MultiSector Dynamics:

Science Challenges and a Research Vision for 2030

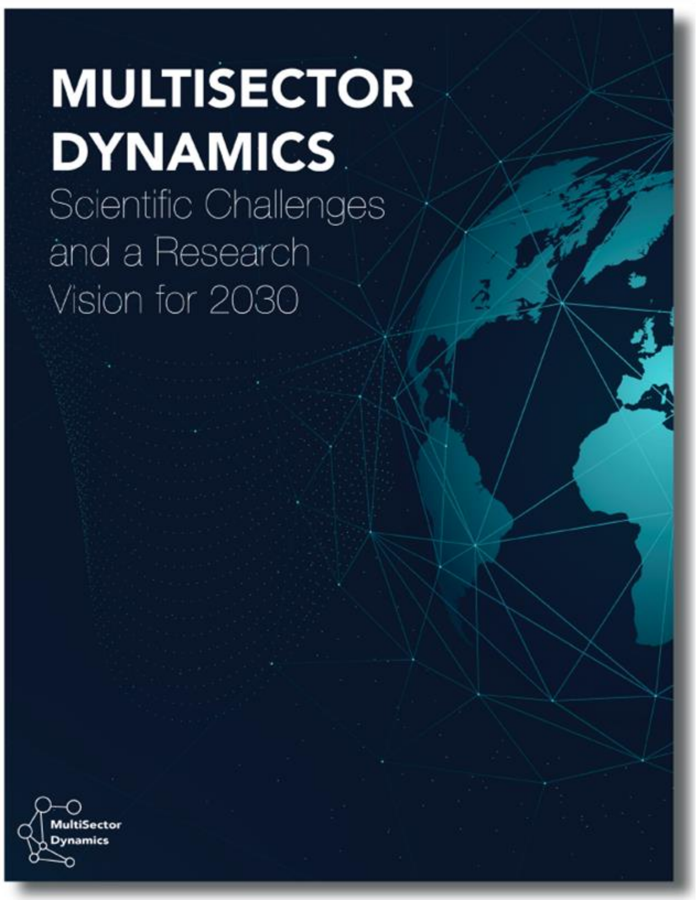
MSD Science Steering Group and Facilitation Team

April 22, 2022
Spring BERAC Briefing

We acknowledge the support of the U.S. Department of Energy, Office of Science, Earth and Environmental Systems Sciences Division, MultiSector Dynamics Program.

Modeling MultiSector Dynamics

The MSD Vision Report in Brief



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Released January 2022

https://multisectordynamics.org/vision/

with MSD CoP Building Activities Ongoing

www.multisectordynamics.org

Twitter: @multi_sector

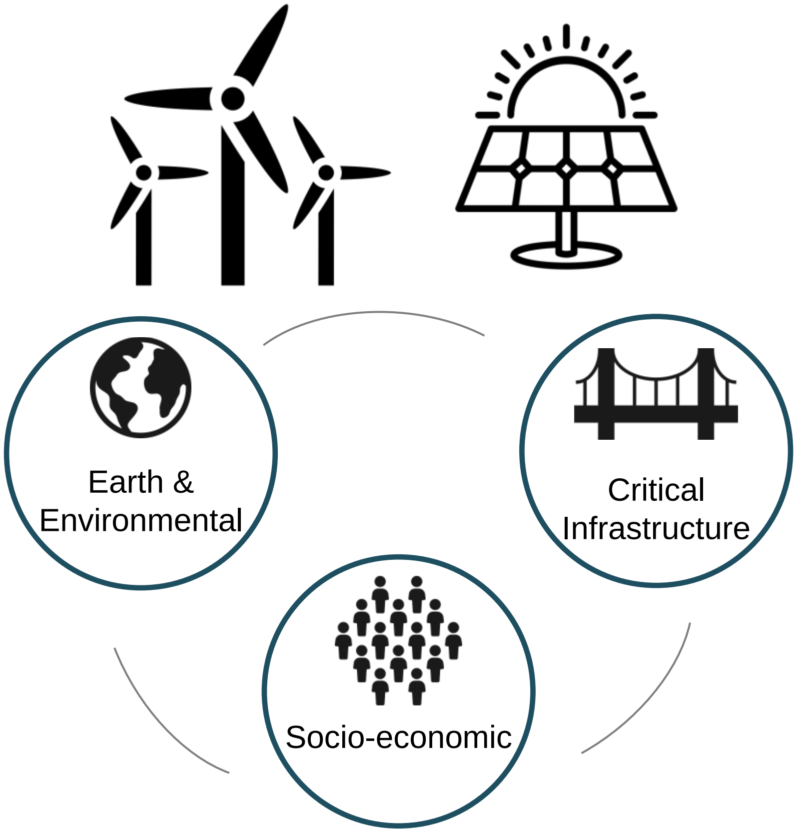
Chapter 1.

Introduction: Critical Pathways of Societal Change

Managing Risks and Transitions in Complex Systems

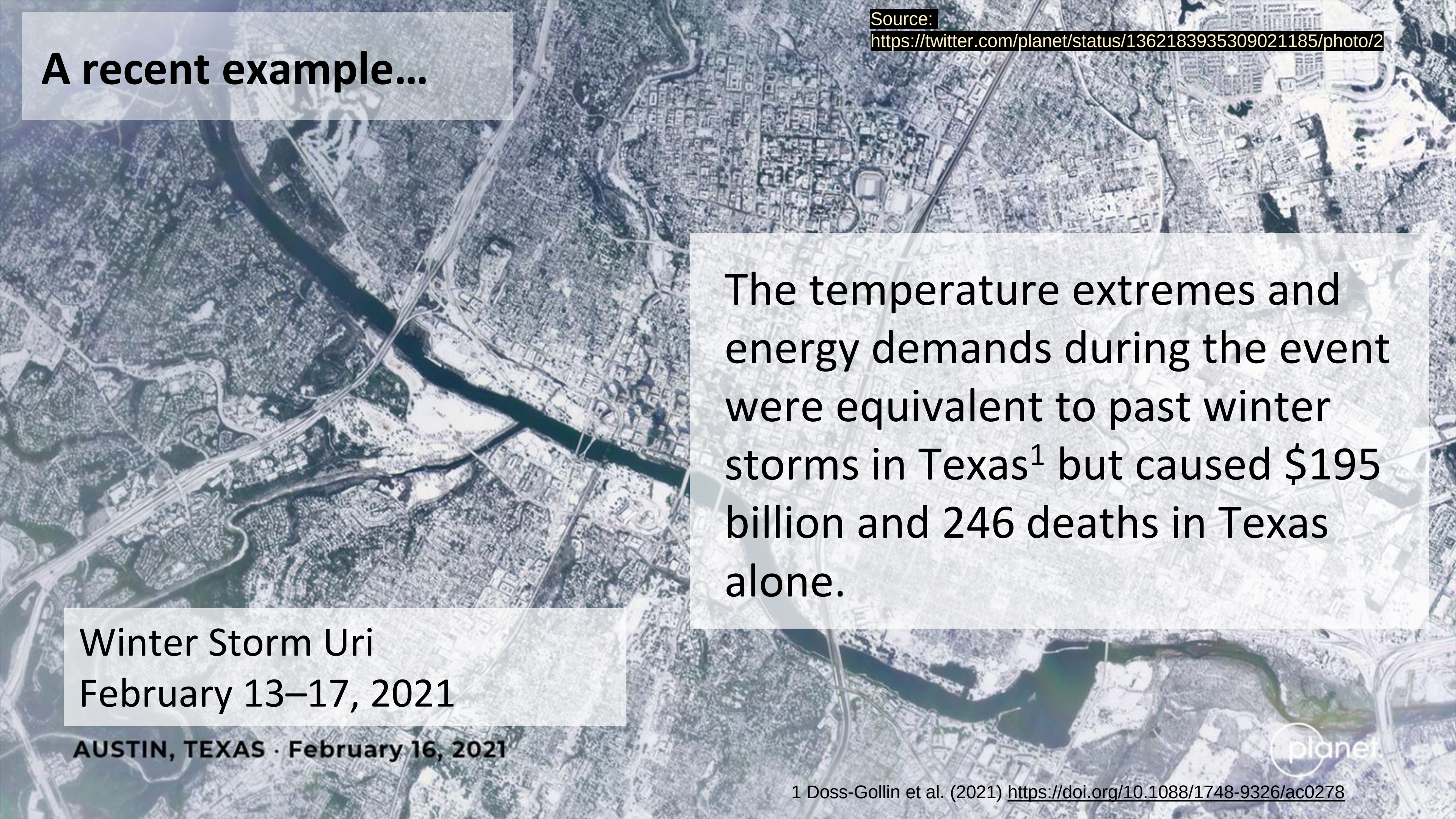
The next decade represents a tremendous opportunity to **address climate, energy, and interrelated sustainability challenges**

Navigating these **transitions** will require a better understanding of the **interdependence** of **Earth and environmental systems** with critical **infrastructure** and **socio-economic systems.**



Source:
https://twitter.com/planet/status/1362183935309021185/photo/2

A recent example…



The temperature extremes and energy demands during the event were equivalent to past winter storms in Texas[1] but caused $195 billion and 246 deaths in Texas alone.

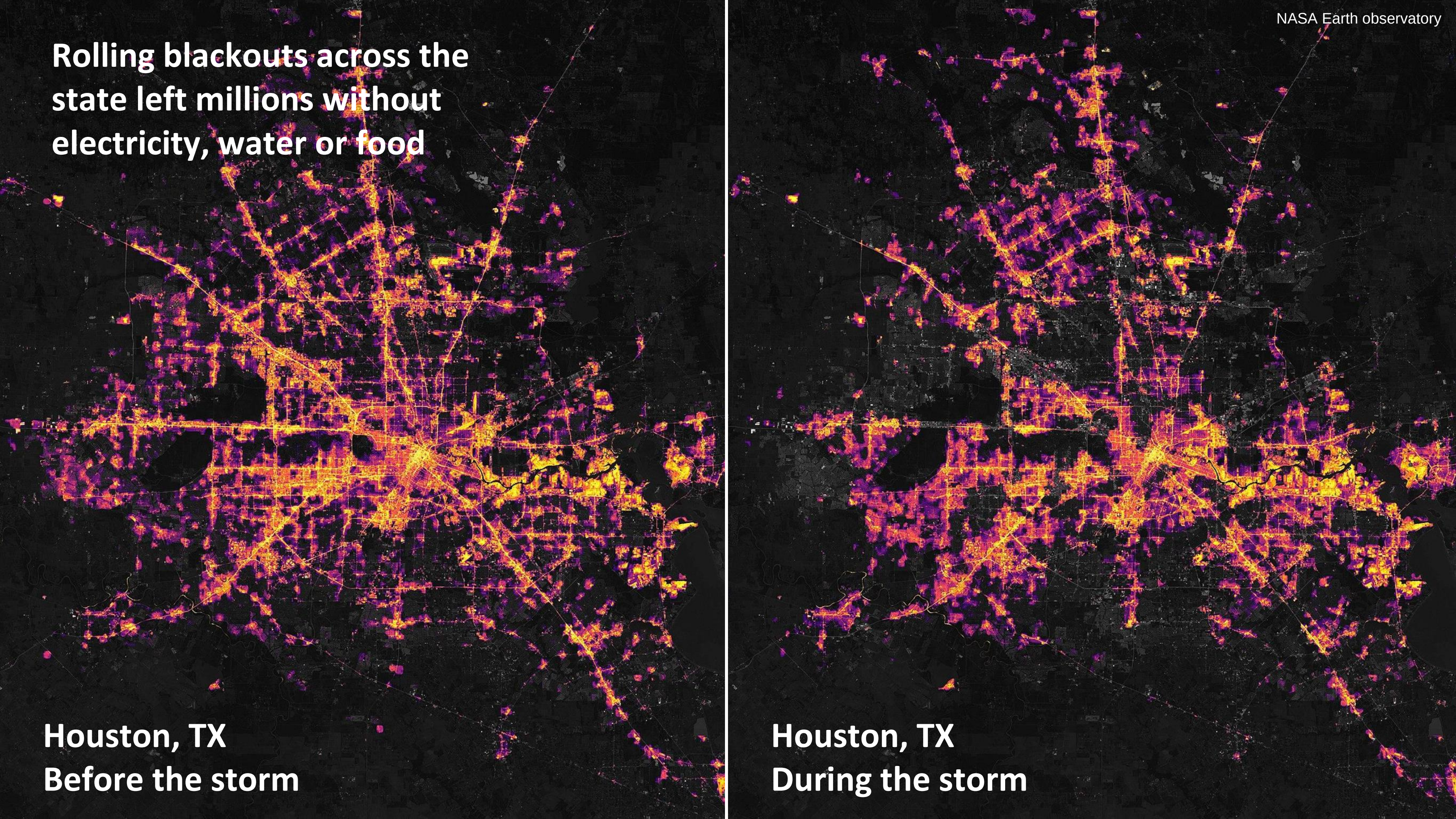
Winter Storm Uri
February 13–17, 2021

1 Doss-Gollin et al. (2021) https://doi.org/10.1088/1748-9326/ac0278

Sergio Flores for The Texas Tribune

Besides the environmental hazard, these impacts were due to several institutional, infrastructural and socio-economic reasons:

- Texas operates on an isolated power grid
- Power generation systems were not sufficiently weatherized
- Insufficient planning for high demands


Rolling blackouts across the state left millions without electricity, water or food
Houston, TX
Before the storm
NASA Earth observatory
Houston, TX
During the storm

Human response:

- Increased energy demands
- Buying additional fuel and generators
- Storing food and water
- Electricity scarcity pricing

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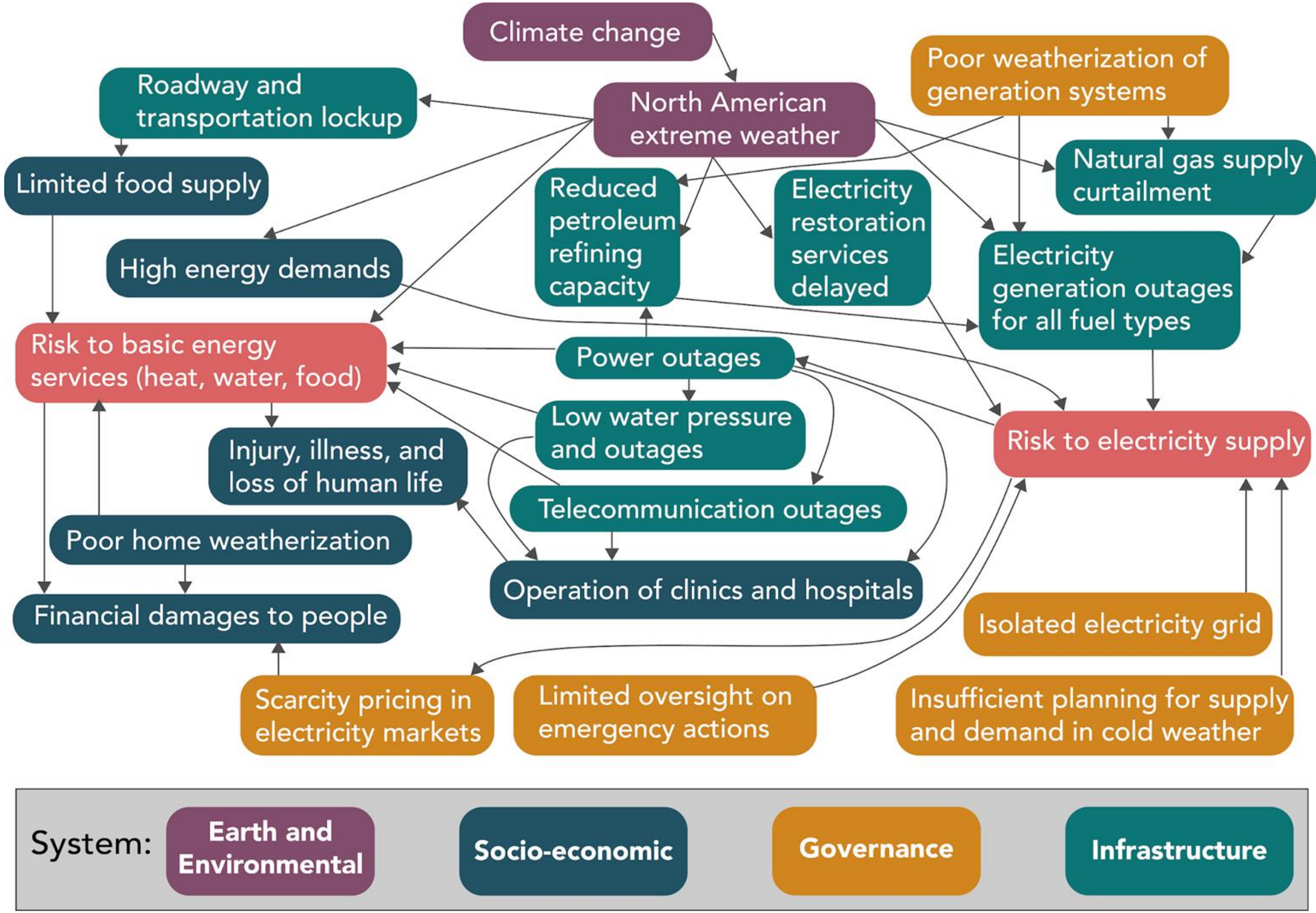
Propane tanks are placed in a line as people wait for the power to turn on to fill their tanks in Houston. (Mark Felix for The Washington Post)

Risk emerged as a result of many **dynamic processes** and actions across many **systems** and across different **scales**



Reed et al. MultiSector Dynamics: Advancing the Science of Complex Adaptive Human-Earth Systems. Earth's Future (2022)

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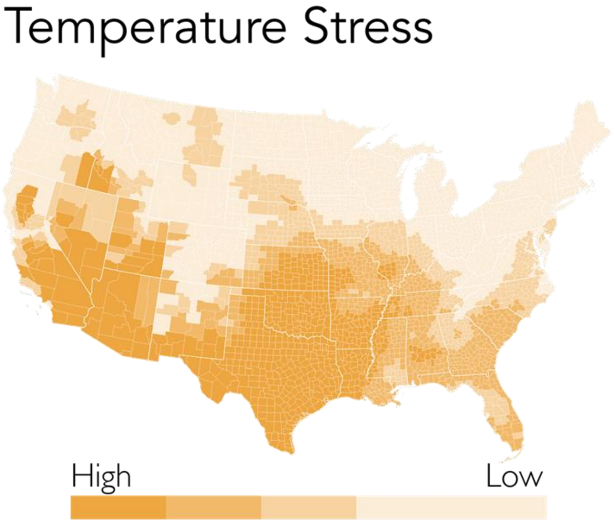
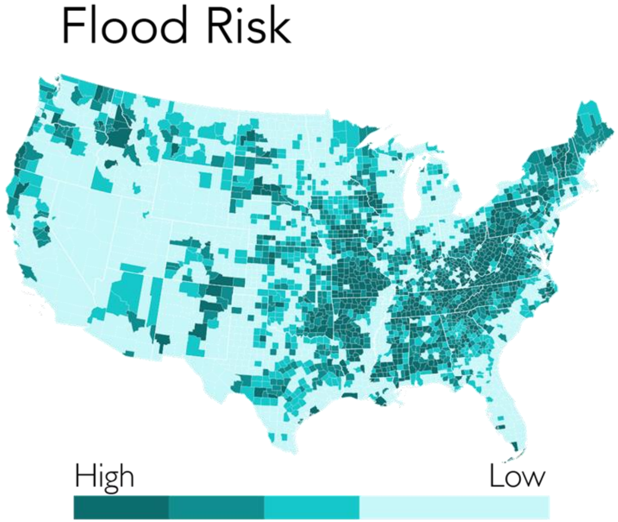
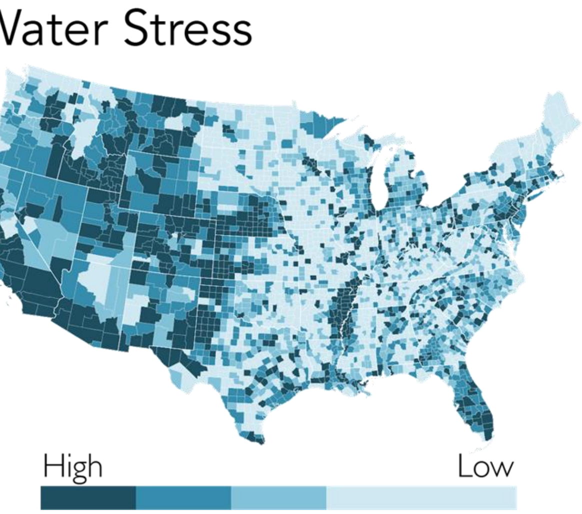
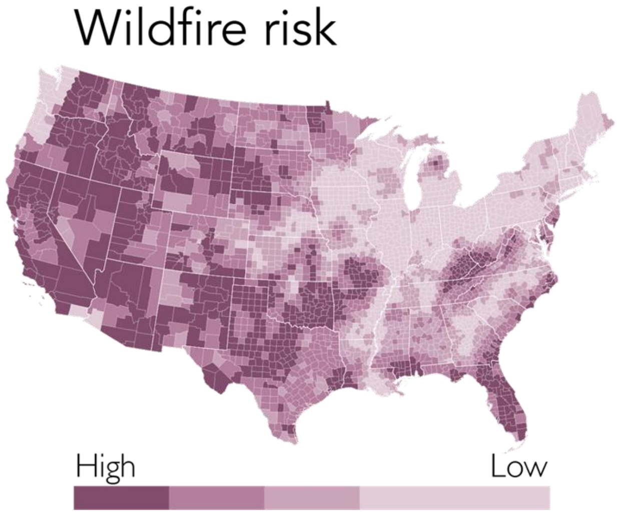
Winter storms are only one type of hazard potentially facing a region









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Created using data from the MIT Socio-Environmental Systems Risk Triage visualization platform at https://est.mit.edu

Globally, we are facing interconnected, multisectoral risks.

A group of refugees and migrants walk towards the border of Greece and North Macedonia. Credit: UNHCR

The MSD Vision Report highlights promising frameworks to help us understand these interactions.

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Feedbacks and interdependencies shape risks

Dynamic relationships between agents, systems and sectors transmit risk from one to another

Interacting drivers amplify (or buffer) existing threats

Need for **fundamental innovations** in risk assessment that account for effects of human responses

→ Unidirectional
↔ Bidirectional
\+ Amplifying
\- Buffering
\- - - - Interactions between determinants

Figure adapted from Simpson et al. (2021). "A framework for complex climate change risk assessment". In: One Earth 4.4, 1648 pages 489–501. ISSN: 2590-3322.

Need to Capture Compounding or Cascading Risks

Interacting risks can **emerge** across scales, systems, and sectors

Human responses can be strong determinants of risk

Combinations of multiple risks pose challenges for model-based insights

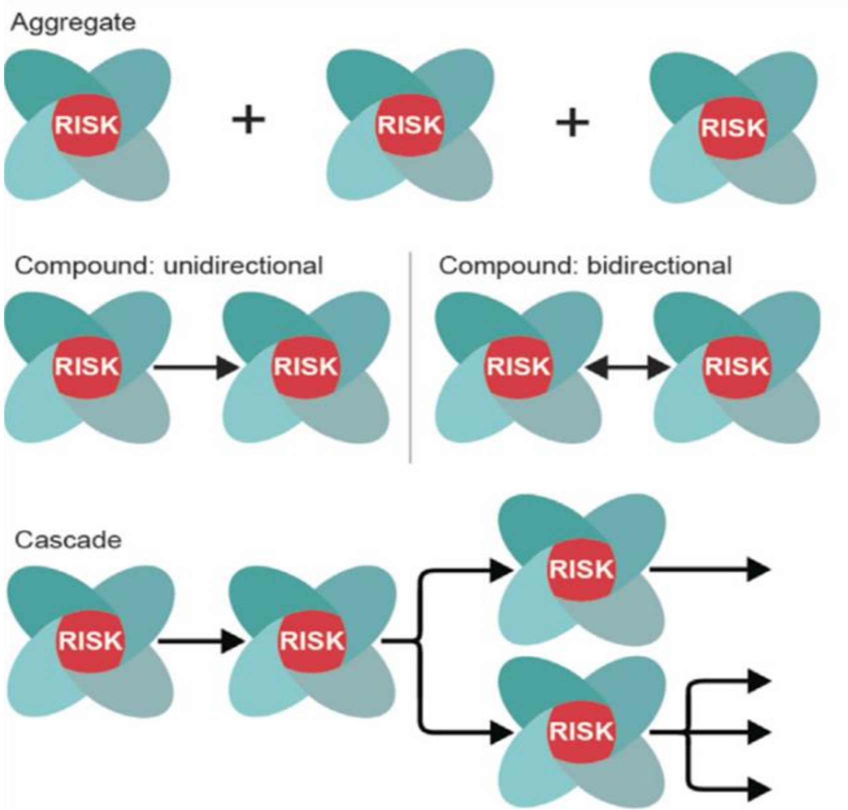

Figure adapted from Simpson et al. (2021). “A framework for complex climate change risk assessment”. In: One Earth 4.4, 1648 pages 489–501. ISSN: 2590-3322.

Chapter 2.

MSD: Definition and Current Research Frontier

What is MSD?

Sector:

" Complex **systems of systems** that deliver services, amenities, and products critical to society. "

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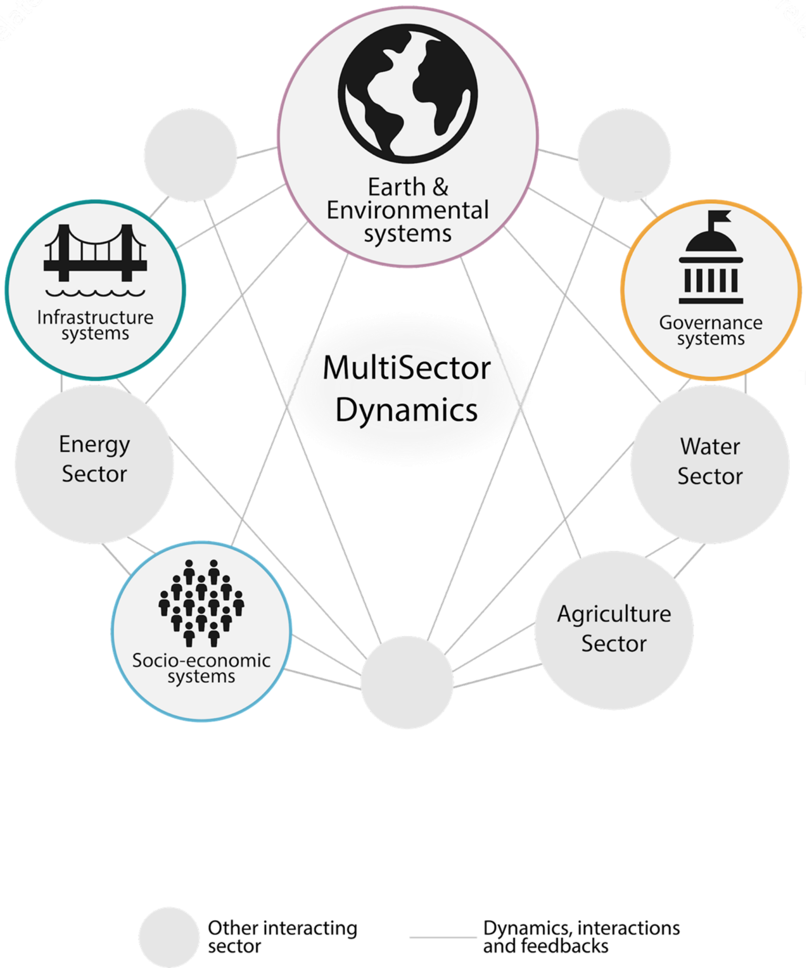
What is MSD?

Dynamics:

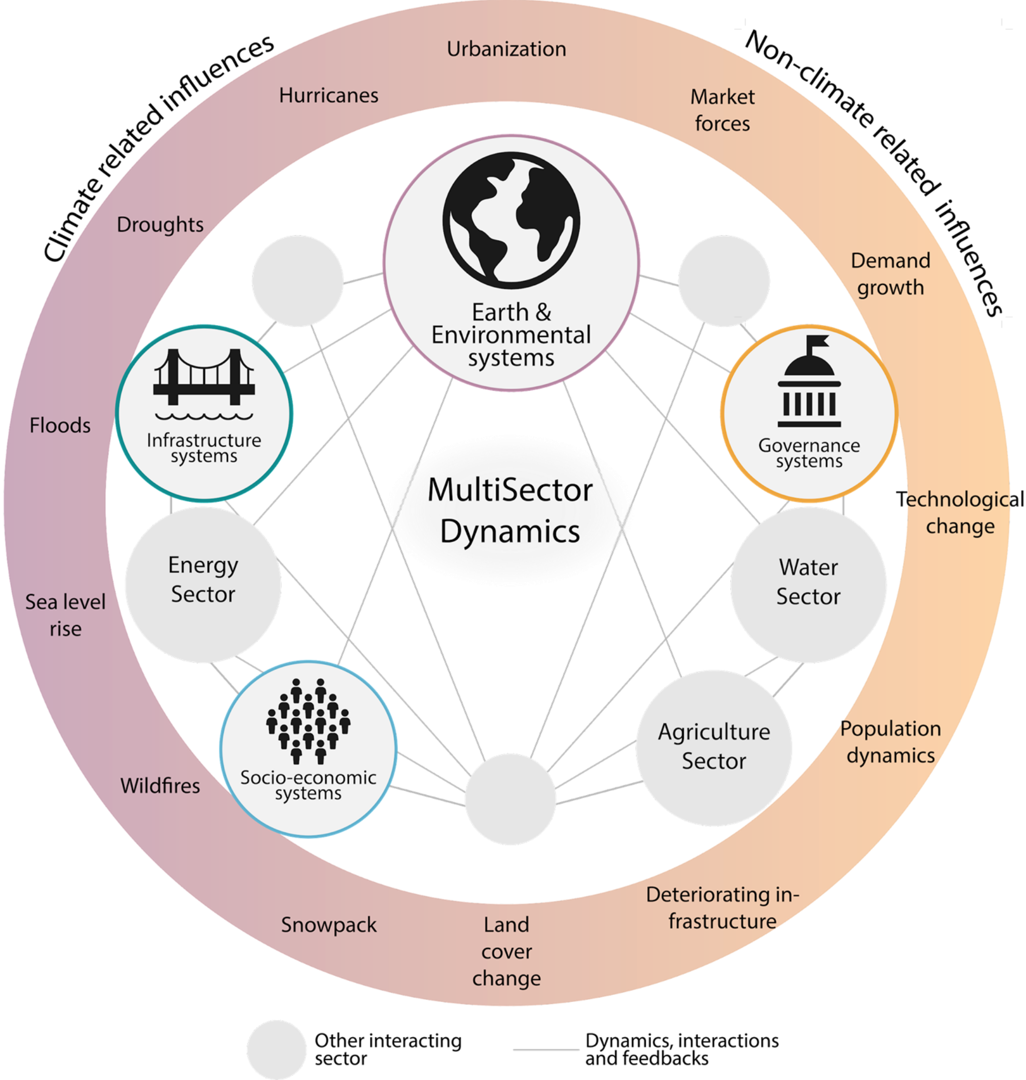
“ **Pathways of change** that result from transitions and shocks. Shaped by their **interdependence-interconnectedness**, irreversible lock-ins, contested perspectives, cross-scale influences and effects, as well as the deep uncertainties that shape their evolution. ”



What is MSD?

The study of how complex built, natural, and socio-economic systems **co-evolve in response to change**.

MSD is a transdisciplinary research area that seeks to advance our understanding of how **human-Earth system feedbacks shape interdependent pathways of societal change across scales and uncertainties**.



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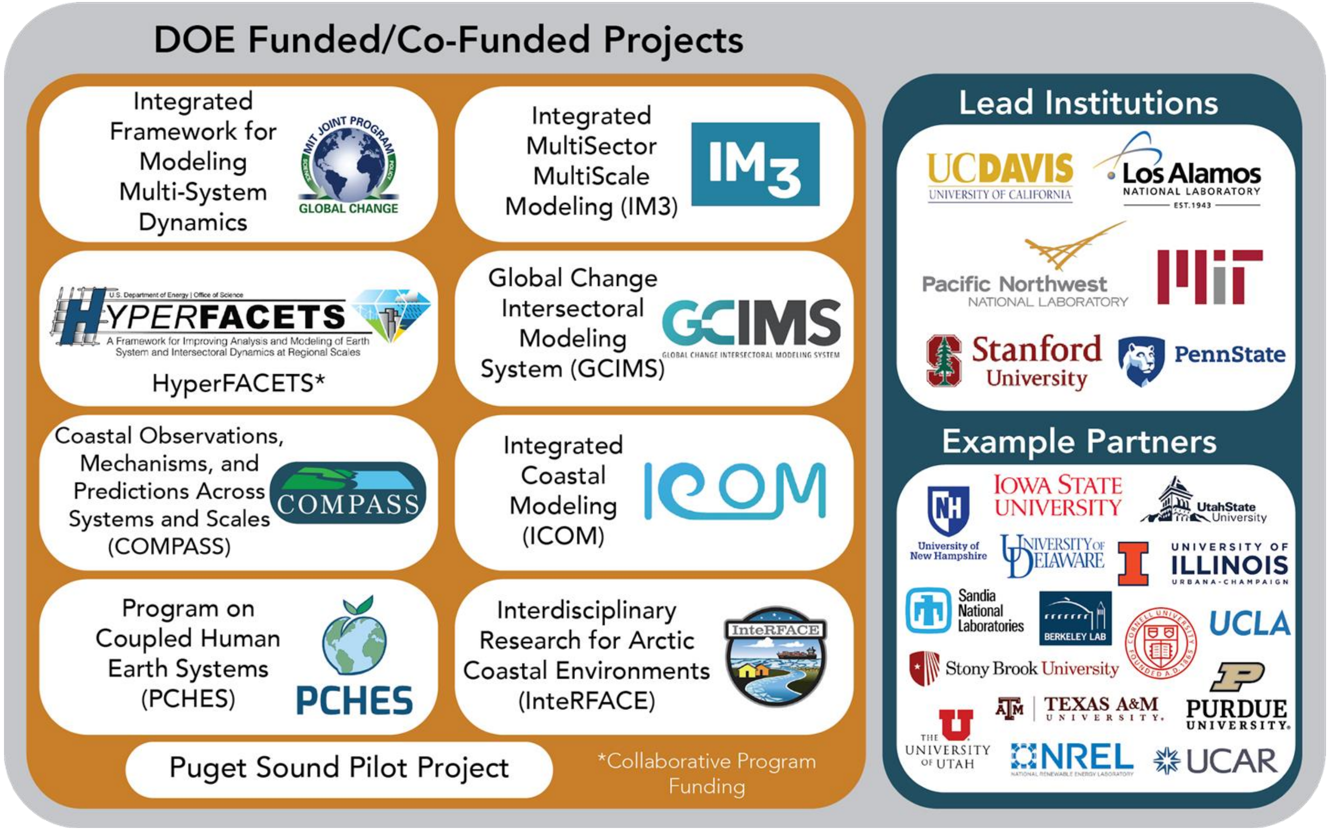
Teaming in an Open Scientific Environment to Confront Complexity



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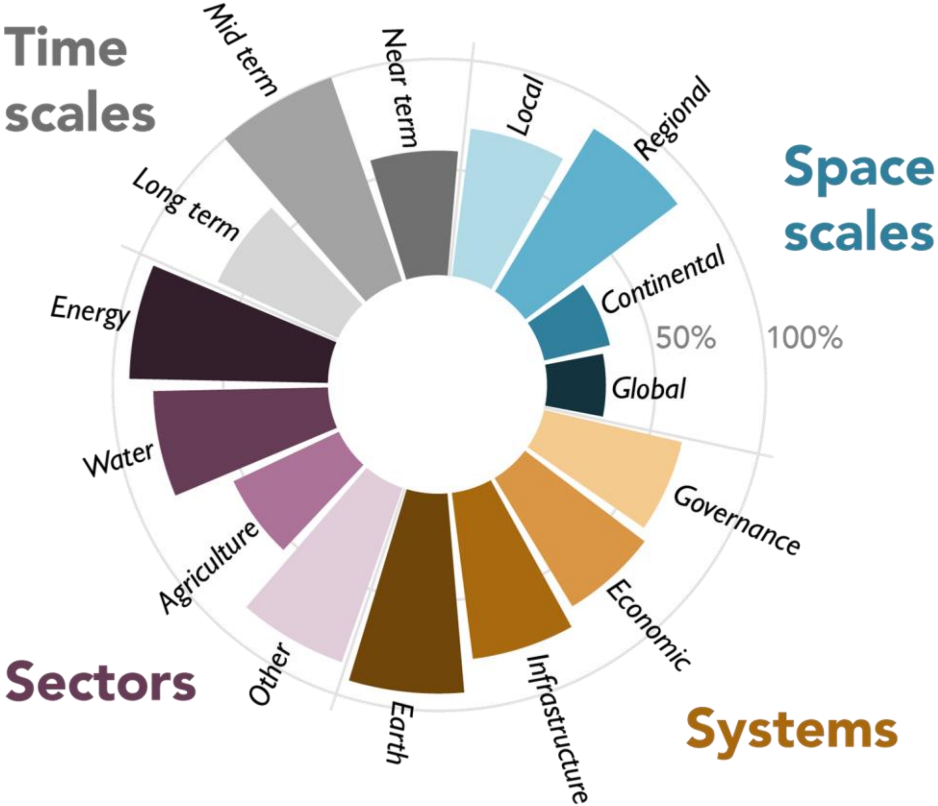
Themes that have emerged across the MSD project portfolio



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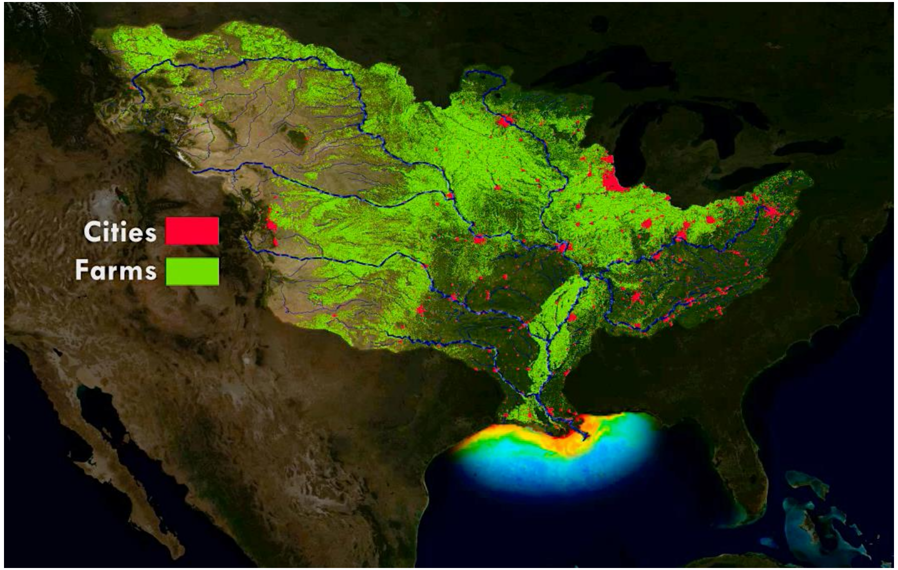
Chapter 3.

MSD 2030: Transforming our Understanding of Human-Earth System Complexity

Example: Competing Objectives and Complexity of Estuaries

Complex estuarine systems have interrelated resource challenges

Competing objectives, **deep uncertainties** and **complex interconnected ecosystems** make management particularly challenging



The Mississippi River Basin

Figure courtesy of NOAA https://oceanservice.noaa.gov

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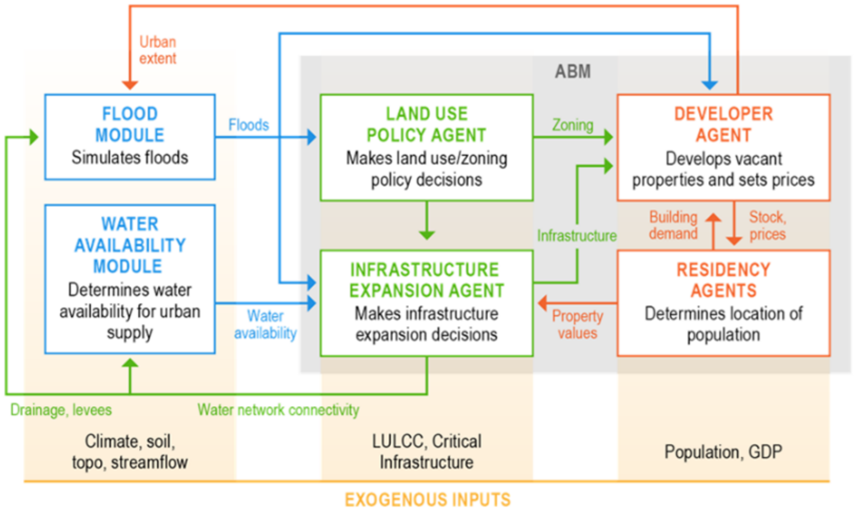
Uncertainty, Adaptivity and the Dynamics of Human Systems

Tools such as **agent-based modeling** provide representations of the **complex interplay** between **human action and adaptation** amid dynamic conditions prone to shocks.



2000–2019 NLCD

Figure courtesy of the ICoM project.

Human-Earth Systems Exploratory Modeling Opportunities

Tebaldi et al., (2021)[7] blend ESMs and **MSD community contributions** for uncertainty quantification and emulation-based analysis of extremes to explore sea level rise risks

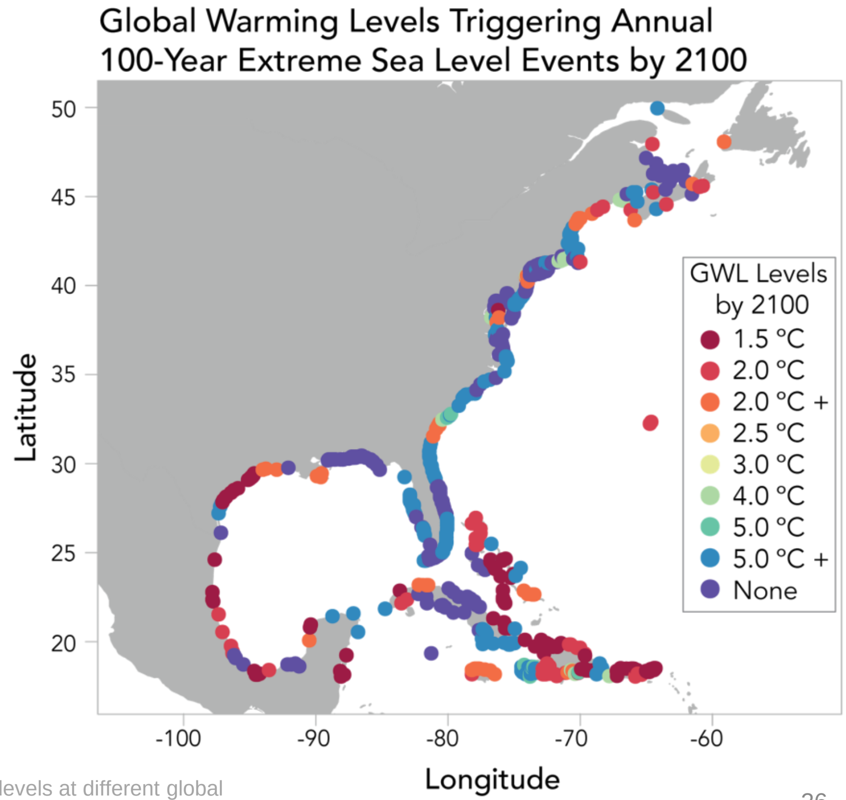


Figure source Tebaldi et al. (2021). Extreme sea levels at different global warming levels. *Nature Climate Change*, 1-6.

These are a few of the report's examples highlighting the value and need for community coordination in strengthening foundational human-Earth systems research capabilities.

The MSD Community of Practice (MSD CoP) represents an effort to accelerate development of needed foundational capabilities.

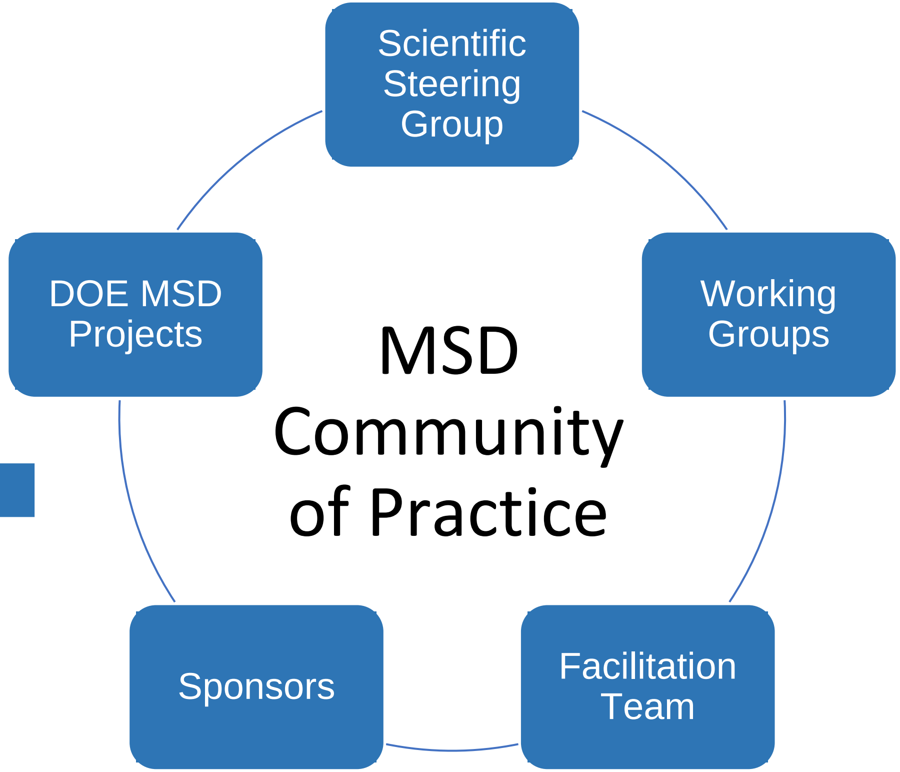
Building the MSD Community of Practice

CoP strategies

Communication
- Website
- Newsletter
- Webinars
- Outreach

Conceptual Framework/SSG
- Vision report
- FT & SSG drafting
- Review process

Technical coordination
- Working groups



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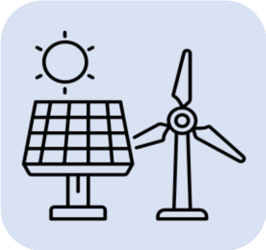
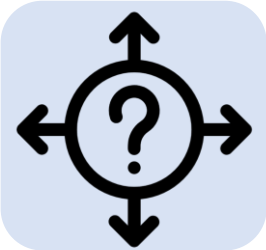
Current MSD Working Groups



MultiSector Impacts of Energy Transitions

Urban Systems

Human System Modeling



Uncertainty Quantification and Scenario Development

Education and Professional Development

Facilitating FAIR Data

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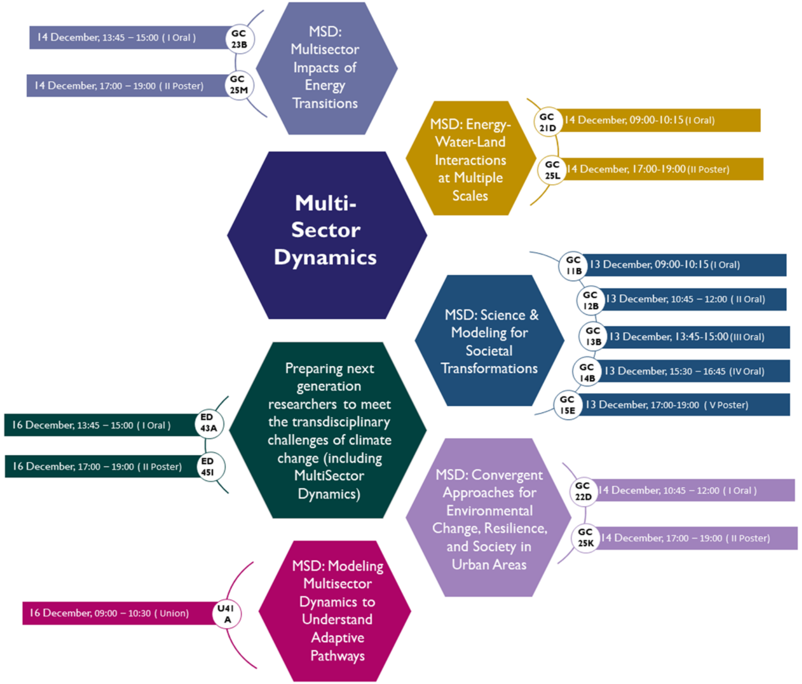
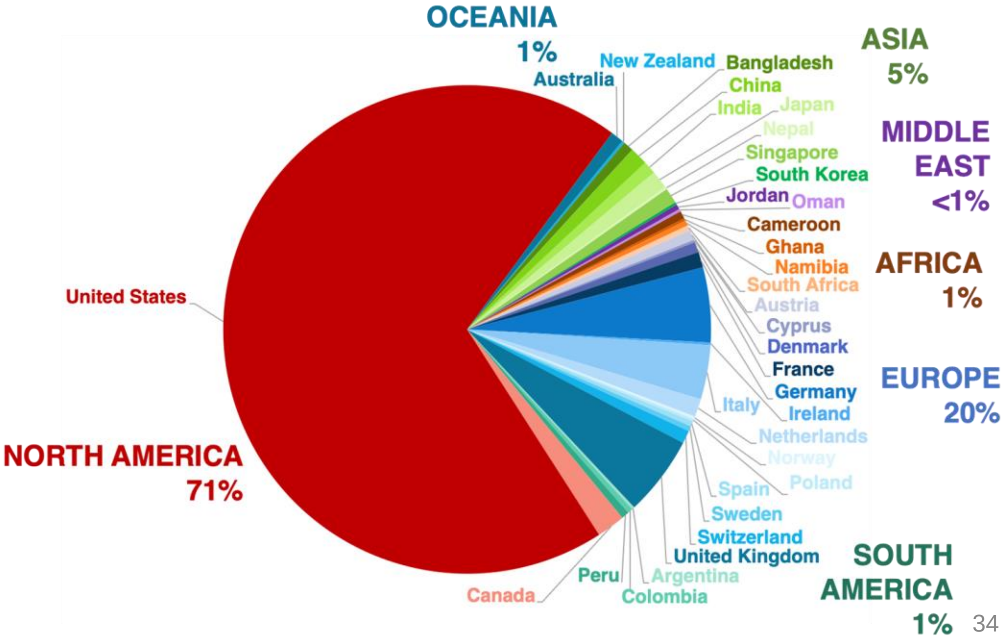
Global Outreach using the 2020 & 2021 AGU Fall Meetings

2021 AGU Fall Meeting

1 DOE Town Hall - 1 MSD Union Session
GEC: 6 MSD oral sessions - 5 MSD poster sessions
EDU: 1 MSD oral session - 1 MSD poster session

127 abstracts
35% of presentations by students
585 authors
From 34 different countries
30% from outside the U.S.





Earth’s Future Special Section

Earth’s Future Special Section

Modeling MultiSector Dynamics to Inform Adaptive Pathways

11 papers out & several in process

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https://agupubs.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)2328-4277.ADTPATH1

Additional CoP Achievements


MultiSector Dynamics
MultiSector Urban Interactions:
Fundamental Science Needs to Inform Pathways to More Resilient Communities in a Changing Climate
Urban Science Workshop - July 21st - 23rd 2021
KEYNOTE PANEL: JULY 21ST 2021 from 10 am – 12 pm (PT)
Anu Ramaswami
Civil Engineering
Princeton University
Luis Bettencourt
Mansueto Institute
University of Chicago
Karen Seto
School of the Environment
Yale University
Paul Waddell
City & Regional Planning
UC Berkeley


Workshop Report:
Multi-Sectoral Urban Interactions: Fundamental Science Needs to Inform Pathways to More Resilient Communities in a Changing Climate
Organized by Christa Brelsford and Andrew Jones
A workshop organized by the MultiSector Dynamics Community of Practice Working Group on Urban Systems
July 21 – July 23, 2021

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Open science is a mechanism to scale and accelerate MSD insights

MSD-LIVE is a **flexible and scalable data and code management system** that is designed to address **community identified challenges** including:

- Finding and managing data
- Training
- Collaborating
- Version control for data and code
- Machine learning
- Handling proprietary data and code

MSD CoP worked with the USGCRP to co-sponsor, co-plan, and co-host virtual workshop series.

“…the challenges of modeling and evaluating coastal landscapes of co-evolving human and natural system”

Addressing extreme weather, sea level rise, human-natural shocks, and climate change.


U.S. Global Change Research Program

Coastal Integrated Hydro-Terrestrial Modeling

A Multi-Agency Invited Workshop

November 2020

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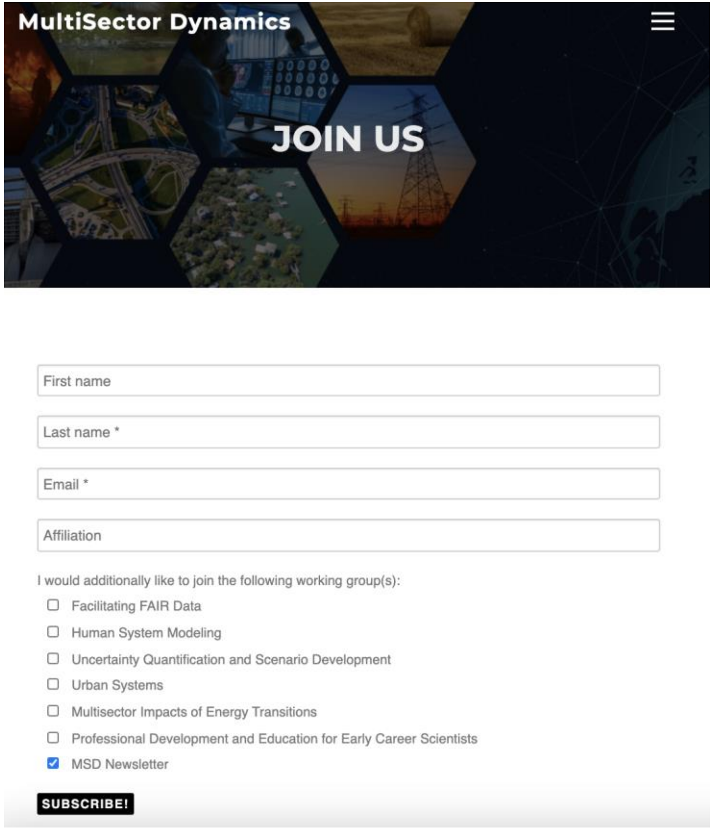
The MSD CoP is now focused on identifying community building opportunities that can leverage our working groups, AGU outreach, and the Vision Report

Thank you

More Information

https://multisectordynamics.org/join-us/



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Supplemental Slides

Why a Community of Practice?

Increasingly interconnected human and natural systems creates risks that we struggle to understand and manage

Improving modeling of the pathways in which risk propagates will improve understanding and societal outcomes

Nationally and globally dispersed research teams and communities are working on related challenges independently

Improved collaboration and synthesis will accelerate discovery and add value to individuals and projects

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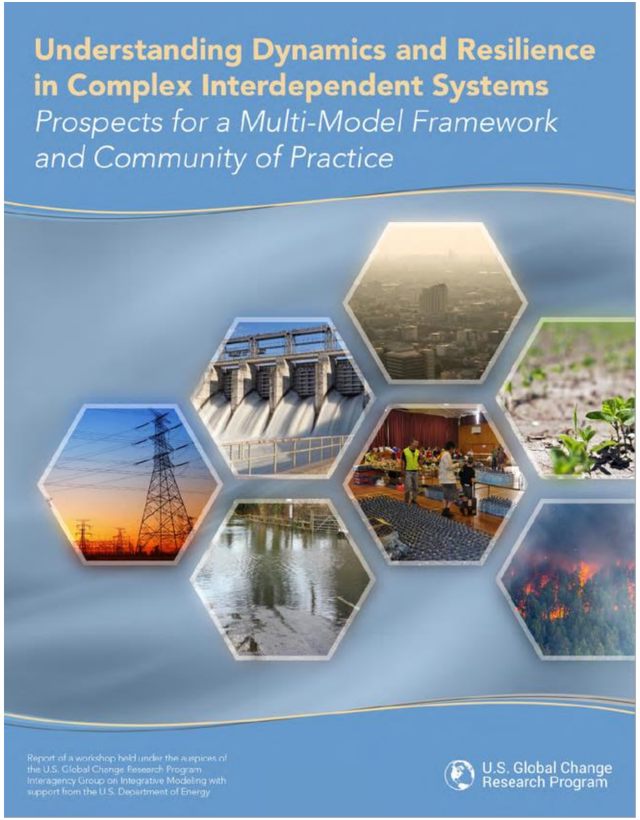
Community Of Practice (CoP) Objective: Evolve a Research "Framework"

- Idea to create a shared conceptual "framework" for MSD identified in 2016 workshop
  - Interconnected models, data, and analysis
  - Shared terminology, questions, uses cases, standards, and methods
  - Not a single model or set of models
- CoP hypothesis: accelerate progress by
  - Community-wide communication
  - Technical/ professional coordinating bodies
  - Research framework
  - Evaluation



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Emerging societal questions call for MSD science advances to better address

- **Prioritization and Investment**
- **Clarifying Context and Consequences**
- **Enhancing Adaptivity and Innovation**
- **Workforce Diversity and Collaboration**

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Example: The Energy Sector

Historical **transitions** shaped by changes in **human systems technology and demands**

Pace of transitions is controlled by the time required to **transform infrastructure systems**

Accelerated pacing of transition and connections with **climate risk** is a unique challenge

Interconnectedness and **interdependency** across energy sector

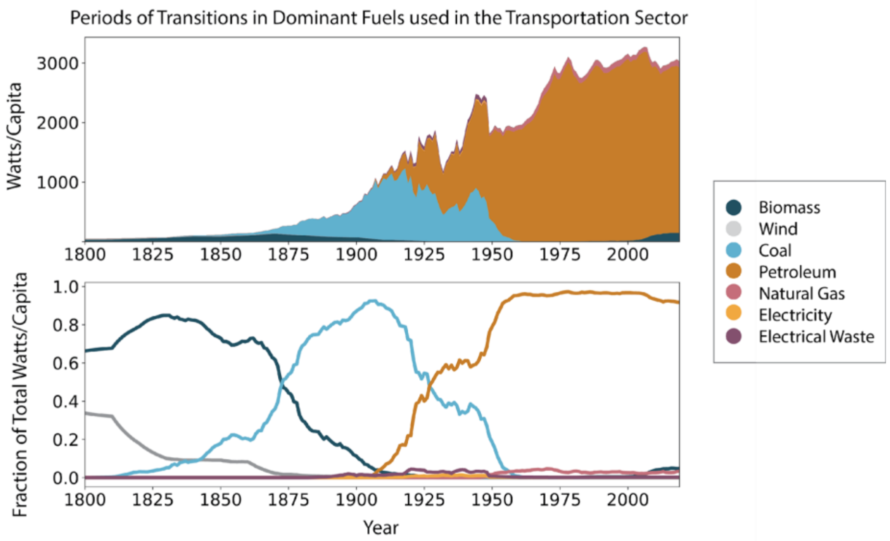

Figure adapted from Suits et al., 2020, Energy Transitions in U.S. History, 1800-2019, Center for Robust Decision Making on Climate and Energy Policy.

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Example: California Droughts

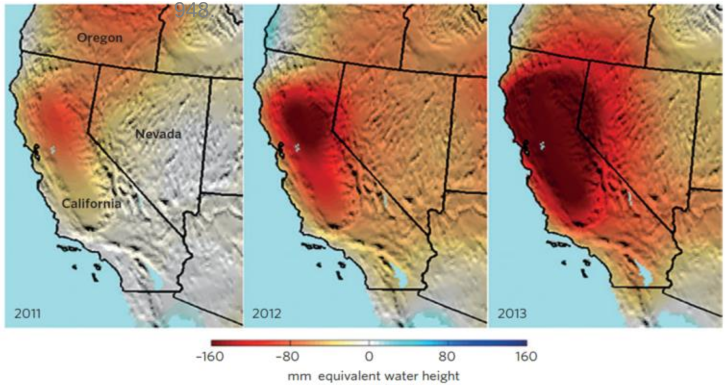
Energy water, and land are **inextricably linked** in California.

Over the period from 2002-2016, **statewide droughts** have substantially impacted much of California's agriculture, where local groundwater has been critical to buffering most agricultural impacts replacing surface water deficits

The groundwater embodied in agri-food products **increased over the course** of the drought, despite significant declines in rainwater and surface water supplies.

In this way, **drought amplifies the teleconnections** between water use and distant consumers of virtual water.

Figure adapted from Famiglietti, 2014, The global groundwater crisis, Nature Climate Change, 4(11), 945-948.



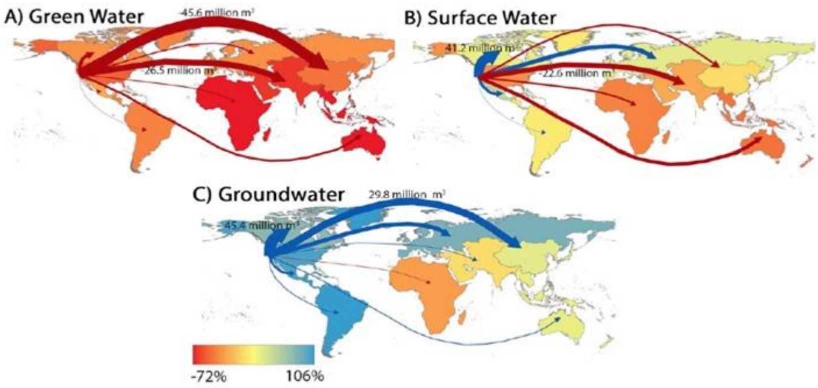


Figure adapted from Marston & Konar, 2017, Drought impacts to water footprints and virtual water transfers of the Central Valley of California, WRR, 53(7), 5756-5773.

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Example: Cities

- Cities create and are composed of **interacting** social, technological, and natural systems
- Cities are keystones for **important multi-scale feedbacks** in human-Earth systems

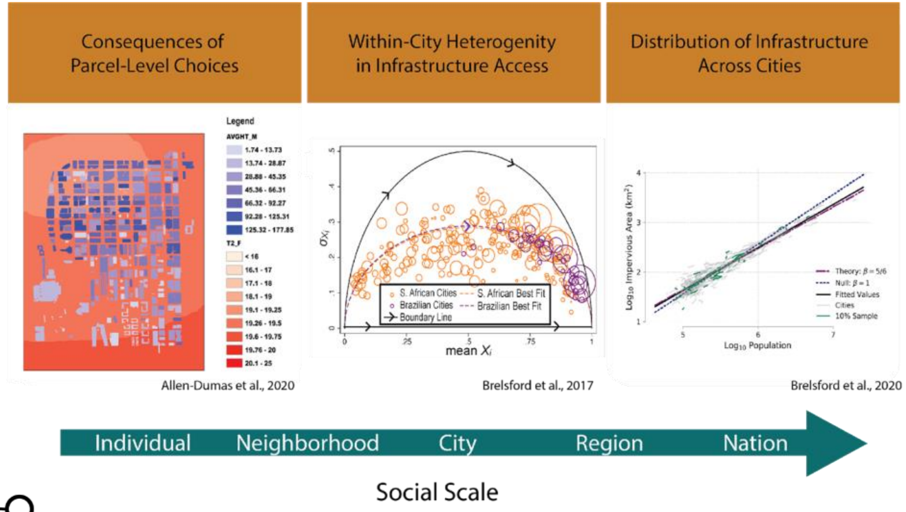

Image credit NASA Earth Observatory

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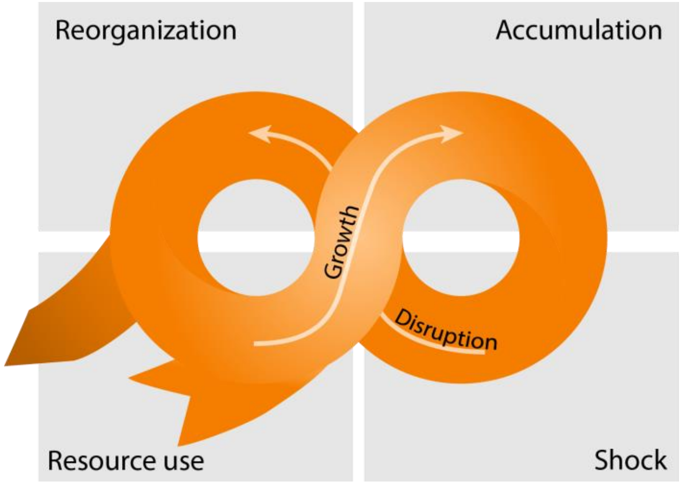
Multisector dynamics emerge from complex adaptive systems of systems

Complex adaptive systems can be conceptualized in terms of **interacting cycles of growth and disruptions**[1,2]

1. **Growth phase** – accumulation of resources and capital
2. **Disruption phase** – occurrence of system shock, subsequent reorganization



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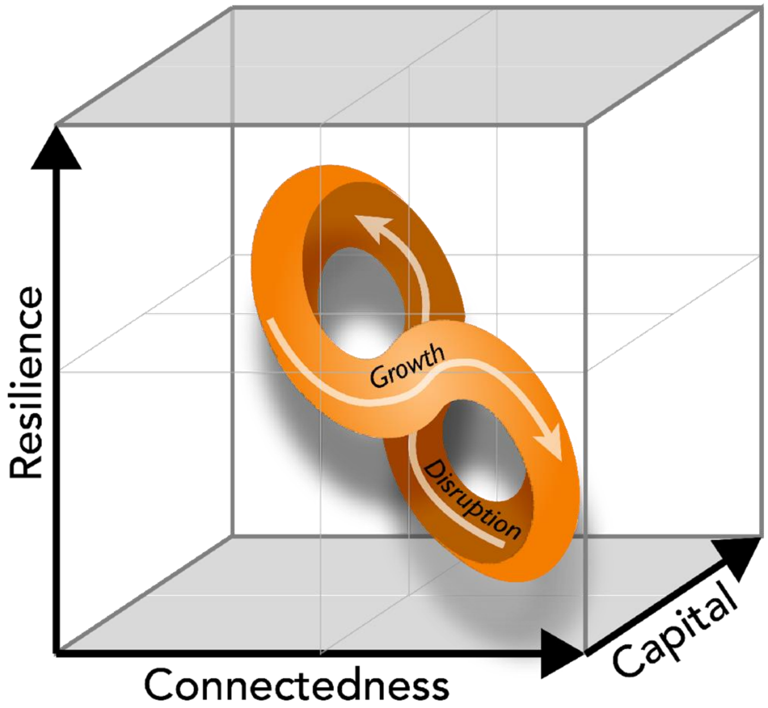
Gunderson, L. H., & Holling, C. S. (Eds.). (2002). *Panarchy: understanding transformations In human and natural systems*. Island press.
Holling, C. (1985). Resilience of ecosystems: local surprise and global change (No. 5, pp. 228-269). Cambridge University Press.

Key system properties

Connectedness: Increases as the system grows, becomes more aggregated and organized

Capital: system potential, reflects natural and human resources, monetary assets or other capacities that accumulate as the system develops or grow

Resilience: the capacity of a system to absorb a shock and adapt to maintain essentially the same function, structure, identity, and component interactions[3,4,5]



Shin et al., (2018). A systematic review of quantitative resilience measures for water infrastructure systems. Water, 10(2), 164.

Pimm et al., (2019). Measuring resilience is essential to understand it. Nature Sustainability, 2(10), 895-897. https://doi.org/10.1038/s41893-019-0399-7, 10.1038/s41893-019-0399-7.

Ossewaarde, et al. (2020). Towards a context-driven research: a state-of-the-art review of resilience research on climate change. Natural Hazards and Earth System Sciences Discussions, 1-40.

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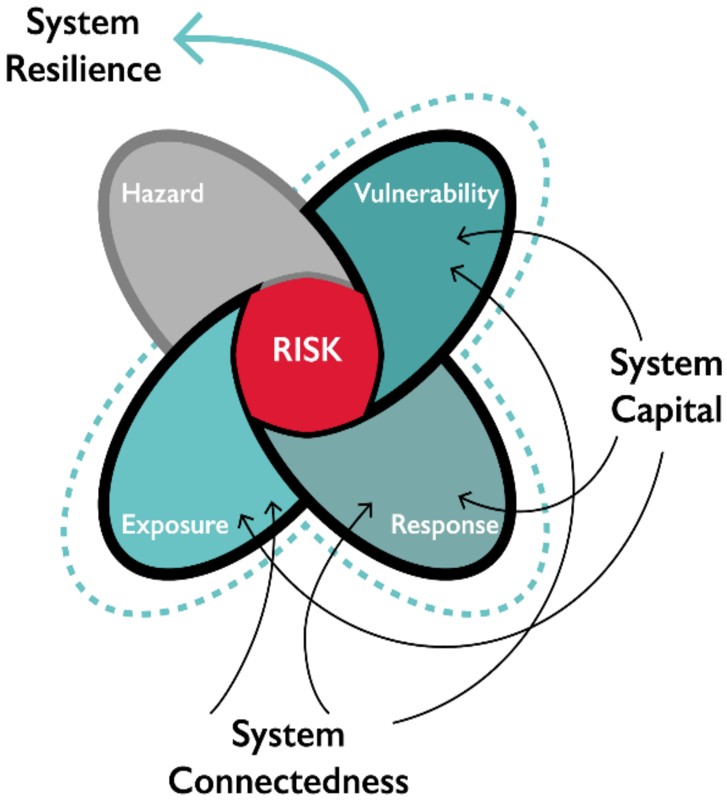
Bridging Risk and Resilience

Through cross-scale processes, **Hazards** can **cascade** between systems and **interact** with drivers of **vulnerability**, **exposure** and **response**

System **organization and aggregation** can **shape resilience** to hazards in both positive and negative ways through the presence of **drivers** and their **interactions**



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Adaptive system cycles across scales

Multi-scale feedbacks are critical for understanding how co-evolving systems, nested processes and interactions:

- Shape path dependencies
- Amplify or dampen dynamics
- Lead to emergent behaviors

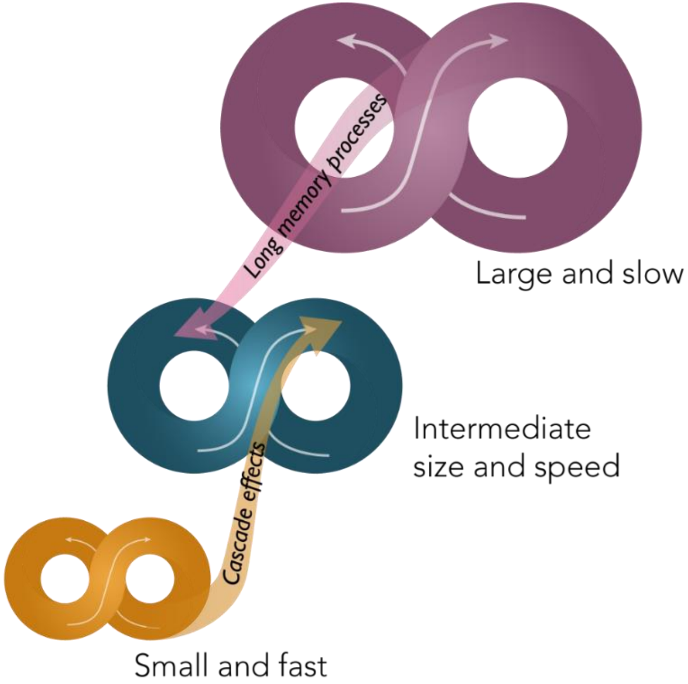
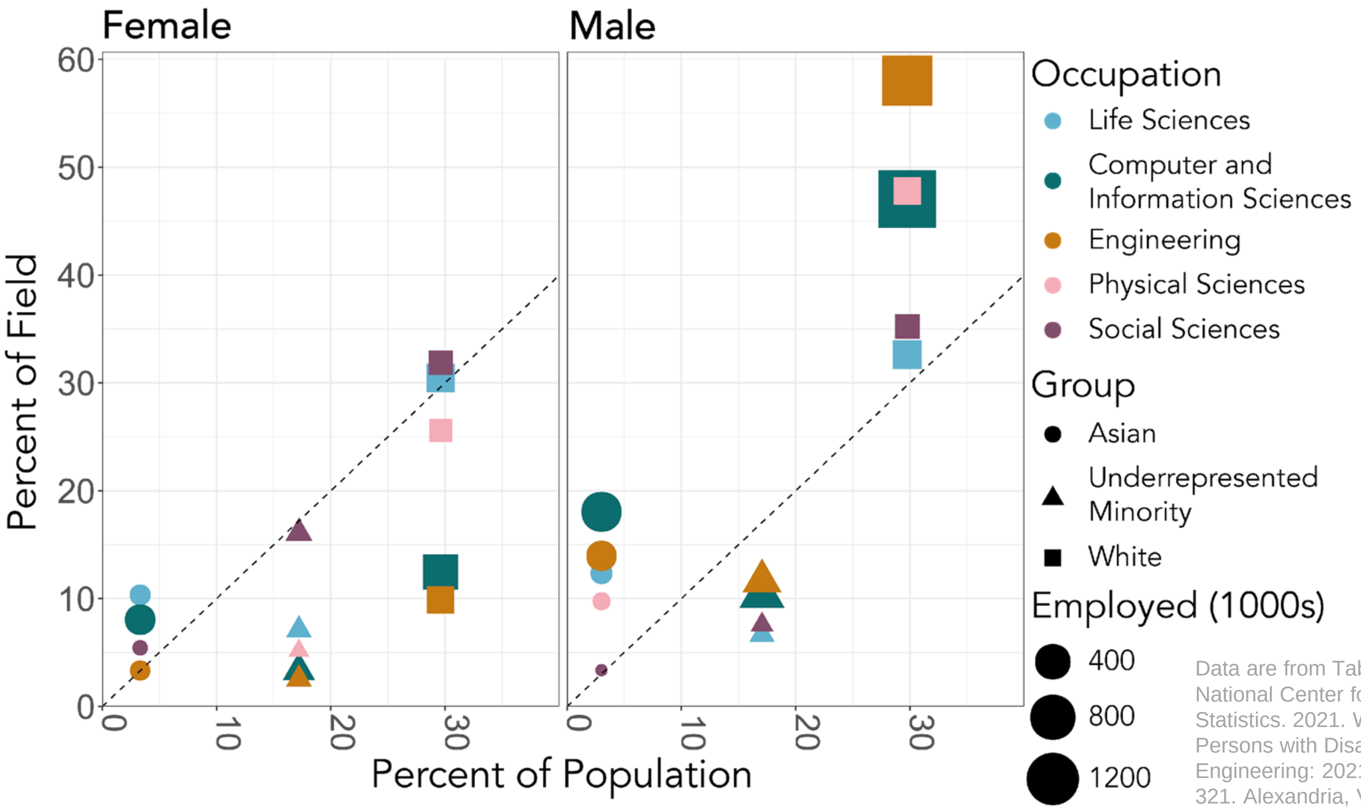


Figure adapted from Holdschlag and Ratter, 2013, Multiscale system dynamics of humans and nature in The Bahamas: perturbation, knowledge, panarchy and Resilience, In: Sustainability Science, 8(3), 407-421.

Mapping MSD research gaps

1. Workforce Gaps
2. Workflow Gaps
3. Methodological Gaps

Workforce development opportunities



Data are from Table 9-7 and Table 1-2, National Center for Science and Engineering Statistics. 2021. Women, Minorities, and Persons with Disabilities in Science and Engineering: 2021. Special Report NSF 21-321. Alexandria, VA: National Science Foundation. Available at https://ncses.nsf.gov/wmpd

Holistic STEM workforce career development

Beyond the "STEM Pipeline":

- Active mentorship, advocacy and promotion for underrepresented scientists are key
- "Many paths" for scientific career development
- Community level support and training

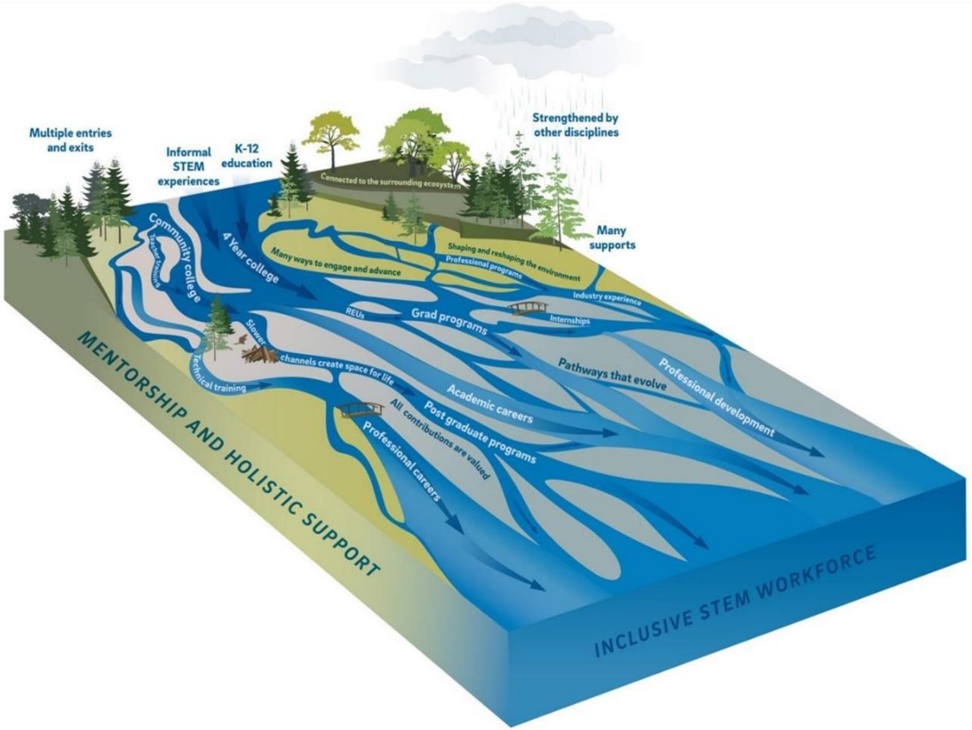
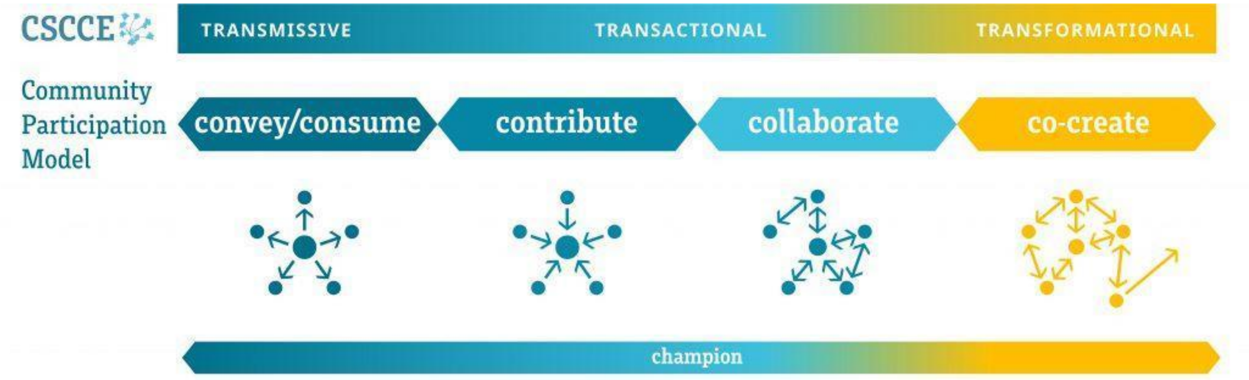


Figure source Batchelor, R. et al. (2021). "Reimagining STEM workforce development as a braided river". In: Eos 102. DOI: https://doi.org/10.1029/2021EO157277.

Growing & Diversifying Who is MSD



INTERACTIONS	one-to-many	crowdsourced	cooperative	community-led
COMMUNITY MANAGEMENT GOAL	inform and inspire	obtain feedback, skills, or information	gather resources, including knowledge, to achieve a common goal	create something new together
COMMUNITY ACTIVITIES	read watch listen	comment vote / like tag	discussion knowledge exchange production	integration and synthesis multi-directional learning co-production
POWER BALANCE	organization as expert	organization as convenor	scaffolded cooperation	mutual sharing and learning; (near) equity
SLOGAN	here's something interesting	give us some feedback	how can we work together?	what shall we do next...?

CSCCE.ORG

Mapping MSD research gaps

1. Workforce Gaps
2. Workflow Gaps
3. Methodological Gaps

Open Science to scale and accelerate MSD Insights

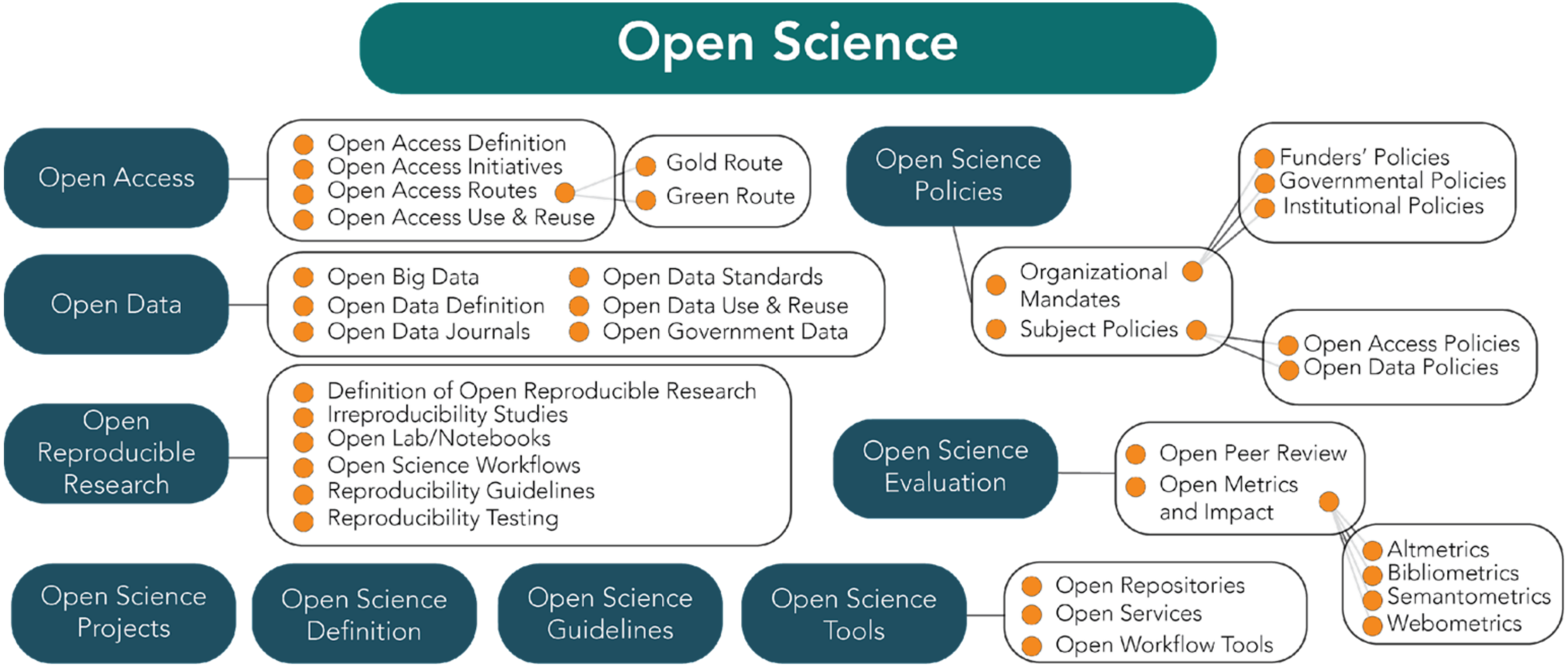


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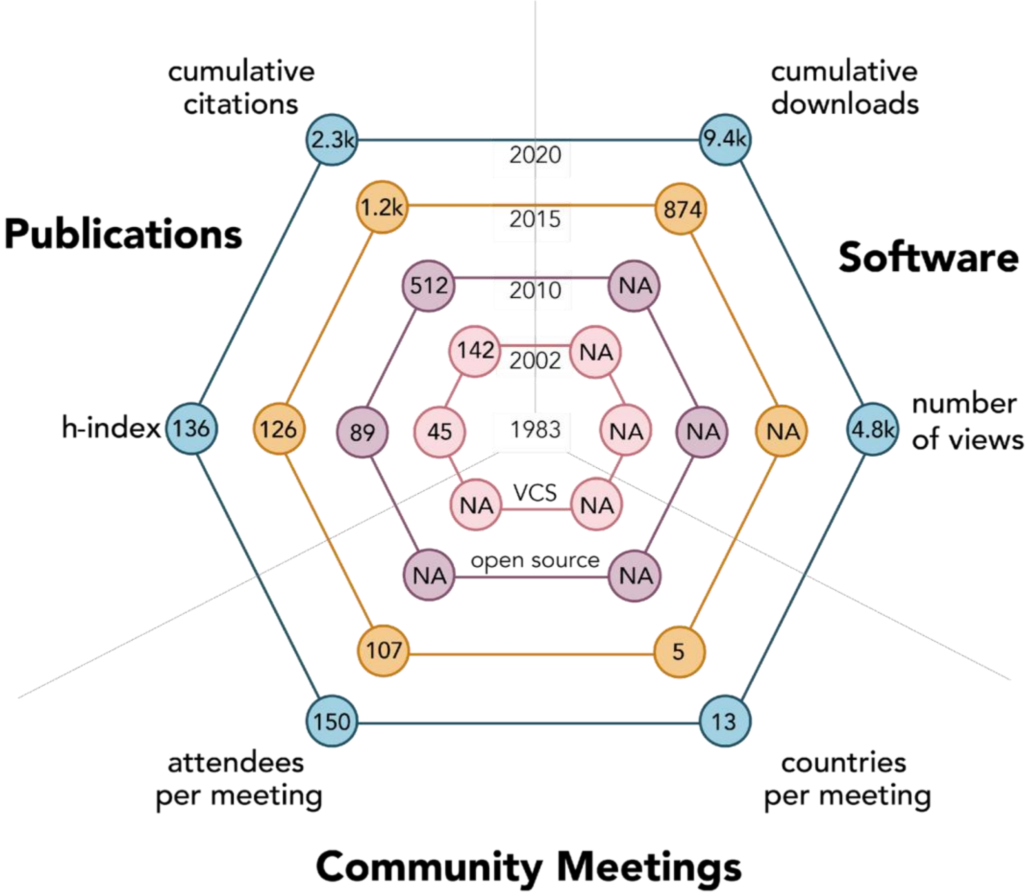
Figure adapted from Pontika et al. (2015), "Fostering open science to research using a taxonomy and eLearning Portal."

Open Science: The growing community employing GCAM



Mapping MSD research gaps

1. Workforce Gaps
2. Workflow Gaps
3. Methodological Gaps

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Harnessing AI/ML innovations

Reinforcement learning policy approximations are an example of how AI/ML innovations can propel MSD science

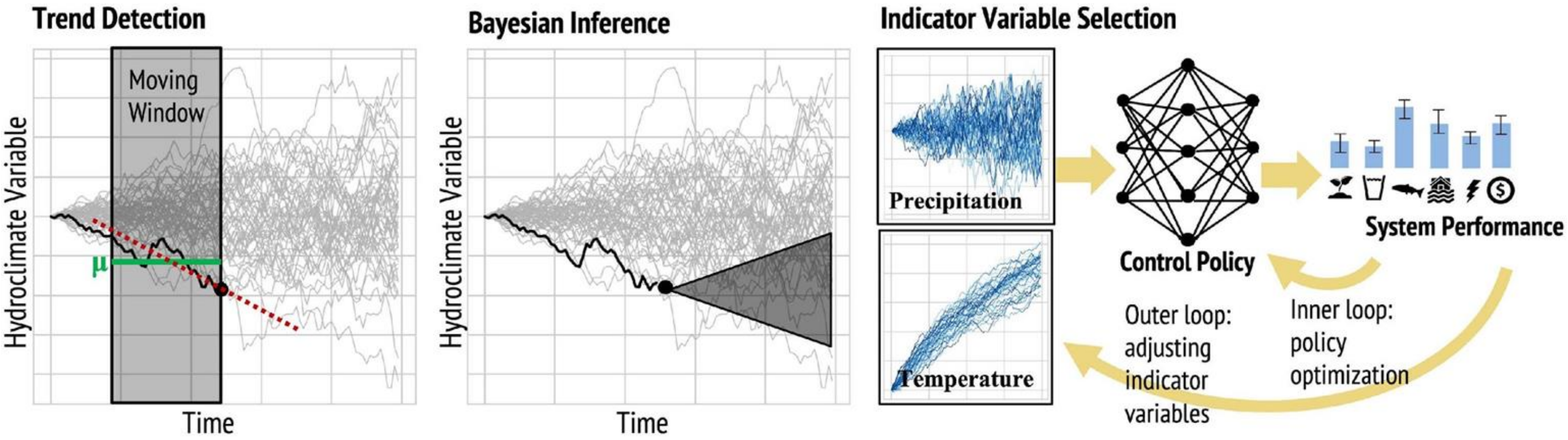
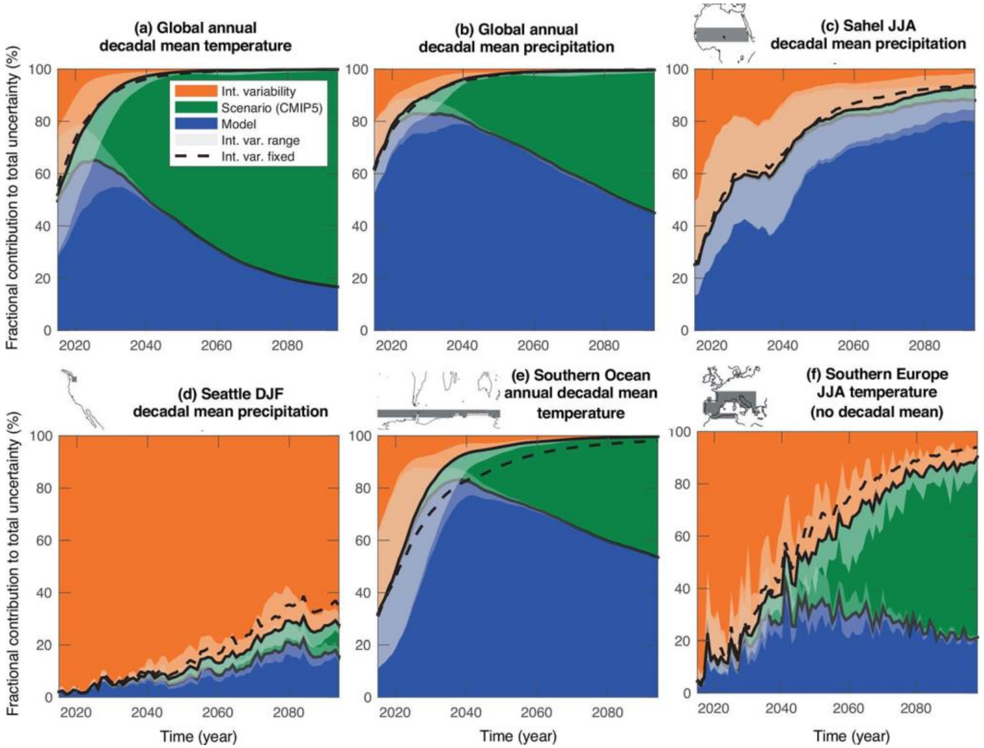


Figure source Herman et al. (2020) "Climate adaptation as a control problem: review and perspectives on dynamic water resources planning under uncertainty.", WRR, 56(2), e243389.

Human-Earth Systems Exploratory Modeling Opportunities

Lehner et al. (2020)[6] utilize SMILEs to **explore** internal variability, model structural uncertainty and human systems forcing shape climate projections



Output from a Single Model Initial Condition Large Ensemble Experiment (SMILEs)[7]

MSD

Figure source Lehner et al. (2020). Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6. *Earth System Dynamics*, *11*(2), 491-508.

Human-Earth Systems Exploratory Modeling Opportunities

Lehner et al. (2020)[6] utilize SMILEs to **explore** internal variability, model structural uncertainty and human systems forcing shape climate projections

The transition to **finer scales and decadal mean states** can yield complex balances for internal variability, forcing scenarios and ESM differences **shape projections**

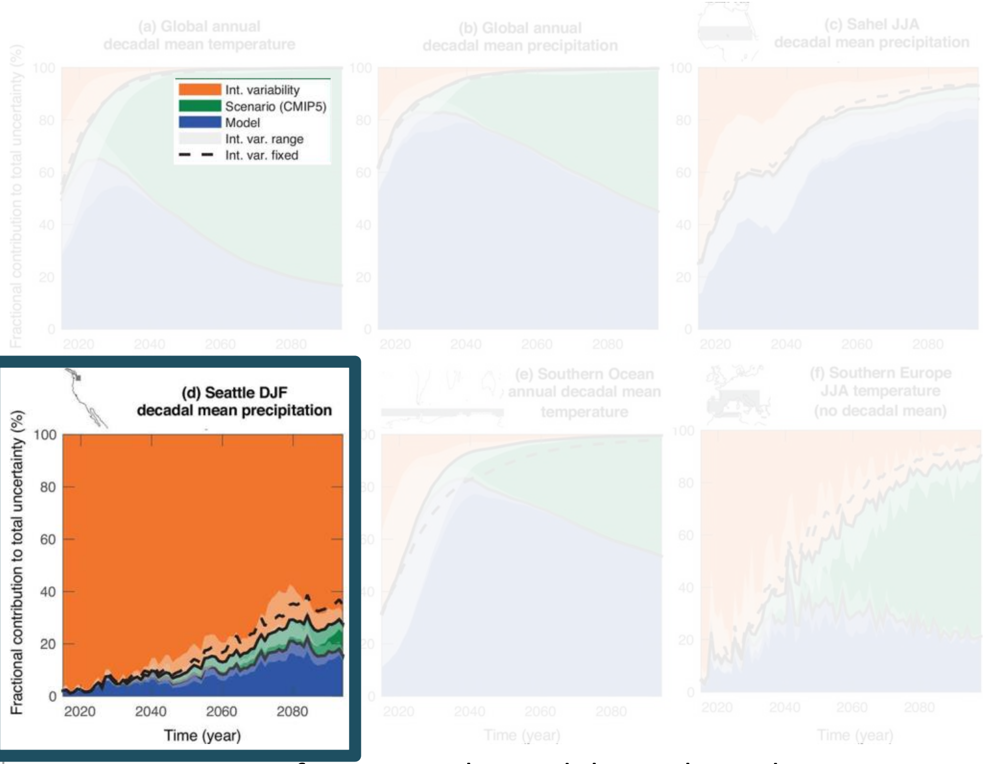


Figure source Lehner et al. (2020). Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6. *Earth System Dynamics*, *11*(2), 491-508.

Output from a Single Model Initial Condition Large Ensemble Experiment (SMILEs)[7]

Human-Earth Systems Exploratory Modeling Opportunities

Dolan et al., (2021)[8] explore the economic implications of water scarcity for 235 global river basins.

Several basins showed vulnerability to economic **tipping points** from a combination of challenging conditions

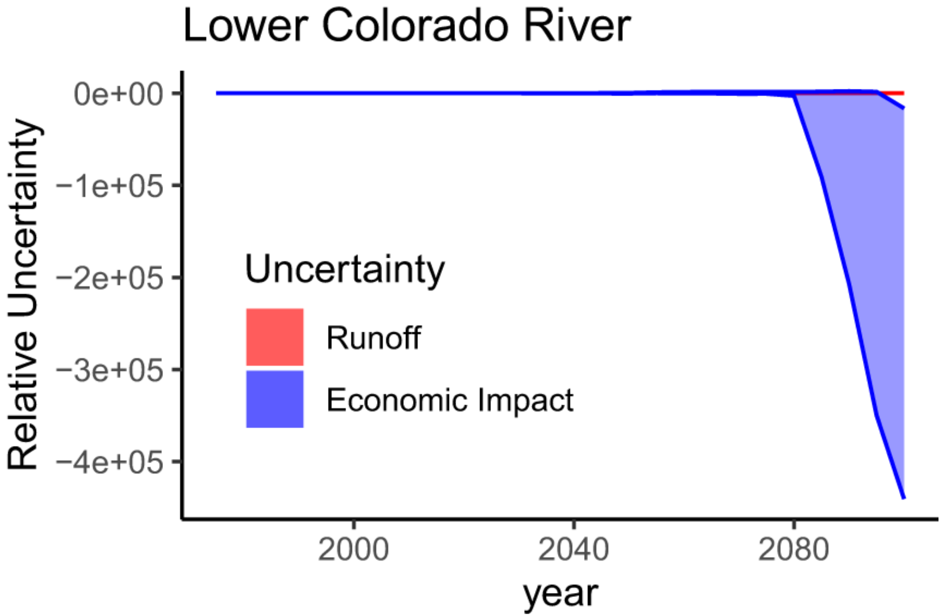


Figure source Dolan et al., (2021). Evaluating the economic impact of water scarcity in a changing world. *Nature communications*, *12*(1), 1-10.

MSD

MSD advances parallel key findings from the Advanced Scientific Computing Advisory Committee

- US competitiveness requires substantial efforts to train a workforce able to use and advance AI/ML technologies in mission critical areas

- AI, growing data resources, and emerging high-performance computing platforms present a once in a generation opportunity to start an ambitious AI for Science initiative

- The MSD community should explore emerging AI/ML multiscale, multisector capabilities to understand risk and resilience for changing human-Earth systems.

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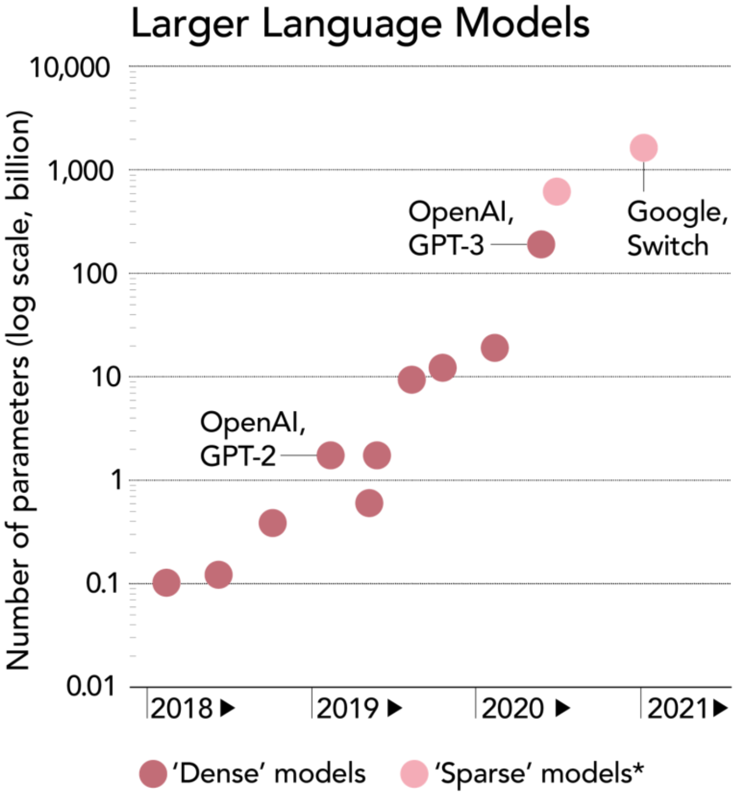
Breakthroughs fuel exponential growth

Example: Natural language processing - exponentially scaled rate of growth in text-generating neural networks

For MSD, these types of breakthroughs can shape the MSD community's ability to engage with the complexity of human-Earth systems



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