

## CLIMATE CHANGE

# Hell and High Water: Practice-Relevant Adaptation Science

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Adaptation requires science that analyzes decisions, identifies vulnerabilities, improves foresight, and develops options.

Informing the extensive preparations needed to manage climate risks, avoid damages, and realize emerging opportunities is a grand challenge for climate change science. U.S. President Obama underscored the need for this research when he made climate preparedness a pillar of his climate policy. Adaptation improves preparedness and is one of two broad and increasingly important strategies (along with mitigation) for climate risk management. Adaptation is required in virtually all sectors of the economy and regions of the globe, for both built and natural systems (1).

However, without the appropriate science delivered in a decision-relevant context, it will become increasingly difficult—if not impossible—to prepare adequately (2). We suggest a number of measures to hasten the development of science to correct maladaptations to current climate variability and support society's increasing need to adapt to a changing climate, drawing on lessons from experience, insights from related endeavors such as sustainability science (3), and input from scientific and stakeholder communities.

## Adaptation Planning, Information Gaps, and the Need for Adaptation Science

Initial adaptation planning is occurring in some sectors, such as water resource management, forestry, insurance, and coastal zone management. A limited but growing number of states and cities are developing adaptation plans. U.S. federal agencies have implemented sustainability plans that include mitigation and adaptation (4).

There are serious science gaps, however (5, 6). In many communities, decision-makers lack climate information or the means to apply it. In others, knowledge of current or potential future impacts exists, but not in a form or context that decision-makers can assimilate or act on in advance. In still



The entrance to a garage in Lower Manhattan on 31 October, 2012, as New York City began clean-up after Hurricane Sandy.

others, engineering innovations are needed, as well as social science knowledge, to guide technology deployment and adjustments to management, investments, and public policy.

A key characteristic of emerging adaptation science is that it is both basic—in that it contributes to understanding fundamental physical, environmental, and socioeconomic research questions—and applied, because it is problem focused. Scientists and practitioners “coproduce” relevant research by jointly defining questions and maintaining frequent interactions (7). Coproduction is challenging to implement and sustain because participants often have different roles, vocabularies, interests, methods, and incentives. The effectiveness of communications and deliberative processes among scientists and practitioners requires empirical evaluation (8).

To support the wide range of necessary adjustments, we outline a comprehensive, integrated approach to research in social, physical, environmental, engineering, and other sciences. We describe adaptation science research needed to under-

stand decision processes and information requirements, identify vulnerabilities, improve foresight about climate risks and other stressors, and understand barriers and options for adaptation.

## Understand Decision Processes and Knowledge Requirements

Adaptation science research must clarify what types of scientific information are required for improved decision-making. Decision-makers are concerned with cost, feasibility, social acceptance, tradition, and other factors. To close a “usability gap,” scientific information must fit into existing contexts (9). Organizational, cognitive, political, ethnographic, and decision sciences research is needed to clarify the problem, the values of participants, and the context in which the information will be applied. Understanding perception and apprehension of climate change risks is also a priority.

## Identify Vulnerabilities

Research to characterize vulnerability and adaptive capacity focuses on pinpointing infrastructure, economic sectors, geo-

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graphic areas, population groups, and ecosystems at greatest risk of harm (10). Two challenges are to:

*Improve data, methods, and scenarios for research on vulnerability and resilience of human and natural systems.* A geo-referenced data system for factors such as population, economic status, preparedness, natural capital, and location of sensitive infrastructure needs to be established and maintained to identify vulnerable human communities and environments. Effective response will be aided by understanding the extent to which vulnerability arises from poverty, under-investment, environmental factors, and their interactions with climate variability and change.

*Identify climate thresholds in vulnerable systems.* Knowledge of climate and related thresholds, points at which fundamental transformations occur in natural or human systems as climate changes, will improve resource management and inform debates about future atmospheric greenhouse gas stabilization. Coupled with time-dependent climate scenarios, improved knowledge of climate thresholds may help in estimating when effects could occur and thus facilitate setting adaptation priorities.

#### Improve Foresight About Climate Hazards and Other Stressors

Physical and biological scientists must study climate processes and develop models to deliver insights about climate features, including temperature and precipitation extremes, and related processes such as evolution of ecosystems, sea level rise, and other first-order effects. Social sciences can characterize human contributions to climate change through emissions and land use and inform mechanisms for improving interactions between climate scientists and potential users (11). Research challenges include:

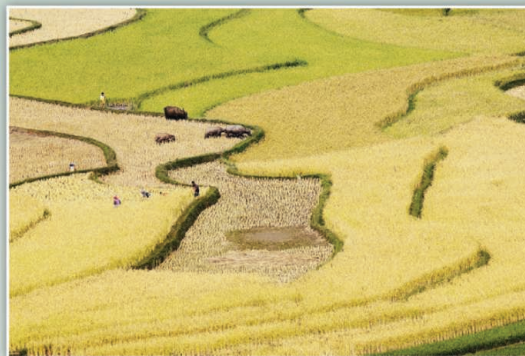
*Understand recent and potential future changes in extreme climate events.* Extremes occur on many spatial and time scales. They include heat waves, droughts, floods, storms, and other events that have major effects on human and natural systems. There is evidence that many of these extremes are intensifying (1, 12). A concerted focus on detecting changes in extremes and improving predictive products can provide important inputs to adaptation planning and preparedness.

*Improve integration of weather and climate information.* Common elements of initializing predictions with observations and providing probabilistic weather and climate information across time scales can consti-

#### Adaptation Science in Action

Scientists and practitioners are collaborating on research and applications to support climate change preparedness and address other nonclimate issues. Case examples document research and actions, such as plans and projects, but do not yet provide evidence of improved outcomes. Improved methods and data are needed for evaluating results (29).

- Well before Hurricane Sandy, New York City established a task force of city officials, utilities, commercial firms, and researchers to support formulation of adaptation options for vital infrastructure.
- Major urban water utilities, university-based research centers, and private-sector firms in the United States are collaborating to pilot applications of climate science and water utility modeling applications to quantify impacts of climate change on their water systems and evaluate adaptation strategies.
- Researchers in Australia developed a plant functional trait database and modeled habitat suitability under climate scenarios for naturalized and invasive plants to enable land managers to make better-informed decisions about land management at a national and regional level.
- Researchers and local practitioners in the Vietnamese city of Hue and the Bangladeshi city of Satkhira collaborated to assess climate-related risks, identify adaptation strategies, and strengthen local capacity to manage the interaction of rapid development and climate impacts.
- Researchers worked with small-scale farmers and agricultural extension officials in sub-Saharan Africa to provide a bridge between scientific and indigenous knowledge of drought onset and coping strategies to improve delivery of drought prediction information for vulnerable, rain-fed farming operations.



tute a unified approach for weather forecasts and climate predictions (13, 14). Decadal climate predictions with next-generation, high-resolution global climate models [e.g., (15)] have the potential to produce probabilistic near-term climate information over the next decade and improve insight into future conditions to which human societies will have to adapt (16). Research is needed to formulate methods for presenting global climate model information in probabilistic form and applying that information to risk assessment and management (17).

*Tailor climate information to facilitate its application in decision-making.* Sustained interactions among researchers and decision-makers are needed not only to understand how climate affects assets or resources but also to identify how climate information can be used in decisions (18). In addition to global climate models, other tools can produce relevant information, such as less computationally intensive intermediate-complexity models [e.g., to assess uncertainty (19)], qualitative scenario planning approaches (20), and decision-analytic approaches to use climate model information in ways that supplement conventional scenario-led studies [e.g., (17)]. Climate and decision scientists can tailor information for application through downscaling of climate model data [e.g., (21)] or running fully dynamical nested numerical models

at regional or finer grid spacings [e.g., the North American Regional Climate Change Assessment Program (22)].

*Establish climate information services at the national and international level to translate and communicate adaptation science to public and private sector decision-makers.* The Global Framework for Climate Services (23) provides a foundation for climate services being developed in many countries. Development of climate services should engage decision-makers, researchers, and others to ensure that products are relevant, uncertainties are explicit, and a portfolio of products that combine monitoring and projections are useable to decision-makers. The U.S. National Academy of Sciences has emphasized the need for climate services (24), and the U.S. Global Change Research Program (USGCRP) has made climate adaptation science that would use climate information a focus of its 10-year plan (25). Current funding levels are inadequate and declining, and incentives and means to engage with stakeholders are lacking, inhibiting service development and delivery (5, 26).

#### Identify Barriers, Broaden the Range of Adaptation Options, and Promote Learning

Options need to be studied to guide adjustments in technology, management practices, public policy, standards, institutions, gover-

nance, and incentives to facilitate adaptation. Four priorities are to:

*Identify, explain, and explore opportunities to overcome barriers to adaptation.* Existing laws, regulations, and other practices can limit adaptation. These include legal and financial mechanisms, from local to international jurisdictions. Research is needed to identify these barriers and develop solutions to minimize or surmount them.

*Develop technologies and performance standards.* A changed climate system with conditions never before experienced by human societies may alter effectiveness of historically successful adaptation approaches and limit types of adaptation (27). Adaptation options are needed that are robust to different climate and socioeconomic development pathways, and are thus effective in both the short-term and the long-term (e.g., improved water distribution or desalination systems, and advances in electricity generation, transmission, and distribution). Organizations and processes for establishing manufacturing, building, and other standards (e.g., the International Organization for Standardization) could contribute to the development of adaptation options.

*Develop indicators and monitoring and evaluation systems.* Monitoring and evaluation will help track progress in enhancing resilience, prioritizing adaptation funding, and evaluating effectiveness of adaptation options. For adaptation options related to infrastructure and some natural resources, relevant indicators are relatively easy to quantify. For measures focused on governance or livelihoods, indirect proxy variables must be defined. Case studies dominate adaptation evaluations, with little comparative research on implementation (28).

*Learn from experience.* A number of knowledge platforms are beginning to catalog and evaluate experiences to promote information exchange and learning. Learning and disseminating of lessons needs to be accelerated to improve decision-making. Enabling private companies to share experiences without damaging commercial interests is a particular challenge.

### Measures to Establish Adaptation Science

First steps in establishing institutions to conduct and support adaptation science are taking place. In the United States, “mission” agencies—including the Environmental Protection Agency, the National Oceanic and Atmospheric Administration (NOAA), and the Department of the Interior—have supported the use of scientific information in adaptation. The Regional Integrated Sciences

and Assessments Program, Climate Science Centers, and other efforts aim at developing a collaborative framework between research and practice (29). The European Union has provided research funding and launched an information portal ([www.eea.europa.eu/themes/climate/european-climate-adaptation-platform-climate-adapt](http://www.eea.europa.eu/themes/climate/european-climate-adaptation-platform-climate-adapt)). Germany, the United Kingdom, and other countries are moving forward to establish services (e.g., [www.climate-service-center.de](http://www.climate-service-center.de)). Australia has made adaptation a priority ([www.csiro.au/Outcomes/Climate/Adapting.aspx](http://www.csiro.au/Outcomes/Climate/Adapting.aspx)).

Advances in adaptation science will not happen without two transformational changes: (i) an institutional structure to catalyze, coordinate, evaluate, and encourage the use of advances in adaptation science; and (ii) an increase in funding. National Research Council reports [e.g., (6)] and recommendations of a U.S. federal interagency committee (30) provide detailed recommendations that would help advance climate adaptation science.

One U.S. approach could be a national institute on climate preparedness composed of research and applications centers for adaptation in priority sectors or challenges. The institute would be geographically distributed and function in some ways similar to the National Institutes of Health. It would build on the current USGCRP, agency sectoral or regional research centers, and regional nodes for the National Climate Assessment’s sustained assessment process. Providing sufficient resources for collaboration and learning would facilitate research on coupled systems and offer an opportunity to better connect adaptation science to interagency programs.

More broadly, sustained support for problem-oriented fundamental research on adaptation needs to be increased at research agencies. A particular challenge is to develop effective approaches to learn from adaptation practice as well as published research. Progress toward achieving the goal of adapting to changing climate will require demonstrating tangible benefits for society by connecting research and applications.

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**Acknowledgments:** The authors acknowledge the Aspen Global Change Institute (AGCI) and its director, John Katzenberger, for hosting a workshop that laid the foundations for this paper, along with the attendees who contributed to discussions. A portion of this research was supported by the Office of Science, Biological and Environmental Research, U.S. Department of Energy. Funding for the AGCI workshop was provided by NASA. The views expressed in this article are those of the authors and do not necessarily reflect the positions of their institutions.

### Supplementary Materials

[www.sciencemag.org/content/342/6159/696/suppl/DC1](http://www.sciencemag.org/content/342/6159/696/suppl/DC1)

10.1126/science.1239569