.g., water levels).
- **Land use and water quality:** land use/land cover change, resource management (land, agriculture, water, fisheries), water quality (agricultural runoff, nutrient loading, hypoxia), agricultural conservation practices, restoration investments, drought resilience, watersheds, ocean acidification.
- **Energy transitions:** resilience of energy systems (e.g., transmission and distribution) in the face of extreme events and demand changes, interactions with coastal processes, thermoelectric cooling and water quality, bioenergy crops and implications (land use, water use, water quality- agricultural runoff), changing policies, climate and energy demand (urban heat effect, building energy efficiency).
- **Model intercomparisons/interoperability experiments:** for land use/land cover change, population dynamics, urban growth, stream flow, energy, extreme events, flooding, etc.
- **National capabilities:** open-source models for stream flow/flooding, human migration, water management, power systems, transportation systems, and other systems/dynamics.

Of the 38 use cases that were suggested in the brainstorming, the breakout groups focused on 9 that were of greatest interest to participants (included in Table 3.1 below and highlighted in blue in Table A.1 in Appendix A).

Table 3.1 Use Cases. *Suggested use cases that garnered the most interest during breakout*

Category	Use Case Proposal	Topics/Dynamics	Geography
Landscape Evolution	Mississippi/Gulf Coast	Regional development patterns and teleconnections; water quantity and quality; resource management; adaptation; resilience; compound extreme events. (Bring together e.g., MIT, USGS, EPA, PSU, ICoM)	Mississippi/Gulf Coast
	Heat waves, urban areas and public health	Complex, interacting social and environmental stressors; human health; equity; mid-large cities (ICLUS/BenMap/TARGET)	Any urban area
	Western U.S. water shortages	Competing water demands; compound extreme events; human system dynamics and responses; water rights; adaptation to risk; equity	West Coast
Climate Change and Compound Extreme Events	Coupled impacts of inland (river) and coastal (storm surge) flooding	Compound extreme events	Gulf Coast; Atlantic Coast
Coastal and Water Management Decisions	Managed/Unmanaged Retreat	Climate adaptation; modeling, land use/land cover change; socioeconomics; environmental and social equity; population dynamics; coastal development; coastal hazards	Coastal regions, but specific lessons learned from New York City/New Jersey, New Orleans

Land Use and Water Quality	Chesapeake Bay	Climate change; land use; restoration investments and policy; data-rich, active stakeholders	Mid-Atlantic region
	Western U.S. water quality and quantity	Resource management; best practices for agricultural lands; land use change; climate change; hydrologic changes; groundwater pumping; fertilization rates	West
Energy Transitions	Energy sector interactions with coastal processes	Resilience (energy and coastal systems); urban coastal growth; energy transitions; transmission and distribution systems; water temperature and thermoelectric cooling; agricultural runoff due to bioenergy crops; extreme weather events	Any coastal area
Model Inter- comparisons	Land use/land cover change scenarios	Modeling (e.g., GCAM-Demeter, IM3 and SELECT); global trade; land use dynamics; urban extent; scale-flexible methodology	Any area

3.3 Opportunities and Potential Paths Forward

Enhanced collaboration on model development and integration with other agencies and CoPs will enable models to address a broader array of societal questions and improve the robustness of decisions made under uncertainty. All of the projects described in the plenary presentations in this session, as well as many of the use cases proposed in the breakout group, have potential for fruitful collaboration. Whether or not this happens depends on agencies and individuals sharing a set of mutual interests and acknowledging the strengths and critical limitations of their models. Collaboration can occur when a common objective is pursued by many and when the strength of one model is another model's limitation. Collaborations that bring together complementary capabilities can further both applied and fundamental research and the interaction/communication between the two, thereby furthering the goals of R2O2R.

This session identified many areas of mutual interest as well as many complementary capabilities and models. The use case brainstorming suggested a plethora of opportunities to connect agencies and communities of practice. A particularly promising path forward in the near term is to pursue low-hanging fruit in the form of subsets of use cases that connect existing related work streams. The use cases that were deemed most interesting by the participants are shown in Table 3.1, with the full list of candidate use cases considered catalogued in Table A.1 in Appendix A. In the future, there is potential to more formally bring together inter-agency/inter-community teams to work together on specific use cases that leverage the strengths of those involved in order to fill scientific gaps and inform real-world decision-making.

4. INTEGRATED MODELING FRAMEWORKS

4.1 Motivation, Objectives, and Organization

Capturing the full scope of challenges facing coastal regions requires not only deep knowledge of the underlying processes driving coastal systems, economic activities, population dynamics, and interconnected networks, but importantly the interactions and interdependencies across these systems (Figure 4.1). Bringing together the C-IHTM and MSD communities at this critical juncture will accelerate our ability to model these complicated and interconnected coastal systems by connecting the process model expertise of the C-IHTM community with expertise on modeling multisector dynamics supplied by the MSD community.

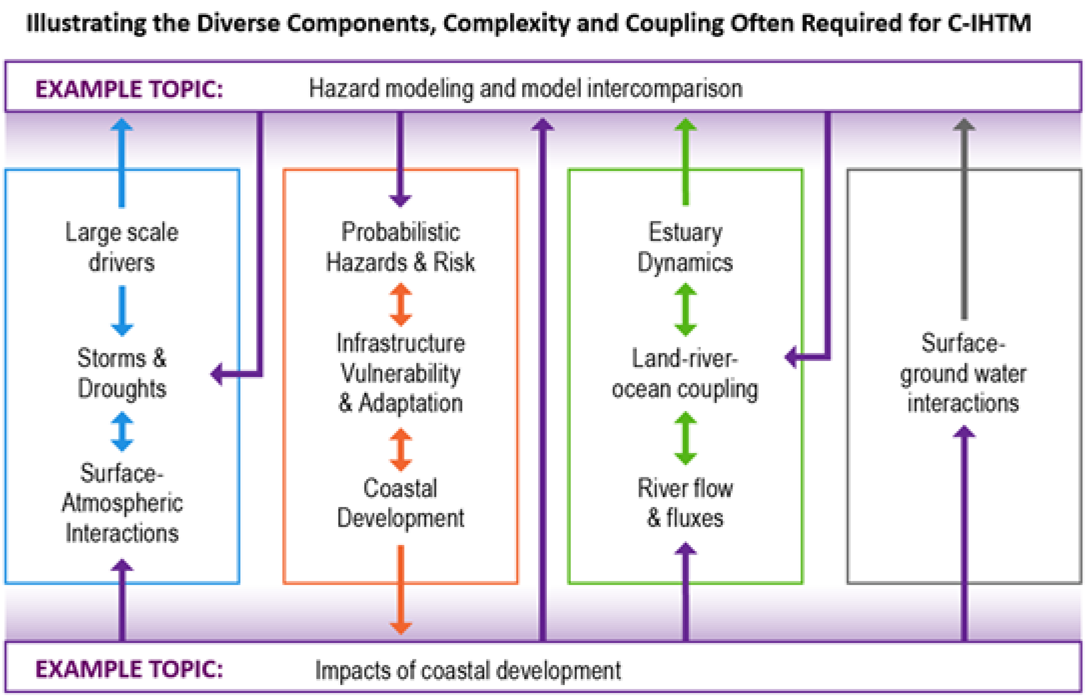

Figure 4.1 *Adapted from PNNL, 2019. Models for coastal hazards and coastal development share – and build connections among – important components and information flows.*

With this goal in mind, the third workshop in the C-IHTM series focused on integrated modeling frameworks to stimulate discussion around multi-agency efforts in integrated modeling and to identify specific opportunities for enhancing collaboration between the two communities. The workshop was organized into four plenary presentations and four breakout sessions, concluding with report outs from the breakout sessions in plenary.

Plenary presentations included tag-team plenary presentations on four topical areas: **1) modeling frameworks for atmosphere–water–land interactions; 2) modeling frameworks in land surface hydrology; 3) modeling frameworks in multisector dynamics; and 4) incorporating stakeholder**

and community interactions in modeling frameworks. The plenary talks highlighted the science questions at the coastal interface, modeling frameworks that are used to address these science questions, and some interesting results of the work. These were followed by deep dives into each of these topical areas in separate breakout sessions tied to each of the plenary themes.

Although organized around different topics, participants in each breakout session were asked to provide input in three areas: **a) existing data, modeling, and decision-support tools/methods related to coastal dynamics; b) important gaps in existing data, modeling, and decision-support tools/methods for addressing the science questions; and c) multi-agency collaborative opportunities to better address the science questions in coastal regions.** Conclusions from the breakout sessions were reported back in a concluding plenary session, stimulating a rich discussion that synthesized key themes across the four topical areas.

4.2. Discussion and Insights

4.2.1 Atmosphere–Ocean–Land Interactions

The first topical area in this workshop considered modeling frameworks for exploring atmosphere–ocean–land interactions. The plenary presentation, delivered by representatives from DOE, UC Davis, and Los Alamos and Pacific Northwest National Labs, focused on a suite of 10 projects funded under DOE's Regional and Global Model Analysis (RGMA) program area within the Earth and Environmental Systems Modeling program. Each of these projects has developed multiscale integrated modeling frameworks that enable analysis of the coupled atmosphere–ocean–land system across a variety of regional and contextual foci. The models ranged from the use of the global Energy Exascale Earth System Model (E3SM) to local and process level models of the natural system that makes connections. Key insights that emerged from the plenary and breakout session on this topic included the following:

Coupled modeling frameworks pose challenges related not just to the integration of the separate component models themselves, but also the integration and coherence of the data that is ingested and generated by these models.

- Most efforts to quantify uncertainties have focused on the use of a multi-model approach that uses uncoupled components but in integrated modeling frameworks. Uncertainty quantification approaches to analyze uncertainties arising due to coupling and the associated feedbacks were also discussed.
- While individual modeling domains may have well-established metrics for diagnostics and evaluation, these are inadequate for integrated frameworks, and appropriate metrics for evaluating the coupled system are often lacking.
- Storylines are emerging as a powerful tool for organizing context-relevant integrated modeling frameworks.

The breakout session also identified a large number of Earth system data sources, regional and global models, and diagnostic tools that can serve as building blocks for creating integrated frameworks to explore coupled atmosphere-ocean-land interactions.

4.2.2 Land Surface Hydrology

The second topical area explored in this workshop examined modeling frameworks in land surface hydrology. Plenary presentations were given by representatives from NASA, the National Center for Atmospheric Research (NCAR), USACE, and USGS, which was followed by a breakout session to further explore existing frameworks, research gaps, and potential opportunities. A few key insights emerged from the plenary presentations and breakout session:

1. Many problems related to land surface hydrology require models that can faithfully capture complex interactions.

2. There is a tradeoff between calibrated, high-order modeling for local decision support and reduced-order modeling for speed and strategy.

3. Scientist-modelers who know the system must be well connected with management needs.

The breakout session identified a number of existing modeling frameworks, most of which are open source, but also identified a number of important gaps. In particular, participants felt that existing land surface hydrology modeling is weak in examining the connection between water quality, ecosystem dynamics, and water quantity; representing human impacts and engineered systems; and modeling subsurface/surface connections, especially at the coast. Participants also stressed that as land surface hydrology modeling becomes increasingly complex, functional testing becomes more difficult yet critically important.

4.2.3 Multisector Dynamics

The third topical area explored in this workshop examined modeling frameworks in multisector dynamics. Plenary presentations from four MSD project teams—the Global Change Integrated Modeling System (GCIMS) project, the Integrated Multisector Multiscale modeling (IM3) project, the Program on Coupled Human and Earth Systems (PCHES) project, and the MIT Multisystem Dynamics Modeling Framework project—provided examples of integrated modeling frameworks designed to capture multisector dynamics across complex interrelated systems and set the stage for the breakout session discussion. A few key insights emerged from the breakout session related to this topic area:

1) First, participants identified a number of modeling frameworks related to multisector and coastal dynamics. Although many are open source, a number were not, suggesting that this is an important issue that needs to be resolved.

2) A second related gap is the availability of data and issues of proprietary datasets and software that limit access to models that use these data and software.

3) A third gap in existing MSD modeling frameworks is the ability to analyze and communicate uncertainties as it propagates far into the future and across multiple interacting systems and sectors.

4) Lastly, participants felt that modeling, understanding, and prediction of collective social processes and institutions has been an area of weakness in these models (although there are notable exceptions) and limits our ability to capture interactions between physical processes and social/human decision making.

4.2.4 Incorporating Stakeholder and Community Interactions in Modeling Frameworks

The fourth and final topical area explored in this workshop centered on strategies for using engagements with stakeholders and decision-makers to inform the design and use of integrated modeling frameworks. Representatives from Penn State, Lawrence Berkeley National Laboratory (LBNL), and the Virginia Institute of Marine Sciences (VIMS) offered plenary presentations focused on examples from the NOAA Mid-Atlantic RISA program, the DOE-supported HypeRFACETS project, and VIMS. A final presentation discussed how mental models can be used to highlight and clarify the values of both scientists and stakeholders that are most relevant for the development of integrated modeling frameworks used for decision making. Key questions and insights that emerged from the plenary presentations and subsequent breakout discussion included the following:

1) How can we assess whether the scientific questions being pursued address stakeholder needs?
2) How can we ensure that decision-support tools actually improve decisions?
3) In what circumstances does "better" risk information actually improve risk perception?
4) The nuanced information that emerges from stakeholder engagements is essential for resolving the dynamics of coupled natural and human systems and understanding the associated uncertainties and interactions across scales.
5) There is a strong need for easy-to-use open source visualization tools to enhance the usability of the rich data streams that come from our integrated modeling frameworks.
6) You may end up with a very different integrated modeling framework design by working backward from stakeholder-identified decision problems than you would by starting with science-driven questions.

4.3. Opportunities and Potential Paths Forward

The first breakout session identified several opportunities for cross-agency initiatives that could help advance integrated modeling of ocean–atmosphere–land interactions. Participants noted that the large number of relevant models and tools supported across multiple agencies made it difficult for individual researchers to understand the full scope of what is available and how it is being used. It was suggested that this challenge could be transformed into an opportunity for inter-agency collaboration through the development of a comprehensive catalog of these models and tools or even an open collaborative environment where codes can be linked using example workflows. Multiple participants suggested that a coordinated data strategy would be highly beneficial for researchers and could help motivate and facilitate inter-agency collaborations.

Similarly, the development of a collection of shared use cases could help facilitate inter-agency coordination, enabling comparisons across a broader array of approaches and creating opportunities for more rapid advancement through sharing of successes and lessons learned. At the same time, it was acknowledged that different agencies often have quite different priorities in terms of science questions and applications contexts, which has implications for the choices of process representation, spatial and temporal scale, modeling scope, use cases, and metrics for evaluation. This poses a challenge but also a substantial opportunity, as transparent discussion of these issues can facilitate more promising and tractable options for cross-agency collaboration.

Opportunities and potential paths forward related to land surface hydrology were identified in both the plenary presentations and the second breakout session. First, it was stressed that efforts should be made to advance community hydrological modeling rather than a community hydrological model. Related to this, participants encouraged a move toward agile model coupling mechanisms to allow for easier use of a variety of tools for specific research questions (e.g., open science with Jupyter notebooks to facilitate sharing). Additionally, participants emphasized that open science (e.g., community standards; scalable and portable architecture; open source; documentation; support; shared workflows) should be a priority for the community.

Lastly, participants identified three important gaps in land surface hydrology modeling where advancements are needed: 1) cross-sectoral problems (e.g., hurricane landfall, coastal water quality, sea level rise); 2) transboundary water problems that require satellite and alternative modeling approaches (e.g., Great Lakes, Rio Grande, Nile); and 3) economics, uncertainty, and risk (e.g., understanding the co-benefits of conservation practices).

The third breakout session examining modeling frameworks in multisector dynamics identified a number of opportunities and potential paths forward. To begin, participants felt that a comprehensive review of the gaps in data, modeling, and analysis capabilities around the three research foci of the IHTM report is needed. Participants also felt that with increasingly detailed and complex models being used, there is a growing need for data. A workshop centered around identifying current and anticipated future data needs to advance modeling capabilities in this area would be helpful to address this issue. Lastly, representing the exposure and adaptation responses of private and public institutions to coastal risk is an important future research area in order to assess whether new institutions are needed or existing institutions need to be modified to respond to coastal risk, and whether current institutions are making the situation worse.

The fourth breakout session identified two key opportunities whereby enhanced collaboration could help advance capabilities for leveraging stakeholder interaction in support of integrated hydro-terrestrial modeling efforts at the coast and more broadly. First, recognizing that stakeholder/decision-maker engagement is a time-consuming process that requires a rather different set of skills than those required for excellence in integrated modeling, participants recommended that agencies support dedicated stakeholder engagements projects to identify opportunities, priorities, metrics, and desired deliverables that can be used to inform the subsequent design of funding programs and the integrated modeling efforts they would support. Participants also articulated a need for broader sharing of approaches, protocols, methods, and evaluation frameworks for stakeholder-informed modeling efforts developed through federal support. While such efforts have long been central to NOAA's RISA program, a broader inter-agency effort on this front could bring substantial benefits to the C-IHTM community.

5. LINKING COMMUNITIES OF PRACTICE

5.1. Motivation, Objectives, and Organization

Coasts support highly interconnected natural and human systems and sectors that are subject to a broad set of influences and stressors. Individual agency capabilities do not adequately address the full range of complex interactions and interdependencies of the highly coupled coastal system. This session explored whether these capabilities could be leveraged through communities of practice (CoPs), and more specifically whether there were opportunities for linking existing CoPs relevant to research in the C-IHTM domain. This session developed concepts and understanding about potential interagency and intercommunity linkages and identified select high priority, near- to mid-term areas for potential collaborations with the goal of complementing existing efforts and creating synergy.

The agenda is provided in Appendix B. The session opened with brief remarks to clarify the session's objectives and define key terms. Four presentations then provided overviews of CoPs already working in areas related to C-IHTM. Building on these presentations, a panel explored the benefits and challenges of working in CoPs, gaps and limitations in existing CoPs for research on C-IHTM, and other collaboration strategies. Following a short break, four parallel breakout sessions identified collaboration opportunities and a concluding plenary shared key points from the breakouts and synthesized results

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5.2. Discussion and Insights

In the context of the workshop, the term community of practice (CoP) connotes groups of individuals who share an interest in a topic or objective and who work together to learn from one another's work. CoPs have been formed in both the MSD and C-IHTM domains among groups of research projects and investigators to address research questions and challenges that were beyond the capacity of any single project or community to address on their own. These include both grand scientific challenges (e.g., theories and epistemologies) and more focused questions related to developing best practices for coastal research and specific datasets, models, and analysis tools. CoPs are more structured than purely informal networks but less so than research projects, and their contribution to progress can be measured by improvements to research practices. Depending on their objectives, CoPs can require considerable infusions of funding and staff time.

Four example CoPs were presented and discussed:

- The MultiSector Dynamics CoP was formed recently (2019) to establish a conceptual framework, data, models, and analysis tools for research on the co-evolution and two-way interactions of human and natural systems, especially related to energy–water–land systems affected by infrastructure, human institutions and behavior, climate, and environmental goods and services. The MSD CoP includes a Scientific Steering Group, six working groups focused on specific methodological challenges, and a small facilitation team. The CoP publishes scientific papers, holds scientific sessions/town halls, convenes webinars, and hosts a website/newsletter. A new initiative is launching a flexible and scalable data and code management system to enable MSD researchers to share documented data, software, and workflows. The MSD CoP initially focused on linking seven research projects funded by the DOE Office of Science and is broadening connections to this research agenda through active participation in the American Geophysical Union, sponsoring a special section in the journal Earth's Future, and other activities.

- The Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) has a 20-year history and links more than 130 universities and research organizations with support from the National Science Foundation. It seeks to foster "an enlarged inter-disciplinary water science" with other fields including social sciences, public health, and other disciplines. Its activities include education, support for data and model development, coordination of cross-cutting research projects, and funding for graduate students, post docs, and early career faculty for travel, networking, and related activities. Of particular interest to the workshop were a variety of tools for data discovery and workflow publication and sharing, as well as technical groups formed around shared interests and challenges.

- The Coastal Coupling CoP seeks to accelerate national coverage of improved water prediction capabilities and delivery of actionable information to stakeholders by facilitating the coupling of coastal models through research, model development and application, data provision, observations, analysis, and service delivery. At the time of the workshop, the CoP included 161 members representing federal and state agencies, national laboratories, academic institutions, and private firms. Activities include a multi-institutional steering committee, webinar series, scientific sessions, a website, and community-supported pilot projects. The Coastal Coupling CoP is launching a data infrastructure pilot project to demonstrate capabilities for a single workflow to coordinate data, run and analyze models, and produce visualizations.

- The Community Surface Dynamics Modeling System (CSDMS) is a diverse community of more than 2000 experts that promotes modeling of earth surface processes (e.g., movement of fluids and flux of sediments and solutes in landscapes and basins). CSDMS is sponsored by NSF and engages community members (in working groups, focus research groups, and research initiatives), provides computing resources, and promotes education. It has articulated a set of high-level research questions, maintains an open catalog and repository for modeling software and tools, and provides member support functions such as proposal support, project support, and online help for use of community data and tools. The community's software cyberinfrastructure provides interface standard (common functions), language interoperability, a model-building toolkit, an execution and coupling framework, and a dictionary of standard variable names.

It was pointed out that these were only examples of the CoPs relevant to MSD and C-IHTM, and that projects and investigators were involved in other CoPs such as the Energy Modeling Forum, the Integrated Assessment Modeling Consortium, the Chesapeake Community Modeling Program, and NSF's Coasts and People projects. A question was raised whether "CoP fatigue" was setting in, given limited time for engaging all of the potentially relevant CoPs. It was suggested that it would be useful to conduct a meta-analysis of existing CoPs; the working group topics and objectives could identify emerging priorities and a way of identifying opportunities for linking CoPs. This could also help to address the question of whether we are engaging the CoPs that would yield the highest payoffs scientifically and for professional development.

A panel discussion explored collaboration challenges and experiences with CoPs from the perspectives of research projects that participate in CoPs. Questions were raised about the distinctions among CoPs, multi-institutional research projects that link researchers from different institutions, and other bodies like professional associations. There are no sharp boundaries, but in general, CoPs are less formally structured than these other groups. A key issue was ensuring there was a well-posed purpose and adequate resources, especially for challenges such as creating open science infrastructure and establishing educational opportunities.

Panelists pointed out that participation in CoPs by their investigators generally occurs from the bottom up, meaning that individuals identify for themselves collaborations and activities that they find useful. This is especially true for university-based research, as projects based in national laboratories do encourage participation in CoPs when a broader programmatic benefit is identified. Top-down buy-in can be key to encouraging participation, particularly with respect to providing resources to facilitate engagement. A bottom-up approach doesn't necessarily lead to prioritizing collaborations that would be best for a project, especially given the general lack of formal communication protocols about CoP engagement within a project.

Benefits of CoPs to projects were identified and were wide-ranging, including accessing data and research infrastructure, identifying research questions, being exposed to new methods and tools in ways that provide greater insight into their uses and limits than by simply reading about them in journal articles, and testing one's models and tools against those of others in inter-comparison projects. There was a spectrum of collaboration noted, from participating in a working group to publishing together, from developing shared datasets to shared workflows of fully coupled models. Remaining challenges include encouraging adoption of new community products, maintaining common data and tool sets, increasing rewards for participation (especially for early career researchers), and training a next generation of interdisciplinary researchers and research software developers trained in a CoP's new approaches to research.

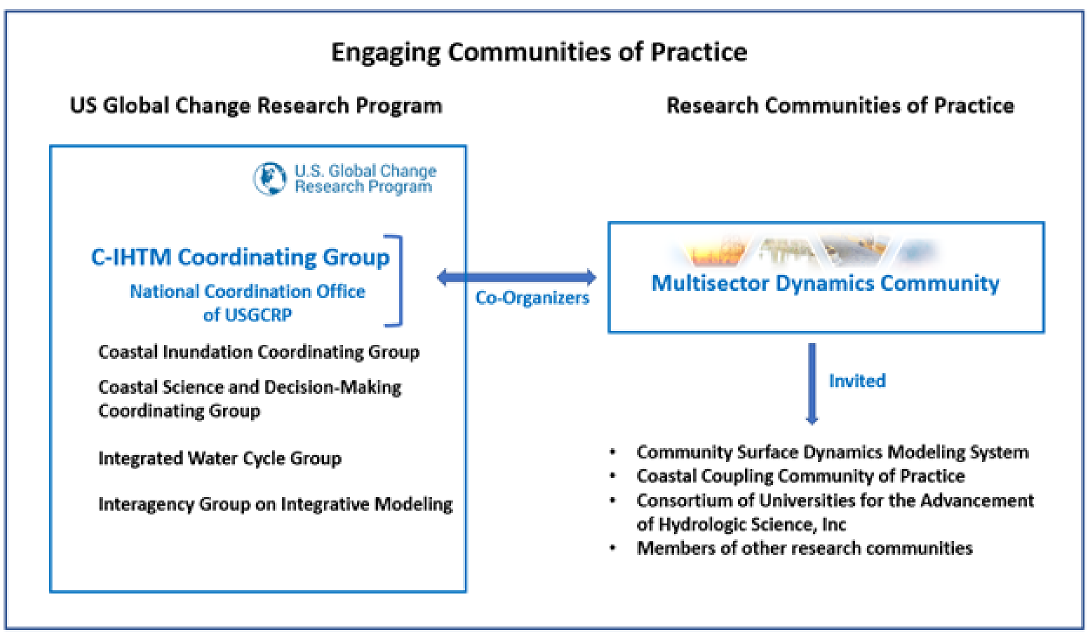

Figure 5.1 *Engaging Communities of Practice. The C-IHTM joint workshop brought in representatives from many different interagency groups and communities of practice.*

5.3. Opportunities and Potential Paths Forward

Four parallel breakout group sessions reflected on the presentations, their own experiences with CoPs, and identified 1) collaborative opportunities that support shared research on coastal modeling, and 2) potential early wins that could leverage and enhance connections across CoPs.

The idea of a meta-analysis of existing CoPs relevant to coastal research was raised by several groups and discussed during the final synthesis session. One idea was to survey and analyze the topical focus, membership, and other aspects of the CoPs to identify overlaps, gaps, and opportunities. Additional suggestions included combining the meta-analysis with a mapping exercise to identify geographical overlaps and collaborations. Another idea was to assess the CoPs' structure and function to identify best practices for using CoPs. For example, how are different CoPs embedding research software engineers? What has been learned about designing an effective, open, and efficient community data and analysis system? What approaches are the CoPs using for engagement with stakeholders, and how do these different approaches lead to greater or lesser alignment of these interests with research capabilities? Results of a meta-analysis could inform guidance on optimizing CoPs for maximum benefit.

A long list of potential collaborative opportunities that support shared research on coastal modeling was generated, including:

- Saltwater impact on and management of groundwater/surface water resources
- CUAHSI and some of the collaborative tools that they develop and use (e.g., Structure for Unifying Multiple Modeling Alternatives - SUMMA) with the goal of advancing modular hydrological processes
- CSDMS and CUAHSI collaboration on salinity gradients from coasts to riverine systems
- How different CoPs are exploring and considering human systems modeling (e.g., CSDMS WG of 171 members)—are there opportunities for co-development?
- MSD ICoM and Coastal Coupling CoP joint activities in the Mid-Atlantic related to inundation/flooding hazards
- Integration of data resources and archiving of model output (Environmental Systems Science Data Infrastructure for a Virtual Ecosystem (ESS-DIVE), Earth System Grid Federation (ESGF), CUASHI, CSDMS)—test cases, use CSDMS common variable name to guide data model integration in archiving
- Comparing how different communities are approaching the challenge of identifying thresholds, key drivers, and stressors that create dynamics and lead to emergent behaviors
- Common data (e.g., infrastructure, socioeconomic, coastal/urban development land use projections), working up to national levels from regional projects
- Common scenarios—climate and coevolution/feedbacks

- Comparing structures of models: telescoping nature, scaling, boundaries (e.g., Hydrologic Unit Code - HUC scales in watershed modeling, developing something similar for coasts); also, linkages across watershed, physical, chemical, biological, socioeconomic systems

- What are the dynamics of exposures and vulnerabilities in coasts from the perspectives of decision-makers and stakeholders?

- Identifying system relationships between social and environmental variables (e.g., the effects of environmental conditions on infrastructure)

Suggested near-term wins included the following activities:

- Identify ways to accelerate interoperability of models and data, including standardized formats and common repositories.

- Foster Collaboration on place-based case studies (e.g., EPA water quality modeling connected to GCAM; see Day 2 case studies discussion). Often, multiple modeling efforts are undertaken in key regional coastal areas of interest, and these would benefit from coordination on data, expertise, and stakeholders. This could include interoperability experiments (e.g., hackathons)

- Create a map identifying coastal modeling CoPs along the U.S. coastline: regional/topical CoPs, possibly expanding to include projects and investigators. A finding from the workshop was that there is limited awareness about existing CoPs, so this map would be useful for identifying resources for new projects and could be expanded to identify stakeholders, capabilities, etc.

- Develop a concisely stated scientific challenge in coastal modeling that draws on a specific set of collaborations across existing CoPs. This challenge would provide an example of how CoPs interoperate and help identify areas for improvement.

6. SYNTHESIS AND POTENTIAL PATHS FORWARD

6.1 Motivation, Objectives, and Organization

The fifth and final day of the C-IHTM workshop began with a summary of the previous four sessions. The session co-chairs then identified several emerging themes from those four sessions. These emerging themes were grouped into application questions and science/methodological questions. The three-application question-related themes were 1) water scarcity, 2) coastal retreat, and 3) water quality. The four methodological themes were 1) teleconnections; 2) integrated modeling; 3) testing, evaluation, and benchmarking; and 4) ensembles and high resolution. These themes are linked both to each other and to the previous sessions. For example, all four of the methodological themes are relevant to each of the three science question themes and vice versa. Similarly, each of the themes could benefit from and/or link to the previous workshop sessions (open science, integrated modeling, use cases, and communities of practice (CoPs)).

The objective outlined for this final workshop session was to construct the Synthesis and Potential Paths Forward for the C-IHTM workshop. The session was structured around four breakout group topics chosen from the seven themes identified above. These topics included two science application question themes (water quality, coastal retreat) and two methodological themes (high resolution or large ensembles, testing and evaluation). These topics were chosen only to give participants something concrete to discuss and the choice of themes should not be used to infer prioritization of topics. For each topic, we held two breakout sessions with different participants, but the same charge. Additionally, we included one short technical presentation in each breakout group to set the stage.

6.2 Discussions and Insights

Each of the breakout groups was asked to answer the following questions:

1) What are the key challenges to advance the science and applications for your topic?
2) How do Open Science, Modeling Frameworks, Use Cases, and Linking Communities of Practice discussed in the earlier sessions provide opportunities to address these challenges?
3) What are some of the concrete actions in the near term (1–3 years) that can be undertaken by you and this community to advance the topic?

A summary of the discussion on each topic is provided in the subsections below.

6.2.1 Water Quality

The breakout session began with a presentation that outlined key issues around modeling and managing water quality in the coastal zones, which include

- Evaluating nutrient loading, hypoxia, and harmful algal bloom, which are identified to be key challenges that pose serious threats to individuals, society, and the national economy (IHTM report, 2020);

- Representing multiple stressors (compounding human and environmental influences) and complex dynamics across system, scale and geography;
- Understanding the impacts of climate change on water quality; and
- Assessing effects of management practices and providing information to support water quality management decisions at appropriate scales.

The session participants discussed challenges to addressing the water quality science and application questions. These challenges are grouped into the following categories around modeling, data, and scenarios:

Modeling Challenges

- Groundwater–surface water–estuary/bay linkages are relatively uncertain; current understanding of interactions between groundwater, irrigation, and runoff quality is limited
- Understanding implications of long-term changes (e.g., land use change, human dynamics)
- Improved understanding of land use and land cover effects on flow path, residence time, and runoff generation, particularly in agricultural lands
- Characterizing uncertainty within regulatory mandate (e.g., meeting bay-wide TMDL)
- Modeling and valuation of economic impacts and feedback (e.g., fishery, ecosystems, human health, diseases, property value, recreation)
- Understanding and quantifying impacts of spatial and temporal variability in coupled hydrologic and biogeochemical processes
- Problems with scale (especially spatial resolutions) between water modeling and human dynamics

Data Challenges

- he lack of unified and harmonized data for modeling groundwater/surface water linkage (e.g., data on the current state and extent of soil, groundwater, and surface water contamination at high spatial detail)
- Observations to support model development and evaluation (with suitable density and sufficient quality)
- High heterogeneity in soil/groundwater conditions complicates data characterization for modeling

Scenarios Challenges

- Future socioeconomic scenarios that capture human decision-making and human activities (e.g., in energy, agriculture, and other sectors) with coastal impacts
- Consistent scenarios for economic and other sectoral developments, land and water analyses

Session participants noted that water quality modeling and regulation have a history of at least 50 years. There are some very well-developed models for most watersheds, and research communities in each of the major watersheds. It would be worthwhile for the MSD community to have further connections with federal agencies to learn more about federal agencies' activities, modeling capability, and needs; and help inform new science directions. It is noted that areas that the MSD community is well positioned to advance the science and add value to the existing efforts are 1) perspectives and modeling of long-term changes (e.g., land use change, human dynamics), and 2) understanding and characterization of uncertainty within regulatory mandate (e.g., meeting bay-wide TMDL).

Session participants discussed several actions that can be undertaken to address the identified challenges:

- A data inventory of what tools are available (e.g., used by regulatory agencies) would be a useful step to assess gaps and needs.
- An inventory of existing CoPs that address various questions (such as water quality, soil, ground water, coastal environmental issues) can help make connections and communication.
- Several participants underscored the need to engage with other scientific communities, especially ones focused on topics in human dynamics, behaviors, public health, and social science.
- In addition, connecting federal agencies and watershed managers with the MSD community is also recognized to be valuable to get input from decision makers to help shape and inform the R2O2R cycle.

As in discussions throughout the workshop, needs around data and tool coordination, open data and code, data quality and consistency, and model testing were discussed for specific aspects of water quality applications.

6.2.2 Coastal Retreat

The workshop attendees considered that key physical and social science questions that informed discussion of coastal retreat included:

- which hazards drive consideration of retreat;
- what characteristics frame choices around retreat options;
- where retreat could happen soonest and for the largest or most significant (variously defined) areas; and
- what consequences from retreat could be planned for and what types of unforeseen consequences could attend retreat.

Applying the overall emphasis of the workshop for these questions concerning retreat, attendees considered the extent to which existing modeling frameworks are sufficient to reveal, develop, organize, and communicate information that can help answer them, and to what extent new frameworks should be developed and employed. A major challenge here is in representing and using the diverse scales required to cut across the physical and social dimensions of coastal retreat and the modeling frameworks—for example, in determining how to develop and connect coastal models at hyper-local and regional physical scales for modeling storms, riverine and estuarine flooding, sea-level change, etc. Modeling and interpreting information on physical and social feedback arising from human migration in response to retreat also cut across the different scales—for example, in determining how wages and the prices of goods, services, and land will change in regions that gain and lose population during and following retreat programs.

This matrix of questions and aspects across scale is relatively small compared to some matrices already used for physical science modeling of coastal forces and fluxes. But the information needed for addressing the questions around retreat can be more difficult to obtain and represent numerically with certainty than some of the physical science information in coastal modeling frameworks. This means that coastal modeling for retreat may require additional work to characterize new sources of socio-economic information, for example, and test additional forms of that information in new modeling frameworks.

Development and rapid testing of flexible candidate models for including more of the important social feedback inputs can help the modeling community to increase its confidence that most of the important inputs and processes are included and appropriately bounded. That, in turn, can lend confidence to policymakers who will take outputs from these models to plan and study the effects of possible retreat scenarios. Importantly, a program of new model framework development and testing will also help establish the sufficiency of existing physical and social data relevant to coastal retreat questions and point to areas where new data are needed.

Workshop attendees explored how the questions of physical scale introduced above imply other questions about how possible geospatial use cases can best be used in model development and application. To what extent can use cases previously used be used again, and how can such use cases – including for communities along the Gulf of Mexico – be usefully integrated into regional or larger sub-continental models to capture more of the long-distance effects and feedback on model-represented processes? Larger modeling domains created to include longer feedback lines can change decisions about model type and model process representation and can influence the relative proportion of work aimed at finer scale versus more members in ensembles built to test model sensitivities or characterize structural and parameter uncertainty.

Because of the considerable uncertainty attached to some data inputs and the need to communicate answers probabilistically for studying unknown future conditions, informational and computational demands will increase as coastal models with more extensive physical and social process representations begin to be exercised for actual conditions. For this reason, workshop participants emphasized the need for enhanced connections and opportunities for multi-disciplinary projects supported through the many CoPs relevant for coastal modeling and considered in the session of this workshop series focused on them.

6.2.3 High Resolution or Large Ensembles

Given computational limits, researchers are often forced to choose whether to focus on high-resolution modeling or on generating large ensembles. The third breakout discussed trade-offs between resolution and ensembles.

The session began with a presentation by Claudia Tebaldi (PNNL), who provided an overview of the benefits to both resolution and ensembles. Essentially, high resolution is very useful for process studies and cases where researchers are quantifying a small number of storylines. Large ensembles are useful for characterizing uncertainty. However, different types of ensembles capture different phenomena; the largest source of uncertainty varies across variable, region, and time; and different sized ensembles are needed to capture different characteristics of the system of interest.

One key message that emerged from the breakout discussions was that researchers did not think they could choose between high resolution[5] or ensembles, but instead that both were required. This was particularly true when focusing on coastal regions where resolution is likely to improve model performance but uncertainties are significant. Given this need, the discussion focused on challenges and potential methods/solutions to address those challenges. The main challenges identified were 1) the large number of uncertainties, including some that are not frequently examined; 2) computational resources; 3) people's time to analyze outputs; and 4) data availability and data wrangling.

A few potential solutions were discussed. First, several participants thought that defining the minimum resolution required to capture processes would be important. Uncertainty characterization could start from that minimum resolution. However, the minimum resolution will depend on the system being modeled and the question asked. There are ongoing efforts to compare models of different resolutions and some rules of thumb on resolution, but there is not a complete taxonomy on minimum resolution by system, model, and science question.

Given the number of uncertainties and the computational expense of modeling the coupled system, brute force methods to quantify uncertainty are likely to be problematic. Other methods, such as Latin Hypercube sampling and machine learning, were discussed instead. Modular modeling, where a component could be isolated from the coupled system, was raised as a potential solution. In this way, scientists can reduce the computational expense of the model without sacrificing resolution. However, not all models are designed to facilitate this effort. Participants also discussed the value of hybrid approaches, where large ensembles of lower resolution simulations are combined with high resolution in a small number of simulations.

6.2.4 Testing and Evaluation

In the two breakout sessions on this topic, a number of key challenges were identified:

- Does a small change actually fundamentally change your inferences?
- How do we take all uncertainties and combine them into our forward-thinking end goal?
- How do we map hazards to what is actually causing the variability?
- How do we decompose uncertainty into internal variability, model structure, and scenario uncertainty?
- How do perspective and field matter in terms of model evaluation?

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[5] Resolution for purposes of this discussion includes spatial, temporal, and process resolution, though not all models have high-resolution capabilities in all areas.

- Do users find that a model is credible if the uncertainty is communicated openly and effectively?
- What metrics (beyond historical observations) would be best to use in assessing model accuracy?
- Is human-side model validation particularly challenging because of the dynamics of variability, including system shocks?
- Should the emphasis now be on near-term needs/actions to provide future optionality?
- How can we identify key drivers of near-term sensitivities?
- How can we inform decision-making under deep uncertainty?
- What hypotheses can we access given our initial model(s)? and
- Do we have the scale or inputs required to use our model(s) to address the key challenges?

These challenges lead to the following major research questions:

- How do we establish theoretical coherence and consistency from short timescale operations to long timescale projections in our model testing and evaluations? This includes the need to avoid conflating predictions vs. projections.
- Are we systematically under-representing the internal variability critical path-dependent dynamics, and the potentially compounding nature of statistical extreme states? If so, how can we collaboratively address this as a community?
- How do we develop the capacity to train C-IHTM modelers in model testing and evaluation at a rate commensurate with the rate of growth for the complexity of our modeling frameworks? This includes the challenge of broadening and exchanging different disciplinary perspectives.
- How well are we capturing the dynamic and adaptive human systems responses that dominate real-world coastal systems? How should we test and evaluate this in our modeling frameworks?

These challenges and research questions led to the identification of a set of recommendations for moving forward, outlined in the next section.

6.3 Opportunities and Potential Paths Forward

Several concrete next steps emerged from the breakout discussions and the synthesis discussion.

In the breakout on water quality, several concrete actions emerged from the session as potential follow-up activities that the community can undertake in the next 1-3 years:

- First, an open webinar series (e.g., one a month or once in a few months) that convenes federal agencies, the MSD modeling community, and a broader set of CoPs to exchange information on existing tool, data and modeling development, ongoing activities, and information needs and gaps to inform water quality management decisions.

- Second, the idea of use cases, such as those that center around a region (e.g., the Mississippi River/Gulf of Mexico) gained real traction among attendees. The use cases are seen to be a rallying point to address the various topics discussed throughout the workshop, such as modeling frameworks; model linkages; data interoperability; data and model standards; open science; socioeconomic, population and land use scenarios; and decision contexts. Regional use cases can also help harness work from multiple agencies and research institutes (e.g., EPA, USGS, MIT in the Mississippi River/Gulf of Mexico). A related idea, a model intercomparison exercise, can also be facilitated in the context of regional use cases to understand differences in methodologies, assumptions, and human decisions.

In the breakout on coastal retreat, participants emphasized the need for enhanced connections and opportunities for multi-disciplinary projects supported through the many CoPs relevant for coastal modeling and considered in the session of this workshop series focused on them.

In the breakout on high resolution and large ensembles, a few ideas emerged for near-term efforts:

- Continue to participate in workshops like the C-IHTM and the MSD Working Groups, which provide lots of information on efforts within the research community;
- Develop an inventory, including active areas of research, resolution requirements for processes/questions, and methods for sensitivity analysis;
- Organize a workshop on how each group is approaching the question of ensembles and resolution;
- Identify important parameters and sensitivity to those parameters in our own models; and
- Conduct model intercomparison focused on parameters and uncertainties, which are useful for evaluating models, particularly when data is limited.

The breakout session on testing and evaluation identified the following set of ideas for moving forward:

- Bridge academic and agency experience to develop training capacity to better keep pace with growing model complexity;
- Use CoPs to help map the state-of-the-art and state-of-practice in key coastal systems;
- Employ new tools such as machine learning and reinforcement learning that can be used multiple ways (reduce computational constraints, better capture dynamic and adaptive nature of systems, etc.);
- Accelerate communication and collaborations across diverse disciplinary and agency perspectives;
- Bring insights and perspectives into MSD research from the literature on decision making under deep uncertainty;

- Focus on use case(s) to put exploratory modeling and uncertainty decompositions/mappings into action;
- Broaden our capability to account for a more diverse set of metrics; and
- Bring together different agencies to discuss ways forward (different stakeholders require different outputs).

APPENDIX A – USE CASES

Table A.1 *Suggested use cases from breakout sessions.* ***Use cases highlighted in blue are those that garnered the most interest during breakout sessions.***

Category	Use Case Proposal	Topics/Dynamics	Geography
Landscape Evolution	Integrated coastal landscape evolution	Coastal and inland dynamics; water and energy issues; drivers of tipping points	Mississippi/Gulf Coast; Mid-Atlantic/ Delaware River/ Chesapeake Bay; San Francisco Bay; Alaska; compare/contrast different regions
	Coastal areas	Modeling complex systems: sea level rise, storm surge, flooding, population dynamics, multisector dynamics, demand for energy, water, land, coastal population vulnerability	Any coastal area
	Mississippi/Gulf Coast	Landscape evolution/regional development patterns (population, economy, energy transition, land use/land cover change) and teleconnections; water quantity (flood, drought); water quality (agricultural runoff, hypoxia); resource management (land, water, energy, fisheries, ecosystems); adaptation; resilience; compound events (flooding; storm surge; sea level rise; drought). Bring together, e.g., MIT, USGS, EPA, PSU, ICoM	Mississippi/Gulf Coast

	Mississippi/Gulf Coast	Climate change; flooding; land use; water use; demographics	Mississippi/Gulf Coast
	Sacramento-San Joaquin-SF-Bay Delta	Regional teleconnections; compound events (sea level rise; saline intrusion); water transfers; resource management (water, land, fisheries); resilience; urban development	Sacramento-San Joaquin-SF-Bay Delta
	Heat waves, urban areas and public health	Complex, interacting social and environmental (climate change, extreme heat, high humidity) stressors; human health; equity; mid-large cities (ICLUS/BenMap/TARGET)	Any urban area
	Coastal areas/ hurricanes	Coastal communities; development; nature-based solutions; human responses	Any coastal area
	Developing countries	Vulnerability of human and natural systems; sea level rise; climate change/extreme events; land use change; interaction of social and natural systems; behavioral change	Any developing country
	Eastern U.S. wildfires	Population changes; fuel availability; precipitation changes; land use change; hydrologic change; vulnerability of eastern U.S, to fires (risk changes)	East Coast

	Western U.S. water shortages	Competing water demands (urban, agriculture, power system); compound events (drought, wildfires); human system dynamics (development, housing, water rights, policy responses/risk management); human responses and adaptation to risk; equity	West Coast
Climate Change and Compound Extreme Events	Coupled impacts of inland (river) and coastal (storm surge) flooding	Compound events (hurricanes/storm surge; inland flooding)	Gulf Coast; Atlantic Coast
	Compound flooding in lowland coastal zones	Compound events; resilience; adaptation (infrastructure); meteorological, coastal, and watershed models	Miami-Dade County
	Groundwater-related subsidence and saltwater intrusion	Resource management (groundwater); compound event (sea level rise; saline intrusion); water demand	Delaware Bay
	Interaction of sea level rise and drought in the watershed with reservoir management, on where the salt front is in the Delaware River	Compound events (sea level rise; drought; saline intrusion); resource management (reservoirs)	Delaware River
	Climate and Irrigation	Climate; land use	Any area
	Elkhorn Slough, National Estuarine Research Reserve, Coastal California	Compound extreme events (fire, drought, saltwater intrusion, SLR, subsidence); novel ecosystem, data rich	California coast

	Forests and fire	Modeling dynamics within forests (e.g., species change); fire; economic and aesthetic impacts	Any forested area
Climate Change and Compound Extreme Events	Coastal protection decisions	Adaptation (infrastructure); compound events (hurricanes and storm surge; sea level rise; inland flooding; subsidence); economics; population dynamics	Gulf Coast
	Investment decision analysis for the port of Los Angeles	Decision analysis; compound events (sea level rise; storm surge); economics	Los Angeles
	Climate amenities and migration	Linking models (e.g. ICLUS, IM3, PCHES; migration; climate amenities)	Any coastal area
	Managed/Unmanaged Retreat	Climate adaptation; modeling; land use/land cover change; socioeconomics and broader environmental and social equity; population dynamics; coastal development; coastal hazards (sea level rise, storm surge)	Coastal regions, but specific lessons learned from New York City/New Jersey, New Orleans
	Great Lakes water level forecasting and management	Resource management; forecasting (seasonal to interannual)	Great Lakes
Land Use and Water Quality	Impacts of agricultural conservation practices on nutrient loading	Resource management (agriculture); agricultural runoff and hypoxia; land use/land cover change	Mississippi River Basin; Chesapeake Bay

	Hypoxic zone	Resource management (agriculture, fisheries); agricultural runoff and hypoxia	Gulf of Mexico
	Estuary water temperature	Resource management (estuaries); ecology; recreation; energy; water pollution; acidification; local weather	Any estuary
	Impacts on fisheries and food	Resource management (fisheries, agriculture); population; economics; temperature; agricultural runoff and hypoxia/nutrient loading	Any coastal area
	Chesapeake Bay	Climate change; land use; restoration investments and policy; data-rich, active stakeholders	Mid-Atlantic region
	Western U.S. water quality and quantity	Resource management (water, forest, agriculture); best practices for agricultural lands; land use change; climate change; hydrologic changes; groundwater pumping; fertilization rates	Western U.S.
	Missouri River Basin	Drought resilience; restoration/ management practices; watersheds; fine scale processes (restoration/management); scale-up results; large-scale hydrology/ water quality models; adaptation at watershed scale	Missouri River Basin

	Ocean acidification and vulnerability of coastal communities with intersection of fisheries impacts in Alaska	Resource management (fisheries); resilience; ocean acidification	Alaska
Energy Transitions	Energy sector interactions with coastal processes	Resilience (energy and coastal systems); urban coastal growth; energy transitions; transmission and distribution systems; water temperature and thermoelectric cooling; agricultural runoff due to bioenergy crops; extreme weather events	Any coastal area
	Biomass co-firing and water quality	Multi-scale effects; energy production; land use; water quality; changing policies	Midwest
	Reducing energy use intensity by 30% by 2030	Population dynamics; land use; energy consumption; climate; urban heat island; building construction materials/processes	DOE's Building Technologies Office
	Climate change impacts on power infrastructure of the Northeast U.S.	Multi-scale effects and boundary conditions; extreme weather events; decreased reliance on natural gas; increase reliance on renewables	Northeast
Model Inter-comparisons	Compare/contrast using different tools/models for a use case in a single area to understand differences in methodologies,	Methods; interoperability experiments	Any area

	assumptions, decisions, etc.		
	Model intercomparison of population and urban extent projection approaches or land use/land cover change in general	Methods; landscape evolution (population, urban growth, land use/land cover change)	Any area
	Land use/land cover change scenarios	Modeling (e.g. GCAM-Demeter, IM3 and SELECT); global trade; land use dynamics; urban extent; scale-flexible methodology	Any area
	Stream flow forecast model intercomparison project	Modeling	Any area
National Capabilities	National capabilities	Stream flow/flooding model; human migration model; water management model; open-source power system models (renewables vs gas); open-source transportation models	National/CONUS

APPENDIX B – WORKSHOP AGENDA

Session 1 Agenda (November 2, 2020)

12:30	**Opening/Welcome/Context**	
12:35	**Overview from other USGCRP Coastal Workstreams**	Inundation – Mark Osler (NOAA) (2-3 minutes) Science & Decision-Making – Lisa Clough (NSF) (2-3 minutes)
12:40	**Perspectives from the Co-Chairs**	Bob Vallario (DOE), Jeff Arnold (USACE), John Weyant (Stanford)
12:50	**Presentation - 2019 IHTM Workshop: Background and Foundations**	Tim Scheibe (PNNL)
1:00	**Session Introduction and Summary**	David Lesmes
1:10	**Facilitating reproducibility and extensibility across the research lifecycle**	How and why to make your work reproducible and extensible – Casey Burleyson (15 min) Reproducible and extensible benchmarking and model evaluation – Chris Massey (15 min)
1:40	**Model interoperability and coupling**	How and why to make your model interoperable – Chris Vernon (15 min) The evolution of granularity in model coupling and interoperability Ethan Coon (15 min)
2:10	**Charge questions for the breakout sessions and open Q&A**	Casey Burleyson (facilitates) – (20 min)
2:30	**Break (10 min)**	

2:40	**Four self-selected breakout groups based on topics above**	Casey Burleyson, Chris Massey, Chris Vernon, and Ethan Coon (facilitate) – (70 min) **BREAKOUT 1:** How and why to make your work reproducible and extensible. (Casey Burleyson) **BREAKOUT 2:** Reproducible and extensible benchmarking and model evaluation. (Chris Massey) **BREAKOUT 3:** How and why to make your model interoperable. (Chris Vernon) **BREAKOUT 4:** The evolution of granularity in model coupling and interoperability. (Ethan Coon)
3:50 – 4:00	**Break (10 min) (Breakout groups prepare for report outs)**	
4:00 – 4:40	**Breakout group reports and Q&As**	All (David Lesmes facilitates) – (40 min)
4:40 – 5:00	**Open Discussion and Meeting Adjourn**	All (David Lesmes facilitates)

Session 2 Agenda (November 9, 2020)

1:00	**Workshop Introduction** **IHTM Report Recap of Use Cases**	Jeff Arnold (USACE) Tim Scheibe (PNNL)
1:10	**Introduce session and speakers**	Susan Julius (EPA)
1:15	**Modeling the Water Quality Effects of Land Use Planning and Land Conservation in the Chesapeake Bay Watershed**	Peter Claggett (USGS)

1:30	**Simulating Locally-relevant Development Patterns Consistent with Global Climate Change Scenarios: loose coupling of ICLUS and UrbanSim**	Phil Morefield (EPA)
1:45	**Integrated Coastal Modeling (ICoM) Experiment**	Dave Judi (PNNL)
2:00	**An Integrated Framework for Modeling Multi-System Dynamics: The Mississippi River Basin**	Jennifer Morris (MIT)
2:15	**Break** (15 min)	
2:30	**Facilitated Breakouts (four in parallel)** (90 minutes)	The questions that each breakout will address are: • What makes a good use case? • Are there good examples out there that we haven't heard much about yet? • What potential new/novel use cases should our community try to take on through multi-agency collaboration over the next 2-4 years?
4:00	**Break (15 min)**	
4:15	**Breakout Group Reports and Q&As** (40 min, 10 minutes for each breakout)	
4:55	**Closing Statements**	
5:00	**Adjourn**	

Session 3 Agenda (November 16, 2020)

1:00	**Workshop Introduction** **IHTM Report Recap and Linking Communities of Practice**	John Weyant (Stanford University) Efi Foufoula-Georgiou (UC Irvine)

1:10	**Introduce Session and Speakers**	Karen Fisher-Vanden (PSU)
1:15	**Modeling Frameworks for Atmospheric-Ocean-Land Interactions**	Renu Joseph (DOE), Yuan-Qian (PNNL), Paul Ullrich (UCD), Joel Rowland (LANL)
1:30	**Modeling Frameworks in Land Surface Hydrology**	Christa Peters-Lidard (NASA), David Lawrence (NCAR), Sujay Kumar (NASA), Mark Wahl (USACE), Lisa Lucas (USGS)
1:45	**Modeling Frameworks in Multisector Dynamics**	Mohamad Hejazi (PNNL), Adam Schlosser (MIT), Jennie Rice (PNNL), Karen Fisher-Vanden (PSU)
2:00	**Incorporating Stakeholder and Community Interactions in Modeling Frameworks**	Rob Nicholas (PSU), Casey Helgeson (PSU), Andy Jones (LBNL), Molly Mitchell (VIMS), Klaus Keller (PSU)
2:15	**Q/A** (15 min)	
2:30	**Break** (15 min)	
2:45	**Facilitated Breakouts (four in parallel)** (75 minutes)	**BREAKOUT 1:** Modeling Frameworks for Atmospheric-Ocean-Land Interactions Lead: Renu Joseph (DOE) Notetaker: Sanjib Sharma (PSU) **BREAKOUT 2:** Modeling Frameworks in Land Surface Hydrology Lead: Christa Peters-Lidard (NASA) Notetaker: Shan Zuidema (UNH) **BREAKOUT 3:** Modeling Frameworks in Multisector Dynamics Lead: Mohamad Hejazi (PNNL) Notetaker: Ellie Lochner (PNNL) **BREAKOUT 4:** Incorporating Stakeholder and Community Interactions in Modeling Frameworks Lead: Rob Nicholas (PSU) Notetaker: Brian Reed (Stanford)

4:00	**Break (15 min)**
4:15	**Breakout Group Reports and Q&As**
4:55	**Closing Statements**
5:00	**Adjourn**

Session 4 Agenda (November 23, 2020)

1:00	**Workshop Introduction** **IHTM - Recap and Linking Communities of Practice**	Jeff Arnold (USACE) Tim Scheibe (DOE)
1:10	**Welcome, Scope, Definitions**	Jennifer Arrigo (DOE)
1:15	**Using a Community of Practice to Coalesce a Shared Framework for MSD Research**	Richard Moss (PNNL)
1:30	**CUAHSI Tools for Model-Data Integration**	Jerad Bales (CUAHSI)
1:50	**Coastal Coupling Community of Practice: A Multidisciplinary Collaboration**	Cayla Dean (NOAA)
2:10	**Community, Computing, and Education: An Overview of the Community Surface Dynamics Modeling System (CSDMS)**	Greg Tucker (CSDMS)
2:30	**Panel – Connecting Projects to CoPs**	Erwan Monier (UC Davis) Moderator, Klaus Keller (PCHES), David Judi (ICoM), John Reilly (MIT Joint Program)
3:00	**Break** (15 mins)	

3:15	**Parallel Breakouts** **1) Develop a list of collaborative opportunities engaging CoPs that will support shared research on coastal modeling** **2) For one (or more) of these, identify early potential wins and where and how can we leverage and enhance connections across CoPs?**
4:00	**Break** (15 mins)
4:15	**Panel Brief-Out**
4:40	**Group Discussion**
4:55	**Concluding Remarks**
5:00	**Meeting Adjourned**

Session Agenda 5 (November 30, 2020)

1:00	**Overall C-IHTM Workshop Themes and Progress**
1:10	**Objectives and Structure of this Synthesis Session**
1:25	**Breakout Groups: Round 1** Water Quality High Resolution or Large Ensembles Coastal Retreat Testing and Evaluation
2:10	**Break**
2:20	**Round 1 Breakout Group Reports to Plenary with Discussion**

3:00	**Breakout Groups: Round 2** Water Quality High Resolution or Large Ensembles Coastal Retreat Testing and Evaluation
3:45	**Break**
3:55	**Round 2 Breakout Group Reports to Plenary with Discussion**
4:35	**Workshop Path Forward with Discussion**
5:00	**Meeting Adjourned**

APPENDIX C – WORKSHOP PARTICIPANTS

Federal Agencies

U.S. Department of Energy

Jennifer Arrigo
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