

GLOBAL KNOWLEDGE ACTION NETWORK

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Abstract

When adaptation joins greenhouse gas mitigation as a major climate management responsibility, it becomes essential to grapple with the great diversity of regional climate change impacts, to understand the highly specific needs of local communities, and to deliver trustworthy knowledge to a huge variety of decision makers. This leaves us with an important question. How can the relatively small science, policy, and technology community develop the capacity to serve the needs of millions of decision makers in thousands of communities with different cultural, economic, and environmental characteristics? Already, the world climate science community is stretched thin in providing the assessments of the Intergovernmental Panel on Climate Change every seven years. Part of the answer to this capacity problem is a planned deployment of modern knowledge management services and technologies to support the assessment process. Add to this a requirement for global, regional, and local coordination and we see that smart cyber-infrastructure that informs and integrates global, regional and local decision-making is needed.

In part 1, we argue that assessment is the critical first step in the management of climate change impacts in an adaptive framework. While adaptation governance requires correlated policies and actions at the global, regional, and local levels, the primary locus of effective adaptation action will be at the level of communities. In any distributed assessment-governance network, success depends upon flexible communication of situational awareness and outcomes of decisions amongst many decision makers and stakeholders. Thus, the precursor to governance is the development of a knowledge action network for adaptation and disaster management. There are few approaches to adaptation that appeal to the interests of both developed and developing countries. However, there is a potential mutuality of interest in a global knowledge action network for disaster management and adaptation. The considerable infrastructure built in the 20th century for the management of research knowledge could and should become the basis of an extended system that supports polycentric decision making for adaptation.

In part 2, we look at how we do assessments from the point of view of local leaders who use them to formulate their adaptation decisions. We describe some of the requirements that assessments for adaptation must satisfy.

We examine how the science, technology, and policy community manages assessments to serve not only the traditional goal of preparing knowledge in the academic literature for non-expert use, but also of prompting timely and coordinated action by the huge variety of decision makers who must use the knowledge. The challenges posed by the way things have been done thus far point to the need to embed the four functions of assessment – certification, assembly and synthesis, translation, and delivery – in a knowledge-rich cyber-infrastructure that supports their decision-making. A key enabling step, one that requires the participation of the world scholarly community to accomplish, is to develop standards that can indicate when research results are ready for practical use. The ultimate goal is to turn assessment from a document that appears periodically to an always-on knowledge management service that experts, decision makers, and stakeholders can access at times and places of their choosing.

Part 1: Assessment-Governance Architecture

Introduction

Roger Revelle made the famous observation that humanity is performing a great one-time geophysical experiment. At the time, he may have meant that people were causing changes in the climate that they could study in their lifetimes when natural processes would have taken hundreds of generations to accomplish. Today, this famous saying of his takes on a darker hue. We know now as he did not that there is more CO₂ in the atmosphere today, almost 50% more than in the preindustrial era, than anytime in the last 800,000 years and it is rising faster than ever before in earth history. We are taking the climate places it has never been. Human civilization is going along for the ride.

We are entering a world new to human experience. Paleoclimatology tells the story. The argument by now is familiar. There is more CO₂ in the atmosphere today than there has been for the last 800,000 years. There were four ice ages during this period; in the warm interglacial intervals separating them, atmospheric CO₂ concentrations peaked at a characteristic limit of 270 parts per million (ppm). We do not know why there was this limit, but there was. We were at that limit before industrialization began 150 years ago, and have blown right through it. The CO₂ concentration has reached 400 ppm and is rising faster than ever before in earth history. We are taking the climate places it has never been. Human civilization is going along for the ride.

Climate forecasts tell a similar story. In recent years there have been numerous assessments of the impacts of future climate change. The idea is to dissect the predictions of climate models to construct a picture of a future

world that could result from what we are doing. One of the most compelling was commissioned by the World Bank¹ and put together by the Potsdam Institute for Climate Research. The Institute scientists described the climate conditions that would prevail if the world warmed to four degrees Centigrade (4C) above preindustrial, a level many observers fear we will reach by the end of this century if we continue with “business as usual”. To convey a flavor of how unfamiliar that world would be, it suffices to note that there will be regions where the *average* summer temperature will exceed the highest temperatures achieved during 20th century. In other words, every day will seem like a heat wave to people like us.

Until very recently many advocates of action on climate change mitigation – the effort to reduce emissions of climate altering gases like CO₂ – disparaged talk of adaptation. There seemed to be a code of silence among climate scientists. It was about morality and morale. If you admitted that people could adapt to climate change, you would absolve gross emitters of their ethical responsibility to mitigate; you would transmit a paralyzing fear that the climate problem is getting away from us. Well, it probably is. It is no less urgent to reduce carbon dioxide emissions, but it is becoming equally urgent to adapt to the climate change we clearly cannot avoid (Pielke, *et al.*, 2007).² Policymakers are beginning to adjust their priorities.

Mitigation and adaptation have different requirements and different policymakers. CO₂ mitigation policy focuses on measures of global reach – things like deployment of green energy technologies and other methods of reducing fossil fuel use, along with macroeconomic, regulatory, and innovation policies. On the other hand key adaptation decisions are about local resilience. They focus on disaster management and known environmental issues that are expected to grow in importance. Adaptation speaks to the practical people who manage local and regional issues on behalf of their communities.

Not only do mitigation and adaptation have different audiences, they have audiences of different size. The IPCC assessments were designed to support a small number of large decisions made by a comparative handful of central decision makers. By contrast, adaptation assessments will be needed for millions of decision makers for hundreds of regions and industrial sectors and thousands of communities.

¹ *Turn Down the Heat – why a 4 C warmer world must be avoided*, World Bank, 2012.

² Pielke, Jr., R., G. Prins, and S. Rayner, *Climate Change 2007: Lifting the taboo on Adaptation*, *Nature*, 445, 597-598, 08 February, 2007.

The past will not be a guide to the future for those decision makers. As we think about how to support them, the most important thing is to remember that their intuitions and past experience will be decreasingly reliable. Of course, forecasts of the future climate will also be imperfect. But they will still have to figure out how to adapt to climate change when they are not entirely sure they know where they are and where they are going.

Assess, Decide, and Act

Adaptive management is what you do when you know you have a problem you can't put off but you don't know how it will unfold. You take stock, figure out what makes sense to do in the short run, do it, and start again. In short, you assess, decide, and act. You *assess, decide, and act* over and over again. You hope successive iterations bring you closer to a more satisfactory solution.³

There is no magic bullet. For climate, we will have to assess, decide, and act for the thousand years or more that the oceans will store the extra heat humans have put into the oceans. Enduring institutions devoted to the management of the climate and its impacts will surely be needed. A governance architecture needs to be thought through, and the *Assess, Decide, and Act* cycle of adaptive management provides a useful conceptual framework for doing so.

A simple analogy can help us understand the task facing us. An international consortium of 14 nations, led by NASA, has put a small planet in orbit around the earth – the International Space Station. This little planet is life-bearing, and there are managers in a control room at the Johnson Space Flight Center in Houston who assess the changing conditions on-board, decide what to do, and adjust the Station's life support systems accordingly. They too assess, decide, and act. The world will have to manage the entire planet the same way, only instead of a single control room in one city, a global network will be required.

³ Working adaptively has several clear advantages, and one major weakness. It does what can be done given contemporary political and economic realities, it leads to incremental progress, you can learn from your mistakes and readjust in the next assessment cycle. This eases stress on the decision maker. At the same time, adaptive management could not cope with a tipping point – a sudden reconfiguration of the climate system. However, you need not be blind to the approach of one. You can look for precursors to an approaching tipping point. The cyclic nature of adaptive management ensures ongoing vigilance, so at least you have some warning and can put into motion the back up plans your assessments have prompted you to prepare.

Think Globally, Assess Regionally, Act Locally

These six words structure an approach to making assessments for adaptation purposes. Clearly, the talents of the international science, technology, and policy community will be as critical to adaptation as they have been to mitigation, but they will have to be deployed differently. The international community's role will be to support regional experts and decision makers as they assess the impacts of climate change in their regions. Their assessments will set the stage for the actions that the local communities within their regions will be called upon to take.

If we keep in mind the two phrases, *Assess, Decide, and Act*, and *Think Globally, Assess Regionally, Act Locally*, it will be easier to follow the discussion of the relationship between assessment and governance that follows.

Assessment and governance

Assessment prepares research knowledge for practical use. In the past, the coalescence of research into practical knowledge was unforced and relied largely on the passage of time for controversies to settle out. Not until the climate clock started ticking was there a need to accelerate this coalescence. The Intergovernmental Panel on Climate Change made its first comprehensive assessment of Climate Change in 1990. Now the climate clock is ticking even faster. Past experience is becoming as uncertain as tomorrow's forecasts.

We said it once; we will say it again; the past is no longer a reliable guide to the future. This stark fact, new to our cultural appreciation of the climate in all its manifestations, implies that assessment and governance are joined at the hip. Like it or not, decision makers will have to trust assessments as much or more than their own intuitions. Like it or not, they will have to pay close attention to what recent research is saying (Tschakert and Dietrich, 2010).⁴

Assessment frames decisions and governance⁵ makes them. By designing an assessment regime, we constrain a governance regime and *vice versa*. In an

⁴ Tschakert, P., and K. A. Dietrich. 2010. Anticipatory learning for climate change adaptation and resilience, *Ecology and Society* 15(2): 11.

⁵ My friends in the social sciences will consider my use of the governance word a naïve over-simplification, and they'll be right. The word governance evokes a wealth of associations in their minds; of treaties, intergovernmental agreements, and other international instruments; of states, alliances, regional associations, bureaucracies, non-governmental organizations, and stakeholders; of regulations, taxes, and incentives. Here we use the term governance broadly, assuming that there is an entity tasked with making climate decisions or at least guiding the evolution of outcomes. The terms "decision" and "decision maker" are equally abstracted from complex reality.

ideal world, assessment would identify a suite of issues and an existing governance mechanism would be prepared to deal with them. We do not live in an ideal world. Assessment considers the issues an existing governing authority has the mandate to decide. This leaves the burden of cleaning up the remaining issues identified by assessment to others, if they can be found. Moreover, the climate is changing so the arrangements we make in one decade may not be helpful in the next. What is needed is a flexible relationship between assessment and governance that can deal with the challenges of adaptive management.

Impatience with the present way of doing things has been growing. David Victor's book, *Climate Change Gridlock*, makes it clear that if we try to govern too broadly, we govern not at all. In the past five years two rather large ideas about how to govern the climate system have emerged. Connected together, they become even more powerful.

Let's start at the global scale. Lael-Aria (2011) recently proposed that specialized forms of international climate governance – in effect, “coalitions of the willing” – are proving more effective than the top-down approach prescribed by the UN Framework Convention on Climate Change.⁶ In the same year, Keohane and Victor (2011)⁷ also argued that sub-global international political mechanisms, to which they gave the names, “regime complexes” or “clubs”, have made progress on more limited climate issues that do not require global unanimity and lengthy negotiations.

What is needed is a global club that encourages action on adaptation.

At the regional and local levels, those who govern environmental decisions today will be among those who make adaptation decisions tomorrow. The complex systems they govern are embedded in other complex systems, and their decisions have ramifications over large multi-disciplinary and geographic domains with fuzzy boundaries. Ostrom (2010)⁸ proposes the name “polycentric” for this kind of decision-making.

What is needed is a way to enable the “poly” in polycentric.

Below is a schematic governance architecture that might satisfy the two needs we just identified above. An approach may be found where *Assess, Decide, Act* intersects with *Think Globally, Assess Regionally, Act Locally*:

⁶ Lael-Aria, Alternative Architecture for Climate Change, *European Journal of Legal Studies*, 4, no. 1, 2011.

⁷ Keohane, R.O. and D.G. Victor, The Regime Complex for Climate Change, *Perspectives on Politics*, v. 9, no. 1, March 2011.

⁸ Ostrom, E., Beyond Markets and States: Polycentric Governance of Complex Economic Systems, *American Economic Review* 100 (June 2010): <http://www.aeaweb.org/articles.php?doi=10.1257/aer.100.3.1>

Think Globally

A loosely organized club of nations generates scientific knowledge and makes much of it freely available. Funds from UNFCCC mechanisms or other clubs of nations and non-governmental organizations provide resources to encourage regional assessments and local participation.

Assess Regionally

Regional or local governing bodies commission multi-level groups to identify issues, assemble pertinent knowledge, and deliver a synthesis in useful forms. Experts interpret international knowledge, regional leaders specialize it, and local decision makers help prepare it for polycentric decision-making.

Act Locally

Communities make the key adaptation decisions. They participate in polycentric decision making by communicating their actions, reactions, and special issues to all three levels.

Knowledge, Governance, Action

	Assess	Decide	Act
Think Globally	Science & Policy IPCC, UNEP, IOC ICSU-Future Earth	Top Down UNFCCC Informal Clubs of Nations World Bank, other NGOs	Global Services Knowledge Sharing Financial support Capacity building Standard setting
Assess Regionally	Specific Impacts Natural systems Human systems Hazards Exposure to risk	Polycentric Consortia Compacts Alliances Information exchange	National Policies Goals, Incentives, Regulations, Technical Services
Act Locally	Strategic choices Vulnerability Capability Feasibility	Bottom Up Trusted local leaders Stakeholders Managers	Adaptation Resilience Disaster preparations Remediation

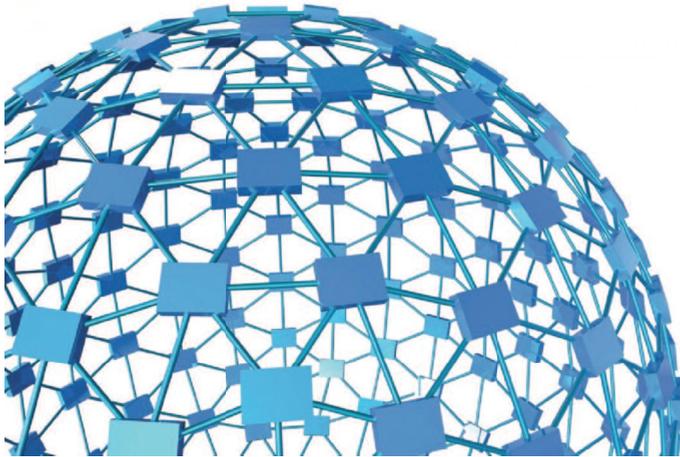
Kennel, C.F., Climate Change: Think Globally, Assess Regionally, Act Locally, *Issues in Science and Technology*, 25, 46-52, <http://trid.trb.org/results.aspx?q=&serial=%22Issues in Science and Technology%22&issue=%22%22>, Publisher: National Academies, ISSN: 0748-5492, Order URL: <http://worldcat.org/issn/07485492>

Success depends upon free and easy communication throughout any distributed assessment/governance network. In the present situation, knowledge needs to be related to action “horizontally” among experts and decision makers at each level, and “vertically”, both up and down, through the global, regional, and local levels.

The precursor to governance in such a scheme is the development of a global knowledge action network for adaptation and disaster management. The schematic drawing below helps to convey the basic architectural principles of such a network, whose purpose is to enable flexible communication among and within the global, regional, and local levels of thought and action.

Global Knowledge Action Network

The Precursor To Governance



Success depends upon flexible communication throughout any distributed assessment/governance network. Knowledge needs to be related to action “horizontally” among experts and decision makers at each level, and “vertically”, both up and down, through the global, regional, and local levels.

Since such a network would be populated at first by knowledge generated in the first-world, proposals to create one could founder on the polarized attitudes generated by adaptation’s primary ethical dilemma – the “north-south” problem.⁹ There are assertions of blame and responsibility but few

⁹ In short, the nations that did the least to cause the climate problem and have the least capacity to adapt are going to suffer the most. It can be no surprise that developing

approaches to the north–south problem that appeal to the interests of both developed and developing countries. However, there is a potential mutuality of interest in a global knowledge action network for disaster management and adaptation. Developed nations will continue to support their knowledge management systems because they will have adaptation problems of their own. Disaster management is already an arena of collaboration between the developed and developing worlds that could be extended to adaptation. A knowledge action network that reaches them would enable communities in developing countries to initiate their own assessments, design their own adaptation strategies, and most, critically, take action on their own without having to wait for ponderous bureaucracies to make up their minds. Communities get a chance to become centers of innovation for adaptation.

Both developed and developing nations would have to invest in enabling the present system, which was created to support research, to enable polycentric decision-making at the community level. Though there will be an asymmetry in scale and nature of investment, both developed and developing countries could well see benefit in investing. It won't solve everything but it could help.

The question is where to start. The future is built on foundations constructed in the past. In Appendix 1A, we summarize some key features of the knowledge management infrastructure created for earth system science (and climate) in the second half of the 20th century. Many of the building blocks of a global knowledge network that can document the impacts of the changing climate were put in place – satellite and ground observations, models, and data archives. There now exist high capacity communications that can handle the exchange of large amounts of data, removing one impediment to cooperative behavior amongst large research institutions. There is even an intergovernmental organization, the Group on Earth Observations (GEO), charged with synthesizing data important to nine societal benefit areas, the kind of data that regional assessments of climate change impacts need. GEO is underfunded and has little influence on the large national systems that collect the data, but is there. If it disappeared, we would have to reinvent it.

countries have demanded compensation for the damages they expect to incur. After all, why should they pay for adaptation when the developed nations caused the problem? This is a valid ethical claim, but developed nations have not responded to it with alacrity. They might ask, for example, how one should calculate how much to pay when no one can say with certainty how much it costs to adapt to problems that have not yet occurred. With one side sticking to the mantra, compensation before adaptation, and the other slow-rolling compensation, there has been inaction on adaptation.

The critical next step is to change today's knowledge management system into tomorrow's knowledge action system, or, in other words, to connect today's research systems to polycentric decision makers around the world. Elsewhere, we have suggested¹⁰ that purposed smaller scale social networks comprising international science, technology, and policy experts, regional thought and action leaders, and local decision makers can effectively link local action to the global knowledge. These would be staffed by secretariats of professional knowledge translators who facilitate the exchange of understanding and motivation among the participants. These knowledge action social networks would be incubated internationally and empowered regionally and locally. The cyber-infrastructure for supporting the knowledge management needs of local decision makers is available.¹¹ Recent developments in "middleware" are enabling such user-providers to find, access, exchange, and use data, software, and computing capacity that reside in remote systems ("the cloud"). Since non-scientific users no longer have to manage their own cyber-infrastructure, cloud services promise to make climate change knowledge management adequate to the challenge of polycentric decision support.

What's missing is the realization that it could be done and agreement that it should be done. We have no illusion that it will be easy; it took decades to bring capabilities to their present state, and it would take decades more to complete the job. That does not mean it is not urgent to get started. At the 2011 UNFCCC meeting in Durban, the nations agreed to provide a US \$100B fund for adaptation by 2020. We have suggested elsewhere (Kennel, *et al.*, 2012)¹² that a fraction be used to develop a 21st Century assessment infrastructure. Moreover, non-Governmental organizations that already support the use of knowledge in managing human and economic development should now also support the management of that knowledge. Shouldn't we all plan for a social and information network of global scale that provides decision-ready knowledge to those who hold the responsibility to act, wherever they are, and at times of their choosing? Should we not start by assembling the social infrastructure – policies, governance, institutions, financing – needed to knit climate knowledge and adaptation action together?

¹⁰ Kennel, C.F., and S. Daultrey, Knowledge Action Networks, Connecting regional climate change assessments to local action, University of California, e-scholarship, 2010, <http://escholarship.org/uc/item/8gd6j0k5>

¹¹ *NSF Report on Revolutionizing Science and Engineering through Cyber-Infrastructure* (Atkins Report) www.communitytechnology.org/nsf_ci_report/

¹² Kennel, C.F., V. Ramanathan, and D. Victor, Coping with Climate Change in the next half-century, to be published, *Proceedings of the American Philosophical Society*, 2012.

Appendix 1A

As the space age unfolded, the earth science community turned to articulating a common vision of what observing systems should do and how they should do it. From the beginning, it was understood that both space and *in situ* observations should be connected together. Satellite observations have been internationally coordinated since 1984 by the Committee on Earth Observing Satellites (CEOS), which today comprises the earth observation program leaders of national space agencies, together with affiliates and associates. Currently, there are 52 member and affiliate agencies. A 1995 white paper of the US Office of Science and Technology Policy urged CEOS to lead the creation of an Integrated Global Observing Strategy (IGOS).¹³ The strategy proposed linking CEOS to the international organizations developing *in situ* observing strategies, the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), and the Global Terrestrial Observing System (GTOS). These discussions proceeded surprisingly rapidly.

The 2002 World Summit on Sustainable Development and the 2003 G-8 Summit called for a “system of systems” connecting national earth observing systems. A ministerial conference in Washington in 2003 was followed by technical discussions that culminated an intergovernmental agreement in 2005 to create the Global Earth Observation System of Systems (GEOSS) and a Group on Earth Observations (GEO) to govern it.¹⁴

GEO measures success not by advancing science but by assembling the information produced by science that is pertinent to nine societal benefit areas: disasters, health, energy, climate, water, weather, ecosystems, biodiversity, and agriculture/desertification. GEOSS has taken on a critical task that is invisible to all but experts: forging articulation standards that enable assembly of a common pool of data from many sources about *all* types of earth observations: space and *in situ*; global and regional; physical, chemical, and biological; atmosphere, land, and oceans. To that end, GEOSS sponsors a “common infrastructure” that promotes data interoperability. In other words, GEOSS is preparing one of the most critical steps along the way to a federation of knowledge management services.

¹³ C.F. Kennel, P. Morel, and G.J. Williams, Keeping Watch on the Earth: an Integrated Global Observing Strategy, in *Consequences: the Nature and Implications of Environmental Change*, v.3, no. 2, pps. 21-32.

¹⁴ As of 2012, 88 governments and the European Commission are GEO members, and 64 other organizations are affiliated with it. The GEO secretariat is at WMO headquarters in Geneva.

Climate science and policy rely upon putting present observations and future forecasts in the context of the past. Thus the preservation and archiving of climate information is essential. The 20th century saw the creation of data repositories for much of the multidisciplinary data required for adaptation. The World Data Center (WDC) system was created to archive and distribute data collected during the International Geophysical Year (1957) and has since expanded to 52 Centers in 12 countries. Its holdings include solar, geophysical, environmental, and human dimensions data. Examples of repositories in the US include NOAA's National Climatic Data and National Ocean Data Centers, the USGS Earth Resources Observation Systems Center, NASA's Distributed Active Archive Centers, and Columbia University's Center for International Earth Science Information Network, which focuses on the human dimensions of global change.

Climate change presents a challenge encountered in no other area of knowledge management: knowledge artifacts must be preserved and used for a thousand years. The world's climate archives will need a common strategy that anticipates technological, institutional, and social evolution. Their most immediate task is to agree on what should be preserved, what should be widely available, and incentives for deposit. This will require a policy framework that includes archiving standards, security, accessibility, meta-languages. Agreements that allocate institutional roles and responsibilities need to be negotiated.

Examples of the high-volume communications technologies needed for federation already exist. NASA pioneered the use of the Internet to connect large numbers of researchers with data and management tools in the late 1980s. NASA's Earth Observing System Data and Information System¹⁵ assembles, processes, archives, and distributes huge volumes of earth science data collected from space. More recently, open non-centrally managed networks have also developed the capacity to deal with huge data volumes. The US National Lambda Rail system,¹⁶ for example, is a university-based

¹⁵ Kobler, B.; Berbert, J.; Caulk, P.; Hariharan, P.C.; "Architecture and design of storage and data management for the NASA Earth observing system Data and Information System (EOSDIS)", *Mass Storage Systems, 1995. Storage – At the Forefront of Information Infrastructures, Proceedings of the Fourteenth IEEE Symposium on*, vol., no., pp. 65-76, 11-14 Sep 1995 doi: 10.1109/MASS.1995.528217 <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=528217&isnumber=11538>

¹⁶ D. Kim, J-B, Kim and J-H Park, *Virtual Federated Network Operations on Future Internet*, Proceedings of the 6th International Conference on Future Internet Technologies ACM, New York, NY, USA, 2011; NLR (National Lambda Rail), <http://www.nlr.net>

high-speed network that connects major research centers in the US via dedicated fiber-optic lines. The US national system connects to subsidiary regional networks, and to Europe, Asia, and Australia.

Part 2: Rethinking the assessment process

Summary of part 1

We are entering a world new to human experience. We cannot go back. Our choices are, in the words of Rosina Bierbaum and Peter Raven, to “avoid the unmanageable and manage the unavoidable”, or, in the terms of the trade, mitigate the causes of climate change and adapt to what we cannot mitigate. Scientists and policymakers alike have to think out how to use their resources to address both priorities simultaneously. The challenges are not the same. Mitigation and adaptation have different requirements and different policymakers. Not only do mitigation and adaptation have different audiences, they have audiences of different size. The IPCC assessments were designed to support a small number of large mitigation decisions made by a comparative handful of central decision makers. Adaptation cannot be managed top-down like mitigation. No central actor – no leader, no committee, no government agency, no global forum – can conceive of all the specific actions needed, much less how they interrelate. The assessments needed for adaptation have to grapple with a great diversity of regional climate change impacts, to attend to the highly specific needs of local communities, and to deliver trustworthy knowledge to a huge variety of decision makers. The enlargement of scope raises an important question that we asked in our first paper. Does the relatively small science, policy, and technology community have the capacity to serve the needs of millions of decision makers in thousands of communities with different cultural, economic, and environmental characteristics?

The past will not be a guide to the future for those decision makers. As we think about how to support them, the most important thing is to remember that their intuitions and past experience will be decreasingly reliable. Of course, forecasts of the future climate will also be imperfect. But they will still have to figure out how to adapt to climate change when they are not entirely sure they know where they are and where they are going. There is really only one practical approach: adaptive management. It is what you do when you know you have a problem you can't put off but you don't know how it will unfold. You take stock, figure out what makes sense to do in the short run, do it, and start again. In short, you assess, decide, and act, over and over again. You hope successive iterations put you on a safer course. The whole process starts with assessment.

What Assessments Do

While there are many variations, assessment usually comprises four basic tasks. The first is a new form of *knowledge certification* that distinguishes between peer-reviewed research and decision-ready knowledge. In peer review, disciplinary experts judge whether a new result merits wider examination by the research community. Decision-readiness is a judgment whether expert knowledge merits use by non-experts. The second assessment task is *knowledge assembly and synthesis* in which knowledge from different sources is gathered and integrated according to the needs of the decision maker. The third task is *knowledge translation*. Complex concepts are condensed into forms non-experts understand, decision options are formulated, and are expressed in politically, economically, and culturally aware terms. The fourth task is *knowledge delivery*. It is important to deliver the results of assessments to decision makers when they need them and where they need them.

Next we set forth arguments that we will need to embed the four functions of assessment – certification, assembly and synthesis, translation, and delivery – in a knowledge-rich cyber-infrastructure that supports decision-making social networks. We examine each of these functions in more detail, reserving certification to the end for reasons that will become clear.

Knowledge Assembly and Synthesis

It is sometime convenient to picture global climate change as triggering a chain of impacts, a global to regional to local cascade. In this way of looking at things, climate scientists forge the first link in the assessment chain. They document how the climate has changed and is changing. They devise scenarios that project into the future the human drivers of climate change, and average the forecasts of several dozen global climate models (Washington, 2006; Washington and Parkinson, 2005). IPCC's synthesis of the worldwide effort in global climate modeling provides the foundation of what happens subsequently in the chain of regional assessments that follows.

The next step is to understand how global climate change affects regional natural systems. First, you need to extract from the global models how the prevailing weather and ocean circulation patterns might change in your region. Then you ask how these changes affect the natural systems there. At this point, other disciplines – meteorology, oceanography, ecology, hydrology, forestry, environmental science, others – come into play. The adaptation analysis starts here, and natural system impact assessments are well under way in many regions around the world. Synthesizing the interactions among the different natural systems is difficult (Warren, 2011), but

it is from the synthesis that the next link in the chain is forged – identification of the impacts on regional technical systems. Here decision makers need answers to questions like the following. How will heat waves affect forest fire frequency, electrical power consumption, or public health? How will changes in mountain snow cover and rainfall patterns affect agricultural and urban water availability? How will changes in seasonality affect the timings of agricultural planting and harvest, or water release from dams?

Humans are at the bottom of the knowledge cascade. Regional natural system change and regional technical system change combine to bear on human welfare at the community level (Kennel, 2009).

The table below is intended to convey an impression of the complexity of the adaptation knowledge cascade. In some very approximate sense, you need to know how climate change affects the layers above before you can assess the changes in what of interest is in your particular layer. But what is given to you is inexact and can only be described in probabilistic terms. You are faced with extracting conclusions from a concatenation of statistical systems. In principle, you might try a hierarchical Bayesian computation but this is very laborious, and to my knowledge, no one has done so for climate. You fall back on applying human judgment to juxtapositions of data, model results, algorithms, and intuitive guidelines. Still, you need access

Adaptation Knowledge Cascade

Weather and Ocean Patterns

Large atmospheric systems-equator to pole heat transport, polar vortex, atmospheric rivers,...

Ocean circulation-El Nino/La Nina, Pacific Decadal Oscillation, Gulf Stream...

Regional characteristics- temperature, wind, rainfall, relative sea level...

Extreme events-heat waves, cold snaps, storms, droughts, floods,...

Regional Geophysical Systems

Cryosphere-Sea ice, Greenland, Antarctic, mountain glaciers and snows, permafrost...

Mountains and Watersheds-river networks, aquifers, deltas, sediment transport...

Deserts-dust transport,...

Regional Ecosystems

Biodiversity: species distributions and abundances...

Biomes- chaparral, grassland, savannah, forest, tundra, marshlands, coastal zones...

Habitats-invasive species, fragmentation,...

Regional Technical Systems

Managed Ecosystems-Agriculture, forestry, fisheries...

Managed Water and Air Supplies-Irrigation, pollution,...

Managed Extreme Events-Disaster response and civil infrastructure...

Managed Human Services-Electricity production and transmission,...

Humans

Health-Malaria, cholera, respiratory diseases, ...

Security-Food, water, and energy, environmental conflict, migration

Economics-Industries, trade, investment

Welfare-Socio-Economic Development

to knowledge sources from many disciplines, and you need to assure your decision makers that you have found the best available. Moreover, if you wait for knowledge to trickle down the chain from the global level you risk waiting too long. Fortunately, knowledge does not only propagate downward. At any time, hundreds of strands of knowledge are propagating up, down, and across a complex network of sources and users. Your job is to locate the strands your community needs and weave them into a fabric of useful knowledge.

Knowledge Translation

In the world of climate assessment, people usually think that the word translation means making technical concepts understandable to non-experts, or explaining uncertainty in layperson's terms. It does, but there is a much deeper function of translation, one even more essential to adaptation than to mitigation, one that requires intimate communication among knowledge generators and action leaders.

People do not live on the globe; they live in communities. Community leaders focus on local trends, and the distant international community competes for their attention with local advocates of social, economic, political, legal, and cultural issues. Climate change operates in the background, and poverty, public health, food availability, land conversion, safety, flood control, fire protection, water distribution, water and air pollution, and congestion all make more immediate demands. Local leaders will pay attention only if their assessments address how climate change affects the specific things they care about.

Communities have their own ways of making decisions. Communities know best what they can and cannot do. Each has to decide what to preserve and what to let go. As they think out what they will do, they will arrive at socially and politically realistic strategies that may differ from those of international policymakers.

Community leaders may be in different political systems, but there is not one that does not appreciate public support. Woe to the assessment that does not take into account local political sensibilities or fails to communicate in culturally aware terms.

Translation goes beyond expressing ideas in accessible ways. It extends to supplementing knowledge assembly and synthesis with social networking in order to promote timely action. Communities are more likely to act promptly when their assessments transmit the motivation to act along with knowledge. The precursor to motivation is trust; do keep in mind that the degree of trust needed to acknowledge the truth of scientific facts is far

smaller than that needed to risk resources and reputation on action. Trust is more easily achieved when there is face-to-face interaction, so when knowledge and action leaders join together in “knowledge-action” social networks, the prospect for timely action is improved. Indeed, a survey of some 20 assessments showed that the direct participation of decision makers does promote action.

Knowledge Delivery

The ultimate assessment task is to deliver translated knowledge to decision makers where they need it and when they need it. This is easier said than done.

There is a looming timeliness problem. According to IPCC AR5 and other expert estimates, the pace of global climate change is expected to double in the coming decades. The Arctic climate is already changing at twice the global rate, so our present Arctic experience suggests what might be in store for the rest of the world in about 20 years.

The structure of the Arctic climate changed between two assessments seven years apart. Between the 2004 Arctic Climate Impact Assessment (ACIA) and its sequel, the 2011 Snow, Water, Ice, and Permafrost Assessment (SWIPA), there was a marked acceleration in the rate of polar warming, and most significantly, a change in the pattern of warming. The retreat of sea ice in the past decade had replaced a white ice surface by darker ocean, leading to increased absorption of sunlight and overwhelming the local warming that had been in progress in 2004. Bottom line: ACIA got out of date in just seven years.

The unexpectedly rapid pace of polar climate change also confounded the fourth IPCC Assessment in 2007; the scientists on its cryosphere panel could not agree on the rates at which the Greenland and Antarctic Ice sheets were melting. Their disagreement would not have had consequences beyond the world of science but for the fact that the ice melt rates are part of the estimation of the rate of sea level rise, in which all kinds of practical people are interested. IPCC, however, prides itself in releasing its pronouncements only when the scientists reach consensus. It chose to release a partial estimate of sea level rise, using only the part due to the much better founded rate that can be calculated from the measured ocean warming. IPCC was careful to list all the uncertainties in the ice melt rates, but practical people are not really very interested in the anxious handwringing of scientists. So a substantial under-estimate got out there. The scientific community, however, was horrified, and a veritable explosion of research followed, so that by the time the IPCC’s fifth assessment was released in late

2013 one could see what had happened in 2007. The ice melt rates had been undergoing a tremendous transformation. IPCC AR5 estimated that the ice melt rate from Antarctica, while uncertain, probably increased by about a factor 5 between the two decades, 1992–2001 and 2002–2011; the Greenland ice melt rates increased by a factor 6 comparing the same two decades. The melt rate had been changing faster than the scientists could document the changes.

If indeed the pace of climate change does pick up around the globe, there may come a time when the global climate assessments also get misleadingly out of date between releases. By that time, communities will likely be dealing with serious adaptation issues of their own. At that time, will they be willing to wait for knowledge to cascade down to them from the next global assessment? Won't their problems be so acute that they will demand immediate delivery of whatever is available?

In addition to the timeliness challenge, there is a coordination challenge. No community is an island unto itself. No community can escape being part of a polycentric governance network in which it is obligated to coordinate its decisions with those of its neighbors. Each has a responsibility to account for the climate benefit or risk it is passing on to others. Each needs to communicate its special needs, vulnerabilities, strategies, and costs to the larger governance network in which it resides. Not until many communities have done so, and the results added up around the world, will global policymakers be able to estimate a truly realistic cost-benefit ratio that balances the costs of adaptation and mitigation. The knowledge flow can never be one way.

To sum up the past three sections, assessments made for adaptation must cope with an extraordinary complexity of knowledge assembly and synthesis, highly specialized requirements of a vast number of decision makers, an increasingly exacting requirement for timely delivery, and a need to coordinate decisions. By now our position should be clear. The challenges of complexity, capacity, timeliness, and coordination can all be alleviated by the purposeful deployment of information, communication, and social technologies. By blending technologies, policies, and institutions, we could turn assessment from a periodically appearing document into an always-on knowledge management service that communities, industries and agriculture, and individuals everywhere can access at any time.

What is keeping us back?

Knowledge Certification

Decision makers are used to acting on less than perfect knowledge, but they do need to know how much trust to place in the knowledge they use.

How do they find knowledge they can trust? How can they judge unfamiliar information sources? Sometimes they cannot wait until a formal assessment is published; what risk do they take if they use research whose practicality has not been evaluated?

Knowledge Certification is the Intergovernmental Panel on Climate Change's most important value added product. In its knowledge assembly function, IPCC's expert sub-panels, through exhaustive small group discussion, judge whether a recent synthesis of research results is ready to be considered reliable knowledge. The sub-panels express their consensus judgments in terms like "virtually certain" to which they intuitively assign an illustrative probability percentage (e.g., 90–100% certain). In this way, IPCC experts estimate the reliability of the knowledge in the academic literature before they pass it on to the policy-maker.

IPCC characterizes research knowledge, and does not assess the uses to which that knowledge is put. IPCC does not and cannot address the reliability of the secondary and tertiary assessments that may be needed to address the highly specific needs of communities, agriculture, and industry. As time passes, and the knowledge is put to work in various adaptation contexts, decision makers with similar issues will want to know how that knowledge has been used. And waiting seven years for the next global level assessment may take too long; as we have already argued, decision makers in need may not wait for knowledge to trickle down. They will want the most up-to-date knowledge, and they will turn to the worldwide web to find it. Non-experts who try it today run into a familiar problem: they do not have a trusted guide to help them hunt for the reliable knowledge in the information jungle.

Embodying in institutional and technical practice the distinctions among peer-review, research impact, record of use, and what we will call decision-readiness could be a key enabling step. In peer review, a few experts evaluate whether a new research paper merits examination by the rest of their disciplinary community. The traditional peer-review process is managed by scholarly journals, whose editorial boards select the reviewers. The subsequent citation history measures impact *in the eyes of experts in the originating or closely related disciplines*. Peer review and research impact are precursors to evaluating knowledge reliability, where the question is to what extent the overall picture emerging from a synthesis of research results is generally accepted by the expert community.

By and large, research impact has been measured by the degree of assent or dissent in the citation history. Knowledge reliability, or general acceptance, has been intuitively evaluated by face-to-face social networking amongst ex-

perts, as with IPCC. This will continue to be the most important process, but we can also ask whether internet-based methods can relieve some of the burden. To what extent can reliability as well as impact be evaluated using a combination of data mining and social networking? For example, one could ask whether citations generated in a basic research discipline have propagated to an applied discipline. One could provide social maps of the knowledge users that track the propagation of knowledge from source to users. Addressing such questions is a task not only for the climate science community but also for the broader scholarly community. Together, they could convene leaders of journals, scholarly societies, libraries, commercial services, and potential users to formulate standards that find a workable balance between information theoretic indicators and human judgment.

There is one further characterization of knowledge that will become more prominent once adaptation proceeds – by decision-readiness. The idea that climate research could be described in terms of decision-readiness levels has been inspired by a successful practice adopted years ago by NASA in which technology in development is characterized by its record of use as it progresses to ultimate inclusion in flight hardware. In the climate case, a judgment of decision-readiness involves both the research and decision making communities. Regional and local decision makers around the world will be facing broadly similar adaptation issues. There will be many of them. They will want to know the practical issues considered by their compatriots in putting the knowledge to use, and they would like to know the record of its use. A characterization of decision-readiness will help them make their own decisions.

Annotated search

We hope we have made our position clear. The more the basic functions of assessment – knowledge certification, knowledge assembly and synthesis, knowledge translation, and knowledge delivery – are carried out by web-enabled services, the more the goal of combined bottom-down and bottom-up adaptation management becomes achievable, the more the goal of globally connected governance of polycentric decision making at local and regional levels becomes attainable, the more communities far from centers of knowledge generation are empowered to take their own adaptation initiatives.

In the fullness of time, there could evolve a search engine that could first supplement and ultimately even replace the burdensome documentary form in which assessments appear today. An annotated search engine would operate in two ways. First, like a globally distributed library of libraries that stores and catalogs the information products needed by researchers and de-

cision makers and facilitates access to vast quantities of knowledge and data. Second, like a multi-disciplinary journal with a huge table of contents that appears every day, every entry annotated by a globally distributed network of expert reviewers and users. The annotation would provide measures of research quality, extent of impact, breadth of expert acceptance, and experience with use. (Sir Bob Watson has argued that reviews be posted in wiki form). The search engine would likely be governed by an IPCC-like organization, but be professionally managed. Its managers and editors would among other things solicit synthetic summaries as soon as an area of new research seems mature, decide which materials qualify for archiving, provide finding and data mining tools, and promulgate quality, impact, and reliability indices. For decision-readiness it would manage reviews that include the user as well as the peer communities. All this is a tall order, but not beyond the kinds of things that are done in the financial world.

A Way Forward

Adaptation requires an international framework of policies, institutions, technical agreements, and finance. In the terms of our two white papers, we can see at least four components of the framework: incentives to incubate knowledge action social networks at the regional and community levels; political understandings that enable knowledge sharing; incentives for existing institutions to integrate research knowledge management with decision support; and steps to stimulate the evolution of a global federation of knowledge management services that support polycentric decision-making.

A club of research knowledge management institutions could get the process started. The diplomatic community could then establish a timeline for the creation of a global decision support federation. This would extend the initiative the diplomatic community took in creating the Group on Earth Observations, GEO. As GEO recognizes, the precursor to connecting knowledge management systems together is agreement on standards; the right standards, especially for decision-readiness, could set the stage for today's research system to be turned into tomorrow's knowledge action system. Standards could be a good place to start.

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Appendix 2A. Natural System Impacts

Some aspect of climate change will have an impact on every region, nation, community, and industry (IPCC Working Group II, 2007; Stern, 2007; Padwardhan, *et al.*, 2009). Here we take an impressionistic tour of the many different types of changes in regional natural systems that communities are beginning to worry about.

If you live in the Arctic, you wonder how long the permafrost will support the structures you have built on it or how caribou migration might change (Arctic Climate Impact Assessment, 2004). If you live along the Indus or Ganges rivers, one of your concerns will be how the melting Himalayan snows (Immerzeel, *et al.*, 2010) and changing monsoon (Aufhammer, *et al.*, 2012) will affect the irrigated agriculture, biodiversity, and populations along the river (Xu, *et al.*, 2009). If you live in a number of places in Asia, you worry about how air pollution and climate change interact to affect public health, agriculture and mountain snows (UNEP, 2008). If you live in coastal Peru, all your fresh water comes from Andes snowmelt, which you know is vulnerable to warming (Vergara, 2007). In Bangladesh, you worry whether villages will cope with floods, storm surges, and the cholera outbreaks that accompany them (Shahid, 2010). If you live in Venice (Carbonin, *et al.*, 2010), London (Nicholls, *et al.*, 2011), Tokyo (Yasuhara, *et al.*, 2011), Bangkok (Dutta, 2011), New York (Lin, *et al.*, 2012), or Amsterdam (Katsman, *et al.*, 2011) you wonder how much it will cost to protect from storm surges the valuable infrastructure you have built over the centuries (Adly, *et al.*, 2011). If you live on a small island, you wonder how long you will be able to do so (Kelman and West, 2011). If you live in Egypt (Serageldin, private communication 2011) or in California's Central Valley (Cloern, *et al.*, 2011), you worry that salt-water intrusions might harm the fabulously rich agricultures of the deltas of the Nile and Sacramento rivers. If you live in the American West (Painter, *et al.*, 2010; Cook, *et al.*, 2009), Australia (Lindenmaier, *et al.*, 2010), or North China (Qian, *et al.*, 2002), you worry about drought, desertification, wildfires, and dust storms. In Western Canada, you worry about the warming-induced infestation of pine bark beetles (Cudmore, *et al.*, 2010) that subjects its boreal forest to fires that put nearly as much CO₂ into the atmosphere as Canada's natural forest growth is sequestering (Running, private communication; Socks and Ward, 2010). In Africa, you worry about how agriculture (Dinar, 2012) and livestock (Thornton, *et al.*, 2009) will fare. And there are a few things that everybody worries

about: food security (Commission on sustainable agriculture and food security, 2011), human health (Bowen, *et al.*, 2012), how nature's wild places will survive (Morzillo and Alig, 2011).

In short, adaptation is an issue for everyone, but not the same issue. People are not interested in everything that can happen, only what could happen to them.

Appendix 2B. NASA Technology Readiness Levels

The following description is taken from a NASA website. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest. When a technology is at TRL 1, scientific research is beginning and those results are being translated into future research and development. TRL 2 occurs once the basic principles have been studied and practical applications can be applied to those initial findings. TRL 2 technology is very speculative, as there is little to no experimental proof of concept for the technology.

When active research and design begin, a technology is elevated to TRL 3. Generally both analytical and laboratory studies are required at this level to see if a technology is viable and ready to proceed further through the development process. Often during TRL 3, a proof-of-concept model is constructed. Once the proof-of-concept technology is ready, the technology advances to TRL 4. During TRL 4, multiple component pieces are tested with one another. TRL 5 is a continuation of TRL 4, however, a technology that is at 5 is identified as a breadboard technology and must undergo more rigorous testing than technology that is only at TRL 4. Simulations should be run in environments that are as close to realistic as possible. Once the testing of TRL 5 is complete, a technology may advance to TRL 6. A TRL 6 technology has a fully functional prototype or representational model.

TRL 7 technology requires that the working model or prototype be demonstrated in a space environment. TRL 8 technology has been tested and "flight qualified" and it's ready for implementation into an already existing technology or technology system. Once a technology has been "flight proven" during a successful mission, it can be called TRL 9.