Evaluating Knowledge to Support Climate Action: A Framework for Sustained Assessment. Report of an Independent Advisory Committee on Applied Climate Assessment

Item Type	Article
Authors	Moss, R. H.; Avery, S.; Baja, K.; Burkett, M.; Chischilly, A. M.; Dell, J.; Fleming, P. A.; Geil, K.; Jacobs, K.; Jones, A.; Knowlton, K.; Koh, J.; Lemos, M. C.; Melillo, J.; Pandya, R.; Richmond, T. C.; Scarlett, L.; Snyder, J.; Stults, M.; Waple, A. M.; Whitehead, J.; Zarrilli, D.; Ayyub, B. M.; Fox, J.; Ganguly, A.; Joppa, L.; Julius, S.; Kirshen, P.; Kreutter, R.; McGovern, A.; Meyer, R.; Neumann, J.; Solecki, W.; Smith, J.; Tissot, P.; Yohe, G.; Zimmerman, R.
Citation	Moss, R. H., Avery, S., Baja, K., Burkett, M., Chischilly, A. M., Dell, J., ... & Knowlton, K. (2019). Evaluating Knowledge to Support Climate Action: A Framework for Sustained Assessment. Report of an Independent Advisory Committee on Applied Climate Assessment. Weather, Climate, and Society, 11(3), 465-487.
DOI	10.1175/wcas-d-18-0134.1
Publisher	AMER METEOROLOGICAL SOC
Journal	WEATHER CLIMATE AND SOCIETY
Rights	© 2019 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).
Download date	27/08/2022 20:53:22

Evaluating Knowledge to Support Climate Action: A Framework for Sustained Assessment. Report of an Independent Advisory Committee on Applied Climate Assessment

R. H. MOSS,[a] S. AVERY,[b] K. BAJA,[c] M. BURKETT,[d] A. M. CHISCHILLY,[e] J. DELL,[f] P. A. FLEMING,[g] K. GEIL,[h] K. JACOBS,[i] A. JONES,[j] K. KNOWLTON,[k] J. KOH,[l] M. C. LEMOS,[m] J. MELILLO,[n] R. PANDYA,[o] T. C. RICHMOND,[p] L. SCARLETT,[q] J. SNYDER,[r] M. STULTS,[s] A. M. WAPLE,[t] J. WHITEHEAD,[u] D. ZARRILLI,[v] B. M. AYYUB,[w] J. FOX,[x] A. GANGULY,[y] L. JOPPA,[g] S. JULIUS,[z] P. KIRSHEN,[aa] R. KREUTTER,[bb] A. MCGOVERN,[cc] R. MEYER,[dd] J. NEUMANN,[ee] W. SOLECKI,[ff] J. SMITH,[gg] P. TISSOT,[hh] G. YOHE,[ii] AND R. ZIMMERMAN[jj]

[a] *The Earth Institute, Columbia University, New York, New York*
[b] *Woods Hole Oceanographic Institute (emerita), Woods Hole, Massachusetts*
[c] *Urban Sustainability Directors Network, Baltimore, Maryland*
[d] *William S. Richardson School of Law, University of Hawai'i at Mānoa, Honolulu., Hawaii*
[e] *Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, Arizona*
[f] *Resiliency Resources LLC, Houston, Texas*
[g] *Microsoft Corporation, Redmond, Washington*
[h] *AAAS Science and Technology Policy Fellow at USDA, Beltsville, Maryland*
[i] *Center for Climate Adaptation Science and Solutions, The University of Arizona, Tucson, Arizona*
[j] *Lawrence Berkeley National Laboratory, Berkeley, California*
[k] *Mailman School of Public Health, Columbia University, New York, New York*
[l] *The Lightsmith Group, New York, New York*
[m] *School for Environment and Sustainability, University of Michigan, Ann Arbor, Michigan*
[n] *The Ecosystems Center, Woods Hole, Massachusetts*
[o] *Thriving Earth Exchange, American Geophysical Union, Washington, D.C.*
[p] *Van Ness Feldman, Seattle, Washington*
[q] *The Nature Conservancy, Arlington, Virginia*
[r] *Office of Air Resources, Climate Change and Energy, New York Department of Environmental Conservation, Albany, New York*
[s] *City of Ann Arbor, Ann Arbor, Michigan*
[t] *Studio30k, Asheville, North Carolina*
[u] *North Carolina Sea Grant, Raleigh, North Carolina*
[v] *New York City Mayor's Office, New York, New York*
[w] *Department of Civil and Environmental Engineering, University of Maryland, College Park, College Park, Maryland*
[x] *National Environmental Modeling and Analysis Center, Asheville, North Carolina*
[y] *Northeastern University, Boston, Massachusetts*
[z] *Environmental Protection Agency, Washington, D.C.*
[aa] *University of Massachusetts Boston, Boston, Massachusetts*
[bb] *Princeton University, Princeton, New Jersey*
[cc] *University of Oklahoma, Norman, Oklahoma*
[dd] *University of California, Davis, Davis, California*
[ee] *Industrial Economics, Cambridge, Massachusetts*
[ff] *Hunter College of City University of New York, New York, New York*
[gg] *Abt Associates, Boulder, Colorado*
[hh] *Texas A&M University, College Station, Texas*
[ii] *Wesleyan University, Middletown, Connecticut*
[jj] *New York University, New York, New York*

(Manuscript received 10 December 2018, in final form 8 March 2019)

Denotes content that is immediately available upon publication as open access.

Corresponding author: R. H. Moss, rmoss@climateassessment.org

DOI: 10.1175/WCAS-D-18-0134.1

ABSTRACT

As states, cities, tribes, and private interests cope with climate damages and seek to increase preparedness and resilience, they will need to navigate myriad choices and options available to them. Making these choices in ways that identify pathways for climate action that support their development objectives will require constructive public dialogue, community participation, and flexible and ongoing access to science- and experience-based knowledge. In 2016, a Federal Advisory Committee (FAC) was convened to recommend how to conduct a sustained National Climate Assessment (NCA) to increase the relevance and usability of assessments for informing action. The FAC was disbanded in 2017, but members and additional experts reconvened to complete the report that is presented here. A key recommendation is establishing a new nonfederal ''climate assessment consortium'' to increase the role of state/local/tribal government and civil society in assessments. The expanded process would 1) focus on applied problems faced by practitioners, 2) organize sustained partnerships for collaborative learning across similar projects and case studies to identify effective tested practices, and 3) assess and improve knowledge-based methods for project implementation. Specific recommendations include evaluating climate models and data using user-defined metrics; improving benefit–cost assessment and supporting decision-making under uncertainty; and accelerating application of tools and methods such as citizen science, artificial intelligence, indicators, and geospatial analysis. The recommendations are the result of broad consultation and present an ambitious agenda for federal agencies, state/local/tribal jurisdictions, universities and the research sector, professional associations, nongovernmental and community-based organizations, and private-sector firms.

1. Focus and origins of this report

Damages and loss of life occurring across the United States from recent floods, wildfires, and heat waves demonstrate the growing risks associated with climate change. The impacts vary from place to place and across diverse communities with different vulnerabilities and capacities to respond. Media attention largely focuses on the costly impacts of more frequent and/or severe extreme events. But slower-onset changes in conditions such as higher nighttime temperatures, reduced snowpack, and more frequent ''sunny day'' nuisance flooding are also having substantial impacts, especially as they interact with other long-term trends such as subsidence of land in coastal areas, expansion of paved surfaces and human settlement, and degradation of ecosystems and vital natural resources. The disruption to communities and lives in both rural and urban areas is widespread, with a particular burden on the working poor (especially those whose livelihoods are directly tied to natural resources), indigenous nations, historically disadvantaged communities, the young and the elderly, and others who lack adequate resources to adapt. All levels of government, the private sector, and individual citizens collectively are already spending billions of dollars to recover from and implement measures to moderate future damages resulting from these interacting forces.

Through their direct experience and reports such as the recent Fourth National Climate Assessment (NCA4; USGCRP 2017a, 2018a), most people have come to accept that climate is changing and will have serious consequences (Leiserowitz et al. 2018). NCA4 shows that extensive changes in climate have been observed in all regions of the country, and that Americans are already being forced to make difficult decisions and are struggling to recover from and prepare for impacts. The report updates a series of prior comprehensive assessments (released in 2000, 2009, and 2014) and extensively documents these impacts. A key message states that climate change ''creates new risks and exacerbates existing vulnerabilities in communities across the United States, presenting growing challenges to human health and safety, quality of life, and the rate of economic growth.'' A recurring finding in many of the sectoral and regional chapters is that among those most likely to suffer these impacts are society's most vulnerable populations. The report finds that without additional large reductions in emissions, ''substantial net damage to the US economy [will occur] throughout this century, especially in the absence of increased adaptation efforts.''

''Now what?'' is the pressing question that many are asking. How can we avoid the worst damages? What can be done to prepare for the impacts we can no longer avoid? And when we do incur damages, how can we recover more quickly and rebuild better? These questions point to many challenges that will require state/local/tribal governments and citizens to integrate science and community values in decision-making. And they highlight the need for additional research and assessment to improve options and knowledge to support implementation. For many communities, the challenge is to incorporate information about climate change and policies into planning economic opportunities, improving social welfare, updating infrastructure, protecting water resources, or conserving natural environments. Others need to manage overt climate threats—reducing risks of calamitous wildfires, containing health threats, managing flooding from record rainfalls, and recouping depressed agricultural production—while navigating challenging legal, financial, and equity issues exacerbated by preexisting burdens such as histories of restrictive zoning, siting of industrial facilities, and inadequate public health infrastructure. For some, the goal is to seize new opportunities such as developing renewable energy options in ways that create economic opportunity for all and maintain energy system resilience.

Navigating the choices and options, most of which involve trade-offs and compromises, will require constructive public dialogue, community participation, and the ability for state/local/tribal leaders and citizens to access our knowledge of climate change and its potential impacts in a flexible and ongoing way. For example, community-based organizations (CBOs) will need to interact with climate-resilience planners and other groups to consider the benefits and trade-offs of proposed actions and to ensure effective implementation that supports increased social cohesion, civic participation, and community stewardship—all markers of resilience in the face of climate change. The motivation for this report is to transition sustained climate assessment to a dynamic process that helps affected jurisdictions, communities, and organizations establish pathways for climate action that support their ongoing growth and development objectives by providing opportunities to interact with authoritative climate information, place-based knowledge, and our understanding of effective solutions.

Significant efforts are already under way both to reduce human contributions to climate change (“mitigation”) and to adjust systems and practices to withstand (or even benefit from) impacts that can no longer be avoided (“adaptation”). With respect to mitigation, U.S. states, local governments, companies, and citizens are contributing to global efforts to reduce greenhouse gas (GHG) concentrations in the atmosphere. Attention and planning have focused heavily on efforts to reduce GHG emissions in the energy sector, transportation, residential and commercial buildings, industry, and agriculture; specific technologies being developed include biofuels, carbon capture, and increasing uptake of carbon on agricultural lands, forests, and marginal lands, among others. These efforts notwithstanding, multiple assessments have concluded that mitigation is not taking place nearly rapidly enough to stabilize atmospheric GHG concentrations at safe levels and that policies at multiple jurisdictions of government—including federal—must be strengthened to avoid unmanageable levels of climate change (e.g., IPCC 2014c, 2018).

Because impacts occur across all sectors of the economy and all regions of the nation and the capacity for individuals and communities to adapt varies greatly, many types of adaptation will be needed to recover from damages that have already occurred and to prepare for projected impacts. Assessments of the state of adaptation have found that adaptation is progressing, but not fast enough to prepare for the existing and projected impacts (e.g., Hansen et al. 2012; Bierbaum et al. 2014; Vogel et al. 2016). For example, a study by Moser et al. (2017) found that “communities across the US are experimenting with adaptation . . . aided by an ever-growing base of knowledge and a plethora of tools. Still, the field remains limited in scope and effectiveness . . . too many adaptation efforts are stalled at the planning stage.” Practitioners are making long-term plans and investments without consideration of future climate changes and impacts likely to affect the lives and livelihoods of U.S. citizens.

To better meet Americans’ needs to increase preparedness and resilience in the face of climate change, in 2016 the National Oceanic and Atmospheric Administration (NOAA) and the Office of Science and Technology Policy of the White House convened a Federal Advisory Committee (FAC) to develop recommendations on how to accelerate development of a sustained National Climate Assessment (NCA). The basic idea of a sustained NCA (Buizer et al. 2013) is to use what is known about making scientific information actionable in order to better support state/local/tribal governments, communities, organizations, and individuals who need to address climate risks. While a sustained NCA will not address all the barriers to meeting community needs for preparedness and resilience, it can develop and deliver answers to many questions and issues that are repeatedly encountered. For example, there are many different sources of climate information and tools; which ones are suited for which applications? Of the many case studies that document practice, which provide “best practices” that are relevant for a specific challenge? What science should inform standard-setting, as engineers, architects, and other professionals update codes and practices to take climate change into account? A sustained assessment can provide essential capacity and knowledge to help all Americans shape and prepare for an uncertain future climate.

Another dimension of the sustained assessment concept is to provide access to evolving knowledge and to highlight research needs. While currently available science *is* robust and based on centuries of research, the science community continues to learn about the interactions of the Earth system with global to local processes. Research across a wide range of disciplines and perspectives is improving understanding of the climate system, options for reducing emissions and managing carbon, and approaches for adaptation. Ongoing monitoring, observations, and modeling—as well as continuing assessments on issues from understanding climate processes to assessing the costs of inaction—will be essential for managing climate risk. Expanding federal research on climate science and solutions is essential, as is diversifying sources of support from other levels of government and the private sector (e.g., research firms and foundations). If properly focused and conducted, a sustained assessment can improve timely access to evolving and relevant information.

The FAC was addressing how to advance implementation of the sustained assessment when, in August of 2017, NOAA announced it would not be continued. However, with support from the State of New York, Columbia University, and the American Meteorological Society, most FAC members reconvened and joined with eight additional experts in early 2018 as the Independent Advisory Committee on Applied Climate Assessment (IAC). IAC members (the main authors of this report) consulted broadly with user groups including state/local/tribal entities, nongovernmental institutions (NGOs), professional societies, and the private sector, as well as with scientists and intermediaries in professional settings who conduct climate research, develop applications, and support adaptation. IAC members also contributed inputs based on the work of a number of related efforts including a ''Science to Action'' collaborative of some 100 organizations and individuals interested in maintaining access to federal scientific information and fostering better science–practice interactions. All these insights increased the Committee's understanding of the current status of activities to adapt to and mitigate climate change, what additional support is needed for implementation, and the evolving practice of ''coproducing'' research that is both curiosity driven and serves applied needs. While the IAC bears sole responsibility for the content of this report, the recommendations would not have been possible without these contributions and the work of the many communities seeking to increase the nation's readiness and resilience.

Through its work, the IAC has reaffirmed the conclusion reached in other reports and by other groups that it is important to transition national climate assessments to a more sustained, user-oriented process. The IAC recommends adding a focus to this process on evaluating how climate-relevant knowledge can be applied in specific types of decisions and actions (among other priorities). The IAC uses the term ''applied climate assessment'' to describe this emphasis: while the term may be novel, the concept is not and is reflected in many ongoing efforts.

We begin with a short review of the challenges of taking action from the perspective of ''practitioners,'' defined here as individuals in state/local/tribal governments, private-sector firms, NGOs, CBOs, universities and other research institutions, professional associations, and other settings across the country where actions to limit and adapt to changing climate conditions are planned or occurring. The report then reviews requirements for a national climate information system and describes the role that assessments have played in providing authoritative information. Based on the needs identified by practitioners, it makes three overarching recommendations, each with a number of related opportunities, which, if implemented, could advance the potential contribution of sustained assessments in providing authoritative, actionable information.

Report recommendations are addressed not only to the federal government, but to all categories of stakeholder groups identified in this report. Encouraging a more active role for nonfederal partners is not intended to replace but would supplement the science and assessment efforts of the federal government, which remain paramount in effectively dealing with the risks of climate change.

Taken together, the recommendations constitute an ambitious agenda of ideas and initiatives. The IAC encourages individuals and groups with an interest in improving climate resilience and preparedness to collaborate in refining and implementing them. The IAC sunsets at the completion of this report, but as described below, with a broader coalition of groups it calls for establishing a new civil-society-based consortium for climate assessment to work toward implementation of these ideas. A more extensive discussion of the ideas presented in this report, including ideas for implementation, is in preparation as a journal special issue.

2. Practitioner perspectives: How assessed knowledge can advance implementation

One of the primary reasons that many adaptation efforts stall after the initial planning phase is that the support systems needed to help practitioners with implementation are lacking. For example, a study by Stults et al. (2015) found that the vast majority of adaptation support tools, resources, and services focus on assisting stakeholders with conducting vulnerability assessments, engaging the public, or creating a climate adaptation plan. Very little support exists for implementing a plan, passing pertinent policies, revising governance and institutional systems, or monitoring results. Businesses and investors face similar challenges in assessing climate risk, developing actionable plans, and implementing those plans. Illustrative challenges include maintaining infrastructure, water supplies, and economic opportunities in light of increases in extreme flooding; identifying thresholds for different types of extreme events and improving preparedness; developing approaches for financial analysis appropriate to evaluating adaptation and mitigation projects; and building adaptive capacity in communities by addressing the underlying causes of vulnerability. These examples are not exhaustive but are meant to demonstrate where and how connecting science to action can help advance resilience efforts and where more applied, digestible, and collaboratively produced science is needed.

In this report, the IAC highlights the opportunity to increase support for practitioners to apply climate-relevant science in multiple ways, including by framing findings and results so they can be integrated into existing decision frameworks and used to implement adaptation and mitigation actions. Practitioners identified a number of ways that assessments could provide value:

- assessing how climate and impacts science can be embedded directly into existing policies, plans, operations, and budget structures;
- signaling the need for transformative action (as opposed to incremental adjustments), including more substantial departures from current policies, infrastructure, institutions, and governance structures, by conducting research that helps identify when small but useful adjustments within current systems or paradigms are insufficient;
- providing scientific resources to support governments and organizations to create and implement codes and policies that integrate future climate considerations;
- developing methods for incorporating climate risk in state, local, and regional financial analysis, bond rating, supply chain risk assessment, and other financial tools;
- supporting capacity building and training for a climate-informed workforce that is able to understand and use climate information, especially in small and rural communities;
- contributing to development of methods and information that effectively communicate the current and future impacts of climate change, including conveying confidence and uncertainty;
- expanding methods and building capacity for state and local governments to engage the public in two-way communication so that planning processes are more robust and support is generated for implementation; and
- aggregating, analyzing, and refining indicators for measuring change in conditions and evaluating effectiveness of adaptation and mitigation.

Practitioners indicate that the capacity and support for action increases if an understanding of climate science and impacts is embedded directly into existing policies, plans, operations, and budget structures (Stults 2017; Woodruff et al. 2019). Integrating climate-relevant science and policy into existing plans and structures (sometimes referred to as ''mainstreaming'') can enable practitioners to act in a timely fashion, identify overlaps with other sectors and stakeholders, and take advantage of funding from multiple sources. Many documents, guidance platforms, and budgeting processes (e.g., sustainability plans, master plans, land use plans, transportation plans, capital improvement plans) could benefit from integrating climate science and information on risks and opportunities. For the most part, when climate information is used in preparing these plans, it is based on historical weather patterns rather than on projections of future hazards informed by climate and impacts science. Without this knowledge, practitioners are making important investment and preparedness decisions based on outdated information—creating a situation where communities, tribes, and states are underpreparing for or maladapting to future hazards. Examples of specific opportunities related to mainstreaming include providing scientific information that can be used in local government planning documents; integrating climate change into dynamic flood maps that include coastal, riverine, and infrastructure-failure flooding; data and projections to support development of climate-smart transportation infrastructure; and tools for scenario analysis and physical risk evaluation that communities can use in planning and decision-making, and that also help companies and investors identify and disclose physical climate risks. It is also critically important to understand the cross-sector effects of adaptation processes to enable pooled resources and protect against unintended consequences of siloed planning.

Another need frequently identified in stakeholder surveys is funding to implement climate adaptation and mitigation actions (Moser et al. 2018). Efforts to obtain funding are held back by a variety of problems, including difficulty in conducting life cycle and benefit–cost analyses (especially for ecological and social costs), lack of familiarity with or access to more sophisticated economic assessment tools under uncertainty, and inability to account for benefits and costs in related areas because financial systems are stove-piped (Moser et al. 2018). In recent years, greater attention has focused on developing and applying a variety of financial analysis methods appropriate to assessing the returns on investment in climate solutions. Among the specific needs and opportunities are improving tools for evaluating costs and benefits of response options (including postponing action or deciding not to act); evaluating debt and investments to reflect changing climate hazards and benefits of resilience measures; assessing the GHG content of different investments and financial instruments (e.g., retirement portfolios); identifying supply chain and other climate-related business risks; and incorporating climate risk in state, local, and regional financial analysis. In addition, practitioners need information on the linkages, synergies, and tradeoffs across adaptation, mitigation, and sustainability measures to enable them to use resources more efficiently when attempting to meet multiple objectives.

Practitioners repeatedly raise the challenge of understanding whether the measures they have implemented are producing their intended benefits, or contrarily producing unintended negative side effects. Practitioners are searching for indicators to monitor changes in physical climate, environmental, and socioeconomic systems that affect vulnerability and resilience at multiple scales, from local to national. Monitoring programs are often difficult to fund so practitioners are seeking inexpensive or reasonably priced approaches to monitor the effects of climate change and response options, especially the effects on the most vulnerable communities. Plans for a comprehensive federal indicator system to monitor ongoing climate changes as well as the implementation and effectiveness of adaptation and mitigation measures (Kenney et al. 2014, 2016) have yet to be implemented, although some groups such as the Urban Sustainability Director's Network (USDN) have developed guidelines for communities to design and implement indicators connected to community adaptation objectives (USDN 2016). A national system could identify standardized categories of indicators with options for local implementation and customization, an approach that would facilitate aggregation of information across different jurisdictions to provide a composite picture of progress across the nation (see section 7c). To ensure relevance and usability, indicators should be developed together with practitioners (Arnott et al. 2016).

3. A national climate information system

As discussed in the previous section, practitioners are seeking knowledge and support for modifying codes, updating regulations and policies, analyzing the financial implications of climate change and solutions, communicating with stakeholders, and monitoring and evaluating results. Some communities and decision-makers do have access to the resources needed to integrate climate change information into their work. If they are fortunate, they may also have financial and other capacities to implement solutions that cut across multiple sectors or objectives. But in most cases, those who are attempting to improve resilience to climate impacts and better manage risks lack the resources to do so. In many jurisdictions, climate issues must be given low priority, often due to inadequate resources and capacity, including funding and staff time. Most jurisdictions and potential users lack knowledge of potentially useful climate information or how to apply it. Also, competing tools and portals can frustrate those who are aware of available resources because guidance for application is lacking.

Practitioners want definitive information on a number of climate adaptation science issues. For example, what are the most regionally robust sources of climate information for assessing specific hazards such as future flood risks, potential for wildfires, recurrence of heat waves, or persistence of drought conditions? How should uncertainty associated with projections of different variables in different regions be taken into account? Can future impacts and avoided damages from adaptation be incorporated in benefit–cost analyses? Which approach to downscaling is appropriate for which applications? What criteria can be used to evaluate proposals for climate services from different providers?

A recent study by the Government Accountability Office (GAO) notes that "the climate information needs of federal, state, local, and private sector decision-makers are not being fully met" and that federal climate information efforts could be improved by establishing a focused and accountable organization that assists in providing authoritative data and needed technical assistance (USGAO 2015). Key organizational and data elements of an effective system include "(1) a focused and accountable organization, (2) authoritative data that define the best available information for decision makers, and (3) technical assistance to help decision makers access, translate, and use climate information in planning" (USGAO 2015). GAO's analysis reviews options for providing climate information and technical assistance including establishment of a new federal agency. They conclude that "a national system to provide climate information to US decision makers could have roles for federal and non-federal entities," with the federal role focusing on providing authoritative data and quality assurance guidelines and nonfederal partners providing technical assistance and connecting decision-makers and intermediaries.

Federal agency efforts during the Obama administration to establish a national Climate Service under NOAA to meet these needs did not receive congressional approval for a variety of reasons. Private-sector climate services are growing in importance as a source of customized climate information on a fee-for-service basis (although paying for these services is beyond the means of many communities and users) and practitioners are increasingly collaborating with climate experts from universities and research centers. What is still missing, however, is an approach for identifying quality assurance guidelines and authoritative data focused on decision-making and a way to scale up the effectiveness of these efforts.

4. A source of authoritative information: Climate assessments

Assessments have strong potential to establish authoritative information on how to use science in making and implementing decisions. Assessments bring together subject-matter experts and produce consensus summaries of the state of the science and the degree of certainty that the experts have in their conclusions. ‘‘Consensus’’ does not mean forced agreement; in cases when participants cannot reach a shared conclusion, they often produce an agreed description of competing explanations and what additional research is needed to reduce uncertainty. Well-known international scientific assessments include the Intergovernmental Panel on Climate Change (IPCC) reports and similar processes focused on ozone depletion and biodiversity loss. IPCC assessments have focused on knowledge about the climate system (e.g., IPCC 2013); impacts and adaptation, including evaluations of adaptation effectiveness (e.g., IPCC 2014a,b); and mitigation (e.g., IPCC 2014c), as well as a variety of special topics such as the implications of limiting the increase in global average surface temperature to 1.5°C (IPCC 2018).

In the United States, Congress placed responsibility for conducting assessments of global environmental issues such as climate change with the U.S. Global Change Research Program (USGCRP), a consortium of 13 agencies that coordinates federal research on climate and global change. Four NCAs have been conducted since the passage of the Global Change Research Act of 1990 (Public L. No. 101-606, 104 Stat. 3096-3104 (1990); https://www.gpo.gov/fdsys/pkg/STATUTE-104/pdf/STATUTE-104-Pg3096.pdf). Volume 1 of the most recent assessment report, NCA4, was released in November 2017 and covers the state of knowledge of climate changes occurring and projected to occur in the United States (USGCRP 2017a). Volume 2, released in November 2018, describes observed and potential impacts and responses in large regions and economic sectors (USGCRP 2018a). Over time, the NCA reports have become increasingly comprehensive and focus on a wide range of sectors, on large geographic regions, and on crosscutting topics (see Fig. 1). A few states and small number of cities/counties (limited to larger and wealthier jurisdictions such as California and New York City) conduct assessments for their own jurisdictions (Bedsworth et al. 2018; NPCC 2015).

I. Overview

II. National Topics

- Our Changing Climate
- Water
- Energy Supply, Delivery, and Demand
- Land Cover and Land-Use Change
- Forests
- Ecosystems, Ecosystem Services, and Biodiversity
- Coastal Effects
- Oceans and Marine Resources
- Agriculture and Rural Communities
- Built Environment, Urban Systems, and Cities
- Transportation
- Air Quality
- Human Health
- Tribes and Indigenous Peoples
- Climate Effects on US International Interests
- Sector Interactions, Multiple Stressors, and Complex Systems

III. Regions

- Northeast
- Southeast
- US Caribbean
- Midwest
- Northern Great Plains
- Southern Great Plains
- Northwest
- Southwest
- Alaska
- Hawai'i and US-Affiliated Pacific Islands

IV. Responses

- Reducing Risks Through Adaptation Actions
- Reducing Risks Through Emissions Mitigation

V. Appendices

- Report Development Process
- Information in the Fourth National Climate Assessment
- Data Tools and Scenario Products
- Looking Abroad: How Other Nations Approach a National Climate Assessment
- Frequently Asked Questions

FIG. 1. Contents of the *Fourth National Climate Assessment, Volume 2*. Adapted from USGCRP (2018a).

For the most part, assessments have not undertaken the challenge of assessing the ‘‘state of practice’’ in using science, traditional knowledge, and other information to manage climate risk—the challenge posed by the GAO in its call for some part of the national climate information system to provide authoritative data and methods to support decisions. Moreover, to date there has been little comparative evaluation of different applications to understand which are robust and can be transferred appropriately from one setting or user group to another. Authoritative and practice-tested information about how to use climate science effectively in practical applications could be the foundation for good practices, capacity building, certification, and scaling up climate services from the private and nonprofit sector to additional communities.

One approach that could help shift the focus to applications of climate science is the establishment of a sustained assessment process—in other words, a process in which users and producers of assessments interact on an ongoing basis, rather than just in the context of developing a report. A 2013 report to the USGCRP from the Federal Advisory Committee for the Third National Climate Assessment Report recommended establishing a sustained assessment process to ‘‘[e]nhance the ability of decision-makers at multiple scales throughout the United States to anticipate, mitigate, and adapt to changes in the global environment’’ (Buizer et al. 2013). The 2013 report recommended that the USGCRP provide four critical elements for the sustained assessment process: 1) establish enduring collaborative partnerships, 2) organize the scientific foundations for climate risk management, 3) provide coordinating infrastructure, and 4) develop clear priorities and a broad base of financial and other resources. While the USGCRP's strategic plan for 2012–21 (USGCRP 2017b) incorporates the objective of sustained assessment and the program established a working group to support the process, the program continues to focus primarily on assessing the state of science in quadrennial and special reports.

The rest of this report discusses the IAC's recommendations for advancing the sustained assessment process.

5. Recommendation 1: Establish a civil-society-based climate assessment consortium

The IAC recommends that national, subnational, and private institutions join together to establish and maintain a *civil-society-based climate assessment consortium* that supports a dynamic assessment process in which practitioners interact with researchers and research agencies/centers, science intermediaries, professional groups, and others to evaluate how to use evolving knowledge to enhance pathways to adapt to and mitigate climate change. The consortium will build on the activities and results of many groups and organizations to assess information needs; identify relevant science and practitioner experience; evaluate alternative methods and data for rigor and usability; develop tested practices, tools, and other authoritative information; increase the accessibility of actionable knowledge; contribute to workforce development and capacity building; and promote science and technology that supports climate risk management. A civil-society-based consortium would complement and build upon—not replace—ongoing federal science and assessment efforts.

The term ''civil-society-based'' is intended to convey an expanded responsibility in governance and agenda setting by nongovernmental institutions. This increased role is essential to facilitate and support sustained dialogue, elevate user perspectives, and thus enable a wider community than is currently the case to shape, access, and use information that supports mitigation and adaptation. It does *not* convey a substantive focus on topics of interest only to nongovernmental organizations. Rather, the consortium would address the needs and interests of governments (particularly state/local/tribal jurisdictions which are taking on much of the burden of implementing adaptation and mitigation measures) as well as those of civil society (broadly defined as formal and informal organizations and groups, including the business and economic sector).

The role of a consortium would be to facilitate the work of participants and bring additional skill and expertise to enable collaborative learning through the interactions of practitioners and experts regarding specific applications of climate information, place-based knowledge, and our understanding of effective solutions. Its functions would include articulating a common agenda and conducting activities that support it. For now, the IAC calls this structure a ''climate assessment consortium,'' but because the concept is likely to evolve significantly in the coming months and years, a different name may eventually be more appropriate.

Specific objectives of a consortium could include

- helping to connect people and institutions who are involved in producing and using global change science (e.g., researchers, professional organizations, intermediaries, and practitioners), including by fostering sustained partnerships such as communities of practice (CoPs) and other mechanisms built around specific challenges and areas of practice;
- using sustained partnerships to evaluate the rigor and utility of tools, products, and activities that are intended to inform practitioners, and to develop and disseminate synthesis products such as good practices, technical guidelines, application templates, indicators, case studies, and other tools (assessing the ''state of practice'' in applying climate science);
- promoting access to climate-relevant science and tools to address adaptation and mitigation needs of high salience to participants;
- synthesizing knowledge of effective collaborative approaches (e.g., coproduction) and reinforce organizations using this approach;
- establishing priority activities and products for collective efforts; and
- engaging with federal institutions and processes to incorporate federal science into applications and provide feedback to federal and nonfederal research efforts on practice-relevant gaps in science and practices.

In addition, a consortium could conduct or support assessments on a limited basis as requested and funded, support strategic planning and communication, and encourage education and workforce development activities.

The consortium could inform implementation of a broad range of climate risk management strategies. In principle, it would focus on topics where evaluating, synthesizing, and integrating science could lead to substantial improvements in planning and enacting different categories of policies and measures. Such a role could be particularly important where there is an emerging body of experience and information but important uncertainties or inconsistencies in approach remain. The topics selected for consortium projects and activities would be determined by its governance process (see section 5c).

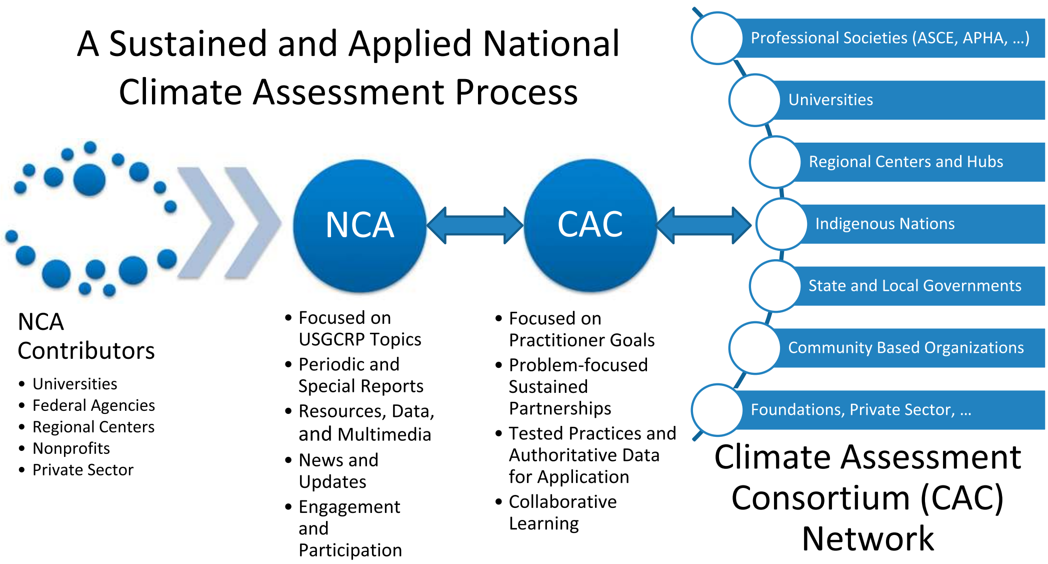

FIG. 2. Conceptual structure of the climate assessment consortium and its relationship to the ongoing National Climate Assessment.

Mitigation-related topics could include a variety of issues associated with managing carbon in the environment. One illustration is the science underlying standards for durable carbon offsets, and the related measurement, reporting, and verification of mitigation commitments. Another potential set of topics concerns how different policies affect flows and stocks of carbon, for example, national policies to reduce carbon intensity of manufacturing leading to importation of carbon-intensive products from overseas, or the flows of carbon across urban to rural environments resulting from city governments' commitments to reduce emissions. Additional work could focus on the environmental, social, and economic benefits of managing different forms of carbon—including carbon in plants and soil organic matter, and carbon contained in different gases such as carbon dioxide and methane—to identify which approaches are more effective. The recently released Second State of the Carbon Cycle Report (USGCRP 2018b) assesses the underlying carbon cycle science but does not address such applied topics in depth.

Illustrative adaptation goals include science and knowledge to improve approaches for preparing for overt climate threats such as flooding and catastrophic wildfires; updating infrastructure for nonstationary conditions; addressing social and environmental justice considerations of climate change and response options; creating opportunities for resilient economic growth; and incorporating climate risk into planning and implementation (see more detailed discussion in section 6).

While the IAC has concluded that there are clear benefits and an urgent need to augment federal science and assessments, it is essential that the federal government continue to research and assess the understanding of the state of climate science through the USGCRP and its ongoing National Climate Assessments. These federal efforts remain crucial to effectively address the risks of climate change.

a. A ''backbone organization'' for existing networks and organizations

The IAC recommends a consortium approach because a large number of groups (too many to name specifically) are working together on an ongoing basis to apply climate information to adaptation and mitigation decisions and actions. These include nonfederal government agencies (state/local/tribal), NGOs (professional societies, think tanks, civic groups, CBOs), research organizations (academic centers, universities, regional science and assessment hubs), and businesses (corporations and other private companies). A consortium could function in the role of a ''backbone organization'' by facilitating a common agenda, shared measurement, mutually reinforcing activities, and communication with respect to collaborative learning, access to authoritative knowledge resources, and applications (Kania and Kramer 2011; Klempin 2016). It is anticipated that many independent initiatives at the state/local/tribal level and a wide range of private sector and NGOs would choose to be members of the consortium (see Fig. 2). In fact, it is the enthusiasm of these existing networks, organizations, and the individuals who populate them that gives us confidence that the idea of a climate assessment consortium is workable. A consortium model would support the widely shared view among those with whom the IAC consulted that there is a significant need to scale up capacity to support reductions in greenhouse gas emissions, preparedness for climate impacts, and resilience.

Coproduction is often central to these efforts and includes potential users as well as researchers in the production of knowledge. It employs iterative processes and promotes mutual learning and growth with the result that all participants, not just knowledge users, evolve in the ways they produce and use knowledge (Meadow et al. 2015). There is a growing body of empirical evidence that coproduction increases knowledge use and allows for customization and tailoring to specific needs of users. It also strengthens relationships and networks and builds overall capacity for the production of usable knowledge and decision-making (Voorberg et al. 2015). Coproduction has gained traction in the last several years (Meadow et al. 2015). As promising as coproduction is, it is not a panacea, and additional work is required to understand effective practices (Lemos et al. 2018). Coproduction can have high transaction costs in terms of time, money, and commitment that make it difficult to scale up, although some of the challenges can be addressed (Lemos et al. 2014).

Additional strategies for supporting development and application of customized approaches for decision support also provide useful methods and lessons for establishing a consortium. These include creating and supporting structures such as problem-focused networks to enable users, scientists, professionals, and other experts to work together; funding research to meet specific needs; and creating boundary organizations that tailor, package, or supply different kinds of knowledge.

The challenge is to work strategically to encourage this ''ground-up'' activity to be more effectively articulated and coordinated. Better coordination could create the enduring partnerships called for in the concept of sustained assessment, encourage collaborative learning, and scale up practice-tested applications of climate adaptation science. The consortium could contribute to learning and development of tested practices by evaluating sources of reliable, relevant, and actionable information. And it could develop resources to guide users to tools and information appropriate for their situation. In doing so, it would work closely with the diverse set of subnational jurisdictions and civil society actors who conduct research and develop applications. In fact, a process that predominantly engages subnational and civil society organizations may be better positioned than federal agencies to sustain partnerships focused on application of science because the participants would be more closely involved in implementing the targeted adaptation or mitigation measures.

b. *Continued importance of a federal role*

To help to advance scientific understanding and provide feedback on research needs, a consortium would interact as closely as possible with the USGCRP and federal mission and research activities. The need for a blended or integrated approach with both federal and nonfederal roles is clear, as noted in the GAO report (USGAO 2015). The federal government, through the USGCRP and its participating agencies, must continue to lead in organizing and funding global change research as well as conducting state-of-science assessments as mandated in legislation. There are a variety of options for ensuring an appropriate division of labor between federal assessments and the work of the consortium. For example, federal reports could continue to assess the evolution of the state of understanding of future climate conditions, observed impacts, and projections of vulnerability at regional and sectoral scales. To complement the federal efforts, consortium-led applied assessments could include convening CoPs around specific user-defined challenges, producing a variety of related products, and providing inputs for future federal reports. It is likely that the role of the federal government and that of the consortium would change over time, and therefore the structure and function of the consortium itself will need to be flexible and resilient.

In addition to their role as major investors in fundamental physical and social science, federal agencies also have management and regulatory responsibilities in many economic sectors as well as in all regions of the nation and have been developing methods and tools for applying science to manage climate risk. Ongoing initiatives such as the U.S. Climate Resilience Toolkit (CRT) would continue to be crucial components of information dissemination and user support. The CRT is a repository of assessment-relevant methods and ''provides scientific tools, information, and expertise to help people manage their climate-related risks and opportunities, and improve their resilience to extreme events'' (U.S. Federal Government 2014). The consortium can add value and leverage CRT and other programs by building the complementary civil society structure needed to incorporate tools and resources developed by additional NGOs and provide evaluation of effectiveness.

c. *Leadership and structure of the climate assessment consortium*

An effective applied assessment process will need to function in a dynamic environment in which the relative contributions of federal and nonfederal components fluctuate over time. Building capacity in civil society to organize and conduct assessments that support decision processes is essential. As civil society's contributions continue to evolve, it will be necessary to revisit definitions of the roles, responsibilities, and institutions needed to manage partnerships between the federal and nonfederal components of the assessment.

To establish the consortium, an organizing process will be needed that engages prospective consortium partners to establish a set of guiding principles, develop a business plan including funding and staffing, evaluate organizational alternatives, and if necessary, incorporate a new entity. As discussed above, many types of organizations and individuals could wish to participate, but to keep this initial process from becoming unwieldy and indecisive, an informal group of conveners is meeting to set the stage for more widespread engagement. Information on initial leadership and engagement opportunities are provided at an interim website (https://www.climateassessment.org/).

Among other matters, the convening process will need to determine whether it is best to establish a formal legal entity such as a nonprofit corporation [a 501(c)(3)] or to pursue some other institutional form. For example, an existing organization or confederation of groups (such as one or more scientific societies or a center based at a university) could house the consortium administratively while allowing for programmatic autonomy. Once an organization is established, its initial governance would incorporate the outcomes of the convening process as the basis for decisions on a series of issues, activities, or outcomes, including

- establishing criteria for and conducting priority-setting and strategic planning for the consortium's activities;
- creating opportunities to gather input from current and potential partners and interested communities and institute decision-making processes;
- obtaining the staffing and tools to support participating networks, CoPs, and activities;
- creating a business model and funding to support coordination and facilitation;
- setting engagement principles, incentives, and criteria for participation;
- establishing peer review and quality assurance procedures to ensure rigor credibility; and
- building communication strategies.

Establishing peer review and quality assurance for consortium products will be essential to maintain the high standard of the current NCA process, which involves review by authors, federal agencies, the White House, the public, and the National Academies. One possible nonfederal model to emulate is the process used by various professional societies to establish and publish practice standards, which also involves significant synthesis of knowledge and engagement with experts and the public. Another important issue is whether some type of screening criteria may need to be applied prior to formal engagement of organizations as climate assessment consortium partners, or whether agreeing to a list of principles will be sufficient. It is critical that the consortium maintain high standards relative to transparency and credibility of its processes and products. However, building credibility cannot come at the expense of timeliness; the consortium will need to address these issues as it begins to provide actionable information during its start-up phase.

d. *Funding*

The challenge of funding the work of a consortium and its partners is a serious one. Resources will be required to support the governance process, a coordinating secretariat, and the specific activities and products of a consortium. Initially, a consortium would depend on contributions from visionary institutions, including state/local/tribal entities, research groups and organizations, private philanthropies, and others. Following this start-up phase (expected to be three to five years), an ongoing, successful applied assessment will require annual funding. The IAC believes a successful long-term business model can include memberships of user communities, project co-funding arrangements with existing centers and organizations with relevant expertise, fee-for-service assessments and other products, collaborations with federal agencies for extending application of federal science, and project-specific support from philanthropies and private sector firms. Ensuring transparency and lack of conflicts of interest will be important for setting priorities for consortium activities and conducting assessments, especially if a funder (e.g., a climate services firm) is submitting results or tools to a consortium community of practice or other process that evaluates scientific credibility of different methods. A distributed funding model, transparency with respect to funding sources, and governance procedures that prevent those with a financial or other interest in a tool or data source from participating in its evaluation will prevent conflicts of interest and skewing of priorities.

6. Recommendation 2: Assess knowledge in the context of how it is applied

To respond to needs identified by practitioners, the IAC advises that a new climate assessment consortium should augment current federal NCA activities by assessing the quality and effectiveness of information and tools being applied to inform adaptation and mitigation. In this report, the term "applied assessment" is used to describe this approach, which will be useful to build sustained partnerships, synthesize tested practices in applying climate science, develop definitive data and methods, and provide feedback to the research community on knowledge gaps. Specifically, the IAC recommends

- convening a technical committee to plan and implement pilot applied assessments and to scope options for conducting them on an ongoing basis and
- developing collaborations with professional societies, university-based research and application centers, regional climate science organizations, and others to conduct assessments focused on specific adaptation and mitigation goals or challenges that evaluate information needs, assess the quality of available information, methods and tools, develop tested practices and standards, and identify gaps and research needs.

The proposed consortium would coordinate these assessments of the application of climate science to address recurring challenges across state/local/tribal jurisdictions of the United States. The mechanism and context for conducting these applied assessments would be a sustained and collaborative consensus process based on principles for effective engagement and coproduction (Lemos et al. 2012; Fujitani et al. 2017). Participants would evaluate information needs as well as the scientific validity and practical utility of different approaches for meeting them. In the case of ongoing assessment activities, sustained partnerships would enable participants to share experiences, evaluate the quality of the information and tools they are using to support adaptation and mitigation actions, and determine the level of confidence and uncertainty that should be attached to that information. Table 1 summarizes how the applied climate assessment proposed here would complement and extend the current NCA process.

TABLE 1. Overview of how "applied assessment" would extend the current National Climate Assessment process.

Current National Climate Assessment	Added dimensions of extended "applied" climate assessment
Organized by sector and region	Organized by practitioner-defined challenges and problems, with attention to cross-sectoral interactions
Produces reports and other products	Supports sustained partnerships (e.g., communities of practice) and produces authoritative "tested practices" and information to support project implementation
Assesses vulnerabilities and risks	Adds assessment of applicability and usability of knowledge and support tools in different stages of implementing projects and improves access and guidance on their use for practitioners
Convened and governed by the federal government with inputs from science community	Coordinated by a consortium of states, local governments, tribes, and scientific/technical groups (research centers, professional societies, NGOs, and CBOs) in collaboration with federal government

a. *Sustained communities of practice*

One model for sustaining these focused partnerships is based on the concept of CoPs. As an illustration, professional organizations such as American Society of Civil Engineers (ASCE), the American Institute of Architects, and the American Public Health Association (APHA) are partnering with other organizations and individuals, including climate scientists to pool their expertise and develop practices, standards, codes and other approaches for incorporating climate risk into their areas of professional practice. These climate partnerships comprise groups of people who gain a greater degree of knowledge of and expertise on a given topic through their regular interaction and thus fulfill the purpose of many CoPs (Probst and Borzillo 2008). CoPs can facilitate sharing of practical knowledge among individuals separated by geographic locations, fields of expertise, and organizational structures. A caveat to their use is that they can require considerable funding and staff time to sustain, depending on their purpose.

This kind of sustained engagement is consistent with the original intent of sustained assessment and can build trust, generate understanding of the appropriate use of knowledge, identify knowledge gaps, and generate additional knowledge and information. In an applied climate assessment, CoPs could be structured to facilitate communication among individuals from the different disciplines needed to

- build relationships, trust, and capacity;
- establish shared terminology and facilitate communication;
- find commonalities among information and support needs across jurisdictions/locations in different parts of the country where practitioners face similar challenges, albeit with different institutional, economic, and other perspectives;
- identify practitioner-defined thresholds and parameters to inform development of future assessment tools and products as well as indicators;
- evaluate the rigor of different methods for meeting information and support needs (e.g., different downscaling methods, methods for modeling flooding, approaches for improved benefit–cost analysis);
- develop tested practices and methods, authoritative datasets, and other resources;

- document results and improve collection of data and information for evaluation;
- disseminate and share resources; and
- identify and fill gaps in knowledge and research needs.

b. *A focus on practical challenges faced by practitioners*

A key issue is how to organize or group adaptation and mitigation activities for the purposes of establishing CoPs and other mechanisms for assessing applied climate science. There are a number of typologies of ''adaptation activities'' (e.g., Biagini et al. 2014) that are both complex and comprehensive that could serve as a foundation. These include activities that protect tangible assets (infrastructure, ecosystems) and community attributes (economic vitality, diversity), as well as enabling activities such as capacity building and warning systems.

Based on its engagement with practitioner groups, the IAC believes one approach that could be tested would be to focus on the practical challenges that multiple communities and jurisdictions across the country or a region are facing. Prioritizing challenges that recur in multiple locations would open the possibility of structured comparative analysis of how groups in these different places are developing information to support decision-making and implementation. More importantly, such a focus would provide practical benefits to a large number of practitioners. Examples of these objectives include

- managing catastrophic wildfire risk;
- reducing impacts of increasingly severe inland flooding;
- managing risks from sea level rise, storm surge, and subsidence;
- planning public health interventions for more severe heat waves and/or changing disease vectors;
- modernizing infrastructure to mediate changing return periods and magnitudes of future climate hazards;
- planning economic development using evaluation of impacts of climate change and response measures;
- siting public or private facilities considering the changing potential for flooding, coastal storm surge, or other events;
- sustaining safe water supply given changing timing/patterns of precipitation;
- conserving ecosystems and biodiversity by anticipating needed changes in management or location of reserves capable of sustaining threatened or endangered species;
- ensuring food security;
- preparing for internal displacement and permanent migration; and
- managing the effects of cascading impacts within and across impacted sectors.

c. *A template for analysis: Stages of project implementation*

Because practitioners indicate that a common challenge is that action plans are stalling at the implementation stage, the IAC explored structuring the content of applied assessments around information needed and used at the different stages of a project implementation life cycle. In cases where uncertainty is considerable, project implementation is often structured as an iterative adaptive learning process (see Moss et al. 2014).

Figure 3 provides a stylized depiction of the stages that a practitioner might go through in implementing an adaptation or mitigation project. In practice, the stages may unfold in a different order and blend together. The point of the figure is not to describe a sequence of steps as experienced in any particular decision, but to systematically identify the different methods and types of information needed to frame problems, design options, make a decision, obtain financing, facilitate action through compliance with codes and standards, and complete other implementation steps. The text boxes that ring the figure provide example topics that the applied assessment would explore with the objective of identifying tested practices and methods that practitioners facing similar climate challenges could start from and adapt to their own circumstances. By focusing this analysis on a specific objective or challenge as described in the preceding section, this assessment could be as detailed as needed to evaluate rigor and suitability of specific types of downscaling, modeling, decision-support tools, and other resources needed.

Possible sources of data and knowledge for these assessments include the experience of practitioners (related to practical matters such as planning, permitting, updating codes and standards, budgeting, etc.), results from ongoing projects, and information from case studies of how different jurisdictions or groups have sourced and used climate knowledge for a given adaptation or mitigation action. An assessment focused on different groups of practitioner challenges would be an efficient way to gather and synthesize lessons learned in order to scale up information services (including private and public sector climate services) and identify areas where innovation and additional research are required because needs are still mostly unmet.

For example, Table 2 illustrates the potential for comparative analysis of methods used in different communities to assess the rigor of each step in a chain of models or evidence required to evaluate how different combinations of stressors could affect stormwater

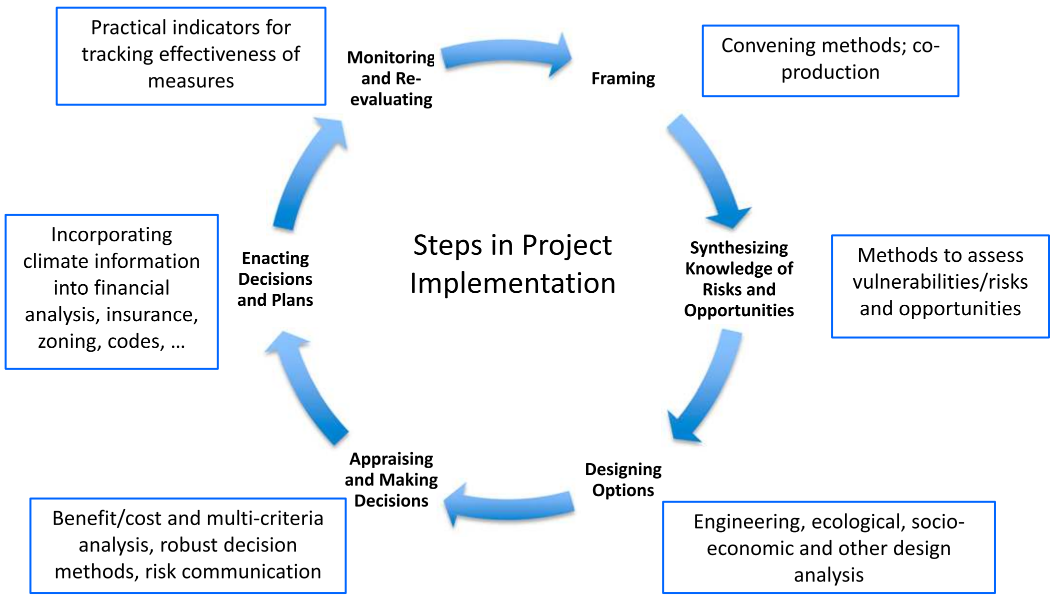

FIG. 3. Identifying and assessing climate knowledge needed to support steps in implementing adaptation and mitigation options. This figure illustrates the range of issues that an applied assessment could address if it focused on evaluating information needed to frame a problem and implement solutions. The figure does not represent a literal process but rather typical stages through which a practitioner is likely to have to step.

infrastructure. The point of this examination is not to critique individual tools but rather to pool knowledge and experience of applying climate-relevant science to establish good or ''better'' practices, specify the contexts and conditions under which they perform well, and identify research needs. In addition to technical analysis of specific impact assessment methods, the assessment could highlight and assess different methods and aspects of adaptation science, including risk assessment, risk communication, risk perception, and risk management in supporting climate-related decisions (Moss et al. 2013).

d. Building a problem-focused national network

The proposed climate assessment consortium will facilitate an applied assessment process by piloting a variety of approaches based on sustained dialogue and communication, sharing of experience and information, and rigorous assessment of competing methods for providing climate information. These processes will produce information based on tested, authoritative practices appropriate for the participants that would also be extensible and provide support to others. The pilot assessments would also be a venue for information sharing and capacity building. Beginning with a small number of pilot projects, the consortium would analyze the effectiveness of its own efforts, develop a workable approach, and establish additional CoPs and/or other processes for different goals or problems, depending on the interest of partners and availability of funding. Over time, this would lead to a distributed, sustained national effort that would encompass a network of networks focused on an array of high-priority adaptation and mitigation challenges.

e. Limits and caveats

In attempting to use the assessment process to scale up support for adaptation and mitigation, the IAC acknowledges the need to determine when and where information needs for adaptation can be aggregated and streamlined, and when standardization is not desirable and can even be potentially dangerous. One example is the trade-off between simplification and complexity of contexts in which standardization may do more harm than good, as when tools that are not fit-for-purpose are applied and lead to poor decisions. The applied climate assessment must be an adaptive organization that works to optimize its own utility while it experiments with additional strategies to build capacity for customized processes and products.

7. Recommendation 3: Advance methods for climate risk management

One of the roles suggested for a sustained climate assessment process in *Preparing the Nation for Change* (Buizer et al. 2013) is to support development of methods for climate risk management. The IAC's third recommendation identifies six opportunities that address specific needs or take advantage of promising methods

TABLE 2. Assessing different approaches for applying science to inform adaptation and mitigation actions. The table is based on case-study examples from the American Geophysical Union's Thriving Earth Exchange (https://thrivingearthexchange.org/projects/) and demonstrates how various strategies to assess impacts and risks adopted by different communities could be compared. Column 1 describes the shared objective of planning resilient stormwater infrastructure and identifies communities where it is being pursued; column 2 illustrates potential information needs; and column 3 highlights opportunities for participants to share experience and methods, learn collaboratively, evaluate different methods and data for rigor and effectiveness, and eventually establish tested practices.

Examples of practitioner adaptation objectives	Examples of recurring information needs	Examples of technical assessment of applied science
Plan climate-resilient stormwater infrastructure + Chicago, Illinois: Identify a fundable strategy to reduce basement flooding + Connellsville, Pennsylvania: Assess flooding for community development + De Soto, Missouri: Manage flooding for preparedness and revitalization + Northern Virginia: Plan climate-resilient stormwater infrastructure for a growing region	1. Project future vulnerability to flooding under climate and growth scenarios	1.1 Assess data quality and methods for correlating observed rainfall and flooding locations 1.2 Assess approaches for projecting rainfall patterns and probability of flood threshold exceedance 1.3 Assess methods for integrating population projections and development scenarios to project change in extent of impervious surfaces
	2. Evaluate benefits of different stormwater infrastructure management approaches (e.g., green vs gray infrastructure)	2.1 Assess use of benefit–cost methods and other approaches for appraising green and gray infrastructure options 2.2 Assess use of GIS-based modeling methods to evaluate green vs gray infrastructure options
	3. Design and implement stormwater infrastructure projects	3.1 Assess information and process needs for mainstreaming information about climate risk in the design of stormwater infrastructure components and measures to promote implementation

and technologies. These are opportunities to evaluate climate information in the context in which it used; improve methods to appraise adaptation and mitigation options; advance climate indicator systems; harness artificial intelligence; apply citizen and community science; and use geospatial analysis methods to assess intersecting climate, environmental, and socioeconomic trends. For each opportunity, we describe example applications and recommend next steps based on an evaluation of the current state of deployment, opportunities or obstacles, and the potential contributions of academia, the private sector, and government. We encourage groups working in these areas to use these ideas in their own work to accelerate innovation and adoption in climate risk management.

a. *Evaluate climate information in the context in which it is used*

A large array of climate information produced using a range of methodologies is freely available. While potentially of great value to practitioners, these various observational datasets and suites of model projections often appear to provide conflicting information or are inappropriate for the particular spatial scale, geographic location, time frame, or phenomena of interest for a given application (National Research Council 2012; USGCRP 2017a). By contrast, many locales do not have much or even any geographically specific, relevant data available and thus depend on generalized information for a region or sector (or even the nation as a whole). How can practitioners choose the information that is most suitable for their particular needs from the many available resources? To what degree does the range of available information characterize or acknowledge legitimate scientific uncertainty and to what degree can some information be deemed of higher or lower credibility for a given application? This problem has been coined the ''practitioner's dilemma'' (Barsugli et al. 2013).

The fundamental mismatch of scales between global climate model (GCM) projections and the information needs of many adaptation practitioners has led to a proliferation of technical methods for translating GCM information from coarser- to finer-scale resolution. While intended to meet practitioner needs, these methods have historically been developed with limited or no collaboration with the end user. While many aspects of climate model performance improve with increased resolution, high resolution does not guarantee that local-scale or regional-scale climate features are accurately represented (National Research Council 2012; CSIWG 2018). Thus, it is particularly important to evaluate GCMs and the various methods of producing finer-scale climate information in the context of particular adaptation challenges to determine how fit the information is for planning and decision-making. This type of evaluation, which includes characterizing uncertainties in a decision-relevant manner, is critical but presents substantial scientific and technical challenges that have only recently begun to be addressed (Shepherd et al. 2018; Hackenbruch et al. 2017; CADWR 2015). Also, while model-evaluation research efforts to date have been important for advancing climate science, most of this work has not been leveraged to advance climate adaptation. There has not been sufficient coordination, synthesis, translation, dissemination, or discussion of the results for users trying to make informed decisions about what climate information and which analysis methods may be fit for particular adaptation challenges. The IAC recommends

- developing approaches for producing and evaluating climate science for applications that involve close coordination between scientific and user communities;
- establishing a trusted and reliable process for providing ongoing guidance to the climate information user community regarding which means of producing climate information are suited to which kinds of adaptation challenges;
- convening a multi-institutional and multidisciplinary technical committee to identify good practices, high-priority research gaps, standards for evaluating progress, and measures for promoting effective scientist–practitioner engagement; and
- training and certifying a new generation of scientific and technical experts capable of effectively and ethically applying climate science in support of decision-making.

b. *Assess methods for appraising adaptation and mitigation options and making decisions*

Those planning and seeking financing for climate adaptation and mitigation actions often choose to use—or in some cases are compelled by decision-making constituencies to use—benefit–cost analysis (BCA) to evaluate whether a proposal's overall benefits are greater than its costs. Some tools and methods derived from the literature on the national-scale costs of inaction (see chapter 29 in USGCRP 2018a) can be applied at the project scale with modifications [e.g., Neumann et al. (2015) and other relevant literature on coastal risks in Moser et al. (2014)]. Adaptation investment planning in international development has also applied BCA frameworks to project-level adaptation planning, and this work includes some creative lessons for dealing with benefit categories that are potentially unquantifiable but known to be important (e.g., Cervigni et al. 2017; Ahouissoussi et al. 2014).

As discussed in section 2, unquantifiable benefits and costs rightfully frustrate practitioners and undermine confidence that BCA calculations are well suited to analyses of climate change measures. BCAs generally fail to consider all relevant costs and benefits, such as the implications for groups that may be affected but whose perspectives and interests are not incorporated into the analysis; effects on nearby communities or groups that can be positively or negatively affected; life cycle cost and benefits; or many intangible as yet unestimated costs and benefits to complex human–environment systems such as climate/economic interactions [limitations are noted explicitly in Hsiang et al. (2017), Chambwera et al. (2014), and Hunt and Watkiss (2011)]. Moreover, BCA is challenged by uncertainty, attitudes toward risk (especially regarding irreversible damages), questions about discount rates and time preference, and longer-than-usual time horizons. As a result, the conclusions of BCA frequently do not reflect the full picture of the implications of proposed measures. Perhaps, at best, they produce suggestive "first cut" insights into narrowly defined net benefits calibrated exclusively in currency—metrics that are useful in the context of additional measures of benefits and costs but are likely to be incomplete. In some cases, this level of analysis usefully guides iterative risk management, as it has for the example of protection of Boston's coastline through alternative modes of coastline hardening (Kirshen et al. 2018).

Meanwhile, uncertainty about how to use the full range of future climate projections, including the tails of distributions of future outcomes, has led to an interest in alternative risk-based decision-analysis frameworks for adaptation, such as robust decision-making (Hallegatte et al. 2012), multicriteria analyses, or qualitative risk matrix calibrations when data are scarce. It follows that greater attention must be paid to evaluating applied assessment processes to the full range of decision analytic methods suited to different applications.

Building on insights from experience, available studies, methods, and guidance documents on applying BCA methods to project-scale analysis of adaptation and mitigation options, the IAC recommends

- assessing currently available tools and approaches and how they can be applied to support diverse adaptation decisions and actions in a special report and related guidance and training materials;
- disseminating tools and knowledge, for example, providing online access to spreadsheet tools, available climate scenarios for mitigation pathways and other relevant data, and self-guided training tools; and
- providing feedback to the research community, tool developers, and grant-making agencies and foundations

about gaps in knowledge or capabilities to foster research on improving application of BCA to climate adaptation projects.

We note the importance of addressing the needs of staff and individuals in small communities (i.e., under 250 000 people) who lack technical expertise and resources to access even basic tools and methods.

c. *Foster collaboration of local and national indicator initiatives*

Interest in using indicators to inform climate-related decisions has increased at many levels of government (NPCC 2010, 2015; Kenney et al. 2014; National Academies of Sciences, Engineering, and Medicine 2016; NYC Office of the Mayor 2018; USDN 2016). Indicators are seen as critical to supporting mitigation and adaptation planning and to evaluate the effectiveness of climate-related actions, particularly at the local level. To advance the usefulness of indicators across multiple scales of governance, we propose to identify and integrate indicators across geographic scales and governance contexts, using urban infrastructure indicators as a possible test case.

The interest in locally driven indicator systems follows on efforts to establish a National Climate Indicators System (NCIS) that evolved from the Third National Climate Assessment, based on recommendations from the National Research Council and others (e.g., Janetos et al. 2012; Buizer et al. 2013; Kenney et al. 2014, 2016). The goal of the NCIS was to provide a method to detect the status, rates, and trends of environmental and socioeconomic variables to support effective climate change mitigation and adaptation measures and inform research, education, and management decisions. The proposal for implementing the NCIS was to pilot a subset of nationally relevant indicators first, then follow up with a larger set, refining and adding indicators where necessary (Kenney et al. 2014). Efforts to develop climate indicators and apply them have become widespread, and the need for such indicators is only growing as investors and other decision-makers seek to understand the effectiveness of potential interventions. In one prominent example at the local level, the USDN supported establishing indicator systems to track condition, vulnerability, and adaptation effectiveness by publishing a process for developing locally specific adaptation indicators aligned with key planning goals (USDN 2016). Other relevant initiatives also provide a foundation for collaborative learning (e.g., U.S. Environmental Protection Agency 2016, 2017; STAR Communities 2019; ND-GAIN 2019).

To support these applications, research is needed to determine what indicators are useful to local communities for aiding adaptation and to explore whether these indicators can be scaled up (aggregated) to provide useful information to support national-scale assessments and decision-making. At the local level, capacity and resources may determine the number and kind of indicators selected. Smaller, more resource-constrained communities may seek to limit the number selected based on their highest priorities, or they may decide not to use them at all due to insufficient capacity to establish and track the indicators over time. Research could evaluate local capacity for developing and using indicators, depending on city/community size and other factors, and how that affects the number and type of indicators prioritized and selected, as well as their ultimate usefulness for supporting adaptation decisions. Likewise, research would help to determine the usefulness of national-scale indicators (e.g., from the NCIS) for providing information on vulnerability and adaptation effectiveness at local and regional scales (Arnott et al. 2016). This scalability of indicators is described in Kenney et al. (2016). The assessment process could also play a role in supporting data collection and aggregation, once useful indicators are identified. Methods for evaluating the scalability of the indicators need to be developed.

The IAC recommends using the applied assessment process to examine the need for and use of locally developed indicators, and to identify potential convergence between national-scale and local- to regional-scale indicators that could shape the future direction of the NCIS. One option is to focus on urban infrastructure indicators as an initial test case, given their widespread relevance and potential for application, as noted above. This pilot activity could include

- taking stock of existing climate indicator efforts for urban contexts to evaluate current applications and outcomes, capacity requirements, lessons learned, constraints and opportunities, what indicators are important but missing, and other questions;
- extending ongoing work on indicators and partner with local communities of varying sizes and contexts to establish a shared framework for further research and assessment;
- conducting pilot urban infrastructure indicator studies using the shared framework, focusing on feasibility, applicability, and potential for integration across local, regional, and national scales; and
- analyzing results from pilot studies and other ongoing initiatives to identify useful and feasible approaches for different local and regional settings, and to inform changes to the NCIS with the objective of linking and integrating local, regional, and national

scale indicators and supporting their transferability to different areas across different scales, to the extent feasible.

d. *Accelerate the use of artificial intelligence to support climate resilience building*

Artificial intelligence (AI) offers opportunities to change how society responds to climate risks. Subdisciplines of AI, such as machine learning (ML) and robotics, have already been applied in climate science and engineering, and their early success suggests there is tremendous potential for AI to improve resilience to climate change. As cities, social systems, and infrastructures grow more complex, and as climates continues to change, AI can reveal impacts, insights, and options that would be difficult to otherwise discover (Ganguly et al. 2018). Recent advances have touched three broad areas of climate: Earth-systems science and modeling (Rasp et al. 2018), assessment and management of risks and adaptation (Chavez et al. 2015), and mitigation (Mascaro et al. 2014). Climate resilience can benefit from domain-specific AI breakthroughs (e.g., disaster robots; Spenko et al. 2018) that may not be immediately recognizable as tools for climate adaptation. But potential risks and challenges—including maintaining transparency, transferring the capacity of individuals to act to automated processes, and societal resistance and restrictions on new technologies that can be seen as ''taking over'' interactions and environments—will need to be thoughtfully explored and addressed, including development of ethical principles to undergird development and adoption of AI applications (Floridi et al. 2018).

The ability of ML to make a difference in recent years has been motivated by a mix of computing power, novel algorithms, and perhaps most important, the availability of unprecedented and increasing volumes of heterogeneous data. In climate science, ''big data'' come from satellite remote sensors and large-scale numerical models and are often owned by government agencies or laboratories and openly shared. Adaptation-specific data, such as those for critical infrastructures and key resources, may be spread across government agencies as well as public and private sectors, often with privacy or security concerns. While academia has spawned innovative AI startups, partnerships with the private and public sectors (and government laboratories and agencies) may have significant roles to play in developing, nurturing, and sustaining wider application of AI in adaptation and mitigation. Research in AI is only beginning to get translated to real-world applications, which in turn are becoming more prominent as tools for community and regional resilience. This emergence is likely to have profound implications for our ability to improve translational climate science, manage climate risks, and inform mitigation policy. However, it is important to continually assess where AI tools are most effective, practical, and sustainable, and where and why gaps remain unfilled. The IAC identifies a number of opportunities for the applied assessment process:

- convening and developing partnerships that include academia, the private and public sectors, and other groups to map and support the key integrators of technical, application, and data science that are related to climate risk management;
- assessing actual usage in decision contexts by conducting a thorough evaluation of the current applications, risks, and opportunities for AI in climate adaptation, including the perspective of practitioners and citizens;
- identifying applications that can be conducted in a test-bed mode to provide the greatest advancement in shared, scalable, actionable information; and
- preparing a special report, potentially produced jointly with the federal NCA process, to synthesize knowledge and identify productive frontiers for further development and deployment of AI in climate risk management.

e. *Launch a rigorous citizen and community science initiative to improve data on impacts and responses*

The term ''citizen and community science'' describes the wide range of ways that people who are not trained as scientists can participate in science processes—from collecting data to co-designing applied research projects that advance local priorities. For example, the long-running Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) draws on over 20 000 volunteers across North America to collect precipitation data to fill in known data gaps, while participants in the USA National Phenology Network who track the phenology of plants and animals in their localities help scientists assess and predict impacts of a changing climate on thousands of species. Other community science projects focus on evaluating and informing strategies to reduce exposure to climate impacts such as flooding in New Orleans or urban heat in New York City. With their diversity and focus on real-world problems, citizen and community science programs are particularly promising for applying climate science to climate adaptation and mitigation. The NCA3 report (Melillo et al. 2014) noted that ''There are opportunities to take advantage of citizen science observations . . . for data-poor regions, focusing on inadequately documented socioeconomic, ecological, and health-related factors, and under-observed regional and sectoral data.''

A recent report also suggests that citizen science can be "a pathway for introducing new processes, observations, data, and epistemologies to science," including climate science (National Academies of Sciences, Engineering, and Medicine 2018).

Despite this potential, citizen and community science is currently underused in climate science and assessment. Increasing its use could help to fill many long-standing data gaps related to local climate extremes and conditions; the impacts of these events on the environment, infrastructure, and communities; and needs for different types of adaptation measures. A particular opportunity is to document and improve understanding of the interactions of climate change with preexisting challenges such as poor air and water quality, exposure to toxic industrial by-products, lack of access to resources for coping and adapting, and other historical problems. Benefits of citizen science projects can include improving observational datasets, informing model development, building awareness within communities of how climate change is affecting them, supporting co-creation of solutions, contributing to monitoring of results in an efficient manner, and deepening and expanding public engagement with climate science and solutions.

It is for these reasons that the IAC recommends that the applied assessment coordinate with citizen science groups and programs to expand the use of citizen science in the sustained assessment process, prioritizing underserved regions and communities where data gaps are most severe. It is essential to co-design projects in a way that encourages broad engagement (especially in areas where economic constraints, lack of opportunity, or cultural differences create barriers for some participants), advances climate resilience, and delivers robust data and tangible benefits. A variety of near-term initiatives would support this broad effort:

- assess current usage of citizen and community science in climate adaptation and mitigation;
- develop standards and protocols to ensure rigor and consistency in data collection, including harnessing emerging technologies such as AI;
- identify ways that citizen and community science provide local contextualization to supplement climate projections and models;
- adapt the participatory methods of citizen and community science to enable climate research to inform community participation in climate policy debates;
- use citizen and community science to better connect climate research to the short-and long-term priorities of historically underserved, marginalized, or oppressed communities.

f. Facilitate use of geospatial analysis

Geospatial analysis, including GIS and other mapping tools, enables practitioners to determine how climate extremes have impacted or will impact things they care about (such as property, infrastructure, and communities) as well as to explore the effectiveness and implications of adaptation options (e.g., trade-offs across ecosystem- and infrastructure-based approaches to flood control). GIS methods are particularly useful for integrating climate data (both observations and projections) with socioeconomic and environmental data on factors that affect vulnerability and risk. Technological innovation has facilitated a transition from maps available at only national and regional scales to the provision of analysis, services, and reports at state, county, and municipal levels. Planners and engineers are moving beyond "response and recovery" to applications that build resilience. Sustainability officers, planners, financial analysts, and other employees are bridging the gaps between different city departments and implementing projects to build resilience. Communities are integrating their quantitative resilience assessments into their comprehensive plans, emergency management plans, and sustainability plans.

Better and more accessible tools to map and integrate data bring with them some potential pitfalls. One is that there is significant potential to overlay data that appear to be connected but on closer analysis are not. It is also possible to mistakenly use data that have not been properly assessed as fit for a particular purpose. For example, while model data can be downscaled to a very high resolution, the resulting maps are usually not accurate or robust, even though they can look very compelling. There are also issues of access: large cities, such as New York, Miami, and Los Angeles, have built capacity to develop applications and conduct their own analyses, and medium-sized cities are partnering with local universities, nonprofits, and firms. But small cities, historically disadvantaged communities, and many rural areas usually lack financial resources, capacity, or data needed to access these tools.

The IAC recommends accelerating efforts to assess different methods and applications for integrating climate, socioeconomic, and environmental data for assessing vulnerability. Developing tested practices on how to apply these tools in a variety of specific settings would be particularly useful. Specific opportunities include

- facilitating ongoing public–private partnerships with regional climate centers and adaptation professional groups that are convening communities of practice around specific mapping approaches using weather

and climate data, including the use of climate indicators and future climate projections;
- collaborating with ongoing efforts such as the CRT (which provides scientific expertise, tools, and information) to develop and apply a rigorous framework to assess practices and methods for applying geospatial data and tools to specific problems, building on learning and evaluation opportunities provided by the explosion of case studies and applications; and
- prioritizing capacity building and access to local climate assessments for small, historically disadvantaged, and rural communities.

8. Closing thoughts and next steps

The Federal Advisory Committee on the Sustained National Climate Assessment was originally charged to provide advice to federal agencies on how to accelerate progress in establishing a "sustained climate assessment" process. While continuing this work as an independent group, the IAC concluded that meeting the challenge of climate change risk management required broadening the scope of assessments and engaging with a wider range of actors beyond the federal agencies. The IAC has identified a very ambitious agenda of initiatives that it believes can advance a sustained assessment and increase the application of climate science and knowledge by practitioners. The central strategy of that agenda is establishing a new and more inclusive assessment consortium. This approach is recommended for a variety of reasons, including the fact that the federal government alone cannot prepare the nation for change, and there is a need to accelerate progress by synthesizing and sharing the lessons currently being learned both inside and outside the federal government. This will require establishing sustained partnerships for knowledge production and application. Defining a more organized role for civil society cannot replace the crucial contributions of federal institutions; most of the science that the nation needs will continue to come from ongoing federal research investments, even as support for research and assessments diversifies. Thus, the IAC urges a range of partners to join forces to address climate adaptation and mitigation issues, including the USGCRP and other federal programs and agencies, as well as the many nonfederal groups working in this area.

The proposed civil-society-based consortium would build on and augment federal climate assessments by synthesizing and evaluating knowledge, generated through multiple ways of knowing and learning, accessing the experience of on-the-ground practitioners, and developing new products to meet the needs of decision-makers across the nation. The consortium would expand the scientific foundations for risk management beyond the investments made in previous assessments. It would also enable its members to address other shared challenges and opportunities, including communication, engagement, and capacity building.

The successful establishment of a consortium and implementation of the ideas in this report will be a turning point for addressing the risks of climate change. These efforts can be a model for collaboration and will support the necessary actions that must be taken to build a culture of preparation and resilience in the face of a changing climate.

Acknowledgments. This report would not have been possible without the support and participation of numerous organizations and individuals. We thank New York State Governor Andrew M. Cuomo for announcing in his 2018 State of the State agenda that the IAC would be reconvened. The New York State Energy Research and Development Authority (Contract ID 123416), Columbia University's Earth Institute, and the American Meteorological Society provided essential financial support and much more, including sage advice and moral support from John O'Leary, Shara Mohtadi, Steve Cohen, Alex Halliday, Peter deMenocal, Keith Seitter, Paul Higgins, and Bill Hooke. We thank the attendees of a workshop, generously funded by the Kresge Foundation in November of 2017, that laid a foundation for the idea to establish a civil-society-based assessment consortium. During the course of preparing the report, IAC members consulted with individuals too numerous to list here—state, local, and tribal officials; researchers; experts in nongovernmental and community-based organizations; and professionals in engineering, architecture, public health, adaptation, and other areas. We are so grateful for their time and expertise. We thank the members and staff of the National Academy of Sciences, Engineering, and Medicine's Committee to Advise the U.S. Global Change Research Program for providing individual comments on preliminary recommendations during several discussions in open sessions of their meetings. The following individuals provided detailed comments on an earlier version of this report, which greatly sharpened our thinking and recommendations: John Balbus, Tom Dietz, Phil Duffy, Baruch Fischhoff, Brenda Hoppe, Melissa Kenney, Linda Mearns, Claudia Nierenberg, Kathleen Segerson, Soroosh Sorooshian, Chris Weaver, and Brian Zuckerman. Mary Black provided insightful copy editing of several versions of the report. We also thank four anonymous reviewers for their effort and care in critiquing and improving the report. It is the dedication, thoughtful feedback, expertise, care, and commitment of all these people and more that not only made this report possible, but allow us all to continue to support smart and insightful actions in a changing climate. We are grateful as authors and as global citizens. Author contributions: RM, SA, KB, MB, AC, JD, PF, KJ, AJ, KK, JK, ML, JM, RP, TR, LS, JS, JW, and DZ were members of the IAC and shared in researching, discussing, drafting, and approving the report. BA, JF, AG, LJ, SJ, PK, RK, AM, RM, JN, WS, JS, PT, GY, and RZ contributed to specific sections of the report.

REFERENCES

Ahouissoussi, N., J. E. Neumann, and J. P. Srivastava, 2014: Building resilience to climate change in the South Caucasus region's agricultural sector. World Bank Report 87601, 167 pp, https://doi.org/10.1596/978-1-4648-0214-0.

Arnott, J. C., S. C. Moser, and K. A. Goodrich, 2016: Evaluation that counts: A review of climate change adaptation indicators & metrics using lessons from effective evaluation and science-practice interaction. *Environ. Sci. Policy*, **66**, 383–392, https://doi.org/10.1016/j.envsci.2016.06.017.

Barsugli, J. J., and Coauthors, 2013: The practitioner's dilemma: How to assess the credibility of downscaled climate projections. *Eos, Trans. Amer. Geophys. Union*, **94**, 424–425, https://doi.org/10.1002/2013EO460005.

Bedsworth, L., D. Cayan, G. Franco, L. Fisher, and S. Ziaja, 2018: California's fourth climate change assessment: Statewide summary report. Report SUM-CCCA4-2018-013, 132 pp., http://climateassessment.ca.gov/state/docs/20190116-StatewideSummary.pdf.

Biagini, B., R. Bierbaum, M. Stults, S. Dobardzic, and S. McNeeley, 2014: A typology of adaptation actions: A global look at climate adaptation actions financed through the Global Environment Facility. *Global Environ. Change*, **25**, 97–108, https://doi.org/10.1016/j.gloenvcha.2014.01.003.

Bierbaum, R., and Coauthors, 2014: Adaptation. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, T. C. Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 670–706, https://data.globalchange.gov/report/nca3/chapter/adaptation.

Buizer, J. L., P. Fleming, S. L. Hays, K. Dow, C. B. Field, D. Gustafson, A. Luers, and R. H. Moss, 2013: Preparing the nation for change: Building a sustained national climate assessment process. National Climate Assessment and Development Advisory Committee (NCADAC) Rep., 73 pp., https://sncaadvisorycommittee.noaa.gov/Portals/0/Meeting-Documents/NCA-SASRWG_Report_Print.pdf.

CADWR, 2015: Perspective and guidance for climate change analysis. California Department of Water Resources Rep., 142 pp., https://water.ca.gov/LegacyFiles/climatechange/docs/2015/Perspectives_Guidance_Climate_Change_Analysis.pdf.

Cervigni, R., A. Losos, P. Chinowsky, and J. E. Neumann, 2017: Enhancing the climate resilience of Africa's infrastructure: The roads and bridges sector. World Bank Rep., 136 pp., http://documents.worldbank.org/curated/en/270671478809724744/Enhancing-the-climate-resilience-of-Africa-s-Infrastructure-the-roads-and-bridges-sector.

Chambwera, M., and Coauthors, 2014: Economics of adaptation. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*, C. B. Field et al., Eds., Cambridge University Press, 945–977, http://www.ipcc.ch/report/ar5/wg2/.

Chavez, E., G. Conway, M. Ghil, and M. Sadler, 2015: An end-to-end assessment of extreme weather impacts on food security. *Nat. Climate Change*, **5**, 997–1001, https://doi.org/10.1038/nclimate2747.

CSIWG, 2018: Paying it forward: The path toward climate-safe infrastructure in California. Climate-Safe Infrastructure Working Group Rep. CNRA-CCA4-CSI-001, 257 pp., http://resources.ca.gov/climate/climate-safe-infrastructure-working-group/.

Floridi, L., and Coauthors, 2018: AI4People—An ethical framework for a good AI society: Opportunities, risks, principles, and recommendations. *Minds Mach.*, **28**, 689–707, https://doi.org/10.1007/s11023-018-9482-5.

Fujitani, M., A. McFall, C. Randler, and R. Arlinghaus, 2017: Participatory adaptive management leads to environmental learning outcomes extending beyond the sphere of science. *Sci. Adv.*, **3**, e1602516, https://doi.org/10.1126/sciadv.1602516.

Ganguly, A. R., E. Kodra, U. Bhatia, M. E. Warner, K. Duffy, A. Banerjee, and S. Ganguly, 2018: Data-driven solutions. *Climate 2020: Degrees of Devastation*, United Nations Association-UK, 82–85, https://www.una.org.uk/climate-2020-degrees-devastation.

Hackenbruch, J., T. Kunz-Plapp, S. Müller, and J. Schipper, 2017: Tailoring climate parameters to information needs for local adaptation to climate change. *Climate*, **5**, 25, https://doi.org/10.3390/cli5020025.

Hallegatte, S., A. Shah, R. Lempert, C. Brown, and S. Gill, 2012: Investment decision making under deep uncertainty: Application to climate change. World Bank Policy Research Working Paper 6193, 39 pp., http://hdl.handle.net/10986/12028.

Hansen, L., R. M. Gregg, V. Arroyo, S. Ellsworth, L. Jackson, and S. Snover, 2012: The state of adaptation in the United States: An overview. MacArthur Foundation EcoAdapt Rep., 118 pp., http://ecoadapt.org/programs/state-of-adaptation/US-state-of-adaptation.

Hsiang, S., and Coauthors, 2017: Estimating the economic damage of climate change in the United States. *Science*, **356**, 1362–1369, https://doi.org/10.1126/science.aal4369.

Hunt, A., and P. Watkiss, 2011: Climate change impacts and adaptation in cities: A review of the literature. *Climatic Change*, **104**, 13–49, https://doi.org/10.1007/s10584-010-9975-6.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis*. Cambridge University Press, 1535 pp., https://doi.org/10.1017/CBO9781107415324.

——, 2014a: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Cambridge University Press, 1132 pp., https://doi.org/10.1017/CBO9781107415379.

——, 2014b: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects*. Cambridge University Press, 688 pp., https://doi.org/10.1017/CBO9781107415386.

——, 2014c: *Climate Change 2014: Mitigation of Climate Change*. Cambridge University Press, 1465 pp., https://doi.org/10.1017/CBO9781107415416.

——, 2018: Global warming of 1.5°C: An IPCC special report. V. Masson-Delmotte et al., Eds., World Meteorological Organization Rep., 243 pp., http://www.ipcc.ch/report/sr15/.

Janetos, A. C., R. S. Chen, D. Arndt, and M. A. Kenney, 2012: National Climate Assessment Indicators: Background, development, and examples. NCA3 Tech. Input Rep., 59 pp., https://doi.org/10.7916/D8RB7D2T.

Kania, J., and M. Kramer, 2011: Collective impact. *Stanford Soc. Innovation Rev.*, **9** (1), https://ssir.org/articles/entry/collective_impact.

Kenney, M. A., and Coauthors, 2014: National climate indicators system report. National Climate Assessment Development and Advisory Committee (NCADAC) Rep., 157 pp., https://scholarworks.umt.edu/ntsg_pubs/376/.

——, A. C. Janetos, and G. C. Lough, 2016: Building an integrated US National Climate Indicators System. *Climatic Change*, **135**, 85–96, https://doi.org/10.1007/s10584-016-1609-1.

Kirshen, P., and Coauthors, 2018: Feasibility of harbor-wide barrier systems: Preliminary analysis for Boston Harbor. University of Massachusetts, Boston, Sustainable Solutions Laboratory Rep., 238 pp., https://www.umb.edu/editor_uploads/images/centers_institutes/sustainable_solutions_lab/umb_rpt_BosHarbor_5.18_15-optimized.pdf.

Klempin, S., 2016: Establishing the backbone: An underexplored facet of collective impact efforts. CCRC Research Brief 60, 6 pp., https://ccrc.tc.columbia.edu/publications/establishing-backbone-collective-impact.html.

Leiserowitz, A., E. Maibach, S. Rosenthal, J. Kotcher, M. Ballew, M. Goldberg, and A. Gustafson, 2018: Climate change in the American mind: December 2018. Yale Program on Climate Change Communication and George Mason Center for Climate Change Communication Rep., 49 pp., http://climatecommunication.yale.edu/publications/climate-change-in-the-american-mind-december-2018/.

Lemos, M. C., C. J. Kirchhoff, and V. Ramprasand, 2012: Narrowing the climate information usability gap. *Nat. Climate Change*, **2**, 789–794, https://doi.org/10.1038/nclimate1614.

——, ——, S. E. Kalafatis, D. Scavia, and R. B. Rood, 2014: Moving climate information off the shelf: Boundary chains and the role of RISAs as adaptive organizations. *Wea. Climate Soc.*, **6**, 273–285, https://doi.org/10.1175/WCAS-D-13-00044.1.

——, and Coauthors, 2018: To co-produce or not to co-produce. *Nat. Sustainability*, **1**, 722–724, https://doi.org/10.1038/s41893-018-0191-0.

Mascaro, J., G. P. Asner, D. E. Knapp, T. Kennedy-Bowdoin, R. E. Martin, C. Anderson, M. Higgins, and K. D. Chadwick, 2014: A tale of two "forests": Random forest machine learning aids tropical forest carbon mapping. *PLOS ONE*, **9**, e85993, https://doi.org/10.1371/journal.pone.0085993.

Meadow, A. M., D. B. Ferguson, Z. Guido, A. Horganic, G. Owen, and T. Wall, 2015: Moving toward the deliberate coproduction of climate science knowledge. *Wea. Climate Soc.*, **7**, 179–191, https://doi.org/10.1175/WCAS-D-14-00050.1.

Melillo, J. M., T. C. Richmond, and G. W. Yohe, 2014: *Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program, 841 pp., https://doi.org/10.7930/J0Z31WJ2.

Moser, S. C., M. A. Davidson, P. Kirshen, P. Mulvaney, J. F. Murley, J. E. Neumann, L. Petes, and D. Reed, 2014: Coastal zone development and ecosystems. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, T.C. Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 579–618, https://data.globalchange.gov/report/nca3/chapter/coastal-zone.

——, J. Coffee, and A. Seville, 2017: Rising to the challenge, together: A review and critical assessment of the state of the US climate adaptation field. Kresge Foundation Rep., 105 pp., https://kresge.org/content/rising-challenge-together.

——, J. A. Ekstron, J. Kim, and S. Heitsch, 2018: Adaptation finance challenges: Characteristic patterns facing California local governments and ways to overcome them: A report for California's Fourth Climate Change Assessment. California Natural Resources Agency Publ. CCCA4-CNRA-2018-007, 184 pp., http://www.climateassessment.ca.gov/techreports/docs/20180831-Governance_CCCA4-CNRA-2018-007.pdf.

Moss, R. H., and Coauthors, 2013: Hell and high water: Practice-relevant adaptation science. *Science*, **342**, 696–698, https://doi.org/10.1126/science.1239569.

——, P. Lynn Scarlett, M. A. Kenney, H. Kunreuther, R. Lempert, J. Manning, and B. K. Williams, 2014: Decision support: Connecting science, risk perception, and decisions. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, T. C. Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 620–647, https://data.globalchange.gov/report/nca3/chapter/decision-support.

National Academies of Sciences, Engineering, and Medicine, 2016: *Pathways to Urban Sustainability: Challenges and Opportunities for the United States*. The National Academies Press, 192 pp., https://doi.org/10.17226/23551.

——, 2018: *Learning Through Citizen Science: Enhancing Opportunities by Design*. The National Academies Press, 204 pp., https://doi.org/10.17226/25183.

National Research Council, 2012: *A National Strategy for Advancing Climate Modeling*. The National Academies Press, 294 pp., https://doi.org/10.17226/13430.

ND-GAIN, 2019: Notre Dame Global Adaptation Initiative: Helping countries and cities counter the risks of a changing climate. Accessed February 2019, https://gain.nd.edu/.

Neumann, J. E., K. Emanuel, S. Ravela, L. Ludwig, P. Kirshen, K. Bosma, and J. Martinich, 2015: Joint effects of storm surge and sea-level rise on US coasts: New economic estimates of impacts, adaptation, and benefits of mitigation policy. *Climatic Change*, **129**, 337–349, https://doi.org/10.1007/s10584-014-1304-z.

New York City Panel on Climate Change (NPCC), 2010: Climate change adaptation in New York City: Building a risk management response: New York City Panel on Climate Change 2010 report. *Ann. N. Y. Acad. Sci.*, **1196** (1), 1–354. https://nyaspubs.onlinelibrary.wiley.com/toc/17496632/1196/1.

——, 2015: Building the knowledge base for climate resiliency: New York City Panel on Climate Change 2015 report. *Ann. N. Y. Acad. Sci.*, **1336** (1), 1–150. https://nyaspubs.onlinelibrary.wiley.com/toc/17496632/2015/1336/1.

NYC Office of the Mayor, 2018: Infrastructure and sustainability. Mayor's Management Rep. September 2018, 257–282, https://www1.nyc.gov/assets/operations/downloads/pdf/mmr2018/2018_mmr.pdf .

Probst, G., and S. Borzillo, 2008: Why communities of practice succeed and why they fail. *Eur. Manage. J.*, **26**, 335–347, https://doi.org/10.1016/j.emj.2008.05.003.

Rasp, S., M. S. Pritchard, and P. Gentine, 2018: Deep learning to represent subgrid processes in climate models. *Proc. Natl. Acad. Sci. USA*, **115**, 9684–9689, https://doi.org/10.1073/pnas.1810286115.

Shepherd, T. G., and Coauthors, 2018: Storylines: An alternative approach to representing uncertainty in physical aspects of climate change. *Climatic Change*, **151**, 555–571, https://doi.org/10.1007/s10584-018-2317-9.

Spenko, M., S. Buerger, and K. Iagnemma, 2018: *The DARPA Robotics Challenge Finals: Humanoid Robots to the Rescue*. Springer, 684 pp., https://doi.org/10.1007/978-3-319-74666-1.

STAR Communities, 2019: STAR Communities: Set goals, measure progress, improve your community. Accessed February 2019, http://www.starcommunities.org/.

Stults, M., 2017: Integrating climate change into hazard mitigation planning: Opportunities and examples in practice. *Climate Risk Manage.*, **17**, 21–34, https://doi.org/10.1016/j.crm.2017.06.004.

——, J. R. Nordgren, S. Meerow, M. Ongun, R. Jacobson, and C. Hamilton, 2015: Assessing the climate adaptation resource and service landscape. *Living with Climate Change: How Communities are Surviving and Thriving in a Changing Climate*, J. A. Bullock et al., Eds., CRC Press, 124–132, https://doi.org/10.1201/b19312.

USDN, 2016: Developing urban climate adaptation indicators. Urban Sustainability Directors Network Rep., 24 pp., http://us.sustain.org/wp-content/uploads/2017/01/Urban-Adaptation-Indicators-Guide-2.9.16.pdf.

U.S. Environmental Protection Agency, 2016: Climate change indicators in the United States: 2016 fourth edition. USEPA Rep. 430-R-16-004, 96 pp., https://www.epa.gov/climate-indicators.

——, 2017: Evaluating urban resilience to climate change: A multi-sector approach (final report). USEPA Rep. EPA/600/R-16/365F, 689 pp., https://cfpub.epa.gov/ncea/global/recordisplay.cfm?deid=322482.

U.S. Federal Government, 2014: U.S. Climate Resilience Toolkit (CRT). Accessed July 2018, http://toolkit.climate.gov.

USGAO, 2015: Climate information: A national system could help federal, state, local, and private sector decision makers use climate information. U.S. Government Accountability Office Rep. GOA-16-37, 49 pp., https://www.gao.gov/assets/680/673823.pdf.

USGCRP, 2017a: *Climate Science Special Report: Fourth National Climate Assessment (NCA4) Volume I*. D. J. Wuebbles et al., Eds., U.S. Global Change Research Program, 470 pp., https://doi.org/10.7930/J0J964J6.

——, 2017b: National global change research plan 2012–2021: A triennial update. U.S. Global Change Research Program, 106 pp., https://www.globalchange.gov/browse/reports/national-global-change-research-plan-2012-2021-triennial-update.

——, 2018a: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment (NCA4) Volume II*. D. R. Reidmiller et al. Eds., U.S. Global Change Research Program, 1515 pp., https://doi.org/10.7930/NCA4.2018.

——, 2018b: *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report*. N. Cavallaro et al. Eds., U.S. Global Change Research Program, 878 pp., https://doi.org/10.7930/SOCCR2.2018.

Vogel, J., and Coauthors, 2016: Climate adaptation: The state of practice in U.S. communities. Abt Associates Rep., 260 pp., https://kresge.org/sites/default/files/uploaded/climate-adaptation-the-state-of-practice-in-us-communities-full-report.pdf.

Voorberg, W. H., V. J. J. M. Bekkers, and L. G. Tummers, 2015: A systematic review of co-creation and co-production: Embarking on the social innovation journey. *Public Manage. Rev.*, **17**, 1333–1357, https://doi.org/10.1080/14719037.2014.930505.

Woodruff, S. C., S. Meerow, M. Stults, and C. Wilkins, 2019: Adaptation to resilience planning: Alternative pathways to prepare for climate change. *J. Plann. Educ. Res.*, https://doi.org/10.1177/0739456X18801057, in press.