Proceedings of the American Philosophical Society

Held at Philadelphia for Promoting Useful Knowledge

VOLUME 156 • NUMBER 4 • DECEMBER 2012

THE AMERICAN PHILOSOPHICAL SOCIETY

INDEPENDENCE SQUARE: PHILADELPHIA

2012

Coping with Climate Change in the Next Half-Century

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GREENHOUSE GAS (GHG) concentrations are trending far off the path needed to avoid dangerous interference in the climate system, and nations are making little progress in the diplomacy to cut their emissions. Reducing carbon dioxide (CO_2) emissions from fossil fuels is the only course of action that stabilizes the climate beyond the year 2100; a recent analysis of California's energy systems illustrates how difficult it will be over the next few decades to put the planet on the path to stabilization. While there is cause for optimism that CO_2 emission controls could have effect after 2050, in the interim the world must prepare for at least twice as much human-caused warming in 2050 as we have seen thus far.

There is a way to moderate the impacts of climate change between now and later in the century when CO_2 mitigation could become effective. Action on short-lived climate warming pollutants such as methane and black carbon can have a fast climate response and reduce the near-term costs of adaptation. The technologies and regional regulatory forums are in place, and the co-benefits are huge; controls on short-lived pollutants, such as soot, can save millions of lives through reductions in local pollution, while also lessening the loss of crops. Focusing on pollutants with large co-benefits could make countries more likely to want to act. Working on issues where short-term success is possible could also make international climate change diplomacy more credible,

PROCEEDINGS OF THE AMERICAN PHILOSOPHICAL SOCIETY VOL. 156, NO. 4, DECEMBER 2012

which would greatly aid in completing the more difficult task of reducing CO_2 emissions.

Nonetheless, significant climate warming now appears unavoidable, so it is also urgent to prepare to adapt. We propose that reduction in short-lived climate pollutants go hand-in-hand with local and regional adaptation efforts. Unlike much of climate change science, which looks globally, adaptation is an intrinsically local affair. Successful adaptation will require new institutions, including climate change assessment networks that directly support local mitigation and adaptation efforts worldwide, and a knowledge-dense cyber-infrastructure that supports them.

Part 1. Why It Will Be Hard to Avoid "Dangerous Anthropogenic Interference in the Climate System"

Here we review for a general educated audience[1] some of the reasons why the present approach to mitigating climate change moves too slowly to prevent significant warming in the next half-century. Experts may prefer to skip directly to the suggestions about what we can do in subsequent sections.

In 1992, in the United Nations Framework Convention on Climate Change (UNFCCC), 154 nations crafted a binding pledge to cut emissions in a way that would "achieve [. . .] the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." As often happens with diplomacy, the UNFCCC created a new term of art, "dangerous anthropogenic interference," but studiously did not define it. Much more recently, starting in 2007, governments adopted a series of agreements that established 2 degrees Celsius[2] as a widely accepted goal for avoiding danger. Because CO_2 from burning fossil fuels is the main cause of climate change, that goal implies the need for major cuts in global CO_2 emissions. The International Energy Agency has estimated that it will require an investment of $45 trillion dollars during the next few decades to cut CO_2 emission by 50%.[3] Even after a 50% reduction by 2050, the CO_2 levels in the atmosphere will continue to increase beyond 2100, because of the long lifetime of the CO_2 molecule. To prevent further increase in CO_2 concentrations beyond 2100 we have to eliminate nearly all CO_2 emissions by about 2050.

To understand the magnitude of the challenge, it is interesting to look at California—perhaps the U.S. state with the greatest political commitment and technical ability to address the challenges. California's Global Warming Solutions Act of 2006 (AB32) and Executive Order S-3-05 require that California reduce its greenhouse gas emissions to

80% below 1990 levels by 2050 while accommodating projected growth in its economy and population.

In its May 2011 report,[4] the California Council on Science and Technology (CCST) designed a technology strategy that could enable the state to meet the 80% below 1990 commitment. There are several ways of doing this, but CCST's assessment gives an idea of the magnitude of the task. Because of expected population growth, greenhouse gas emissions per person would have to be cut by almost 90%. Even with optimistic assumptions, no single technological approach would suffice. *All* currently available low-carbon energy technologies would have to be deployed at technically aggressive rates without undue political or social resistance. Among the diverse actions CCST evaluated are the following:

- The state would need thirty new nuclear power plants, one per year beginning in 2020. At present, California has six operating nuclear power plants.
- New building standards would have to be in place by 2015 and every old building retrofitted by 2050, so that an 80% improvement in the energy efficiency of the built environment can be accomplished.
- Transport networks would need massive redesign. Included in the changes would be shifting 60% of light-duty vehicles to electric power and putting low-carbon liquid fuels in widespread use to achieve a 58 mpg fleet average for liquid fuels, or 87 mpg (greenhouse gas equivalent) including electrical vehicles. In 2010, U.S. corporate average fuel economy standards were 27.5 mpg for passenger cars and 23.5 mpg for light trucks.
- What is most important, as much energy use as possible should be shifted to the electrical power system, and *all* electricity generated without CO_2 emissions. The power grid would have to be redesigned to achieve "zero-emission load following" to cope with the intermittency of wind and solar power. Without the smart grid, emissions from back-up conventional plants could actually increase total GHG emissions.

CCST found that getting to 60% below 1990 is doable with existing technologies.[5] The last 20%—allowing California to reach its ultimate goal of an 80% reduction by 2050—would require technologies that are not on the market, or even in demonstration. Innovation is likely to be even more critical than these figures suggest.

Can California-like goals be achieved worldwide? We are skeptical, and we explore next some of the practical economic and political barriers to effective CO_2 mitigation at the global level.[6]

Of all the greenhouse gases, CO_2 is the most difficult for society to regulate. CO_2 emissions are a fundamental byproduct of the contemporary industrial system, which relies heavily on fossil fuels—especially in the rapidly developing emerging markets that account for most growth in emissions, where coal remains the principal energy source.[7] Coal produces 60% more CO_2 per unit energy than natural gas, and has serious air pollution and other environmental costs. Nearly all the growth in future coal consumption will come from China and India—countries unlikely to reduce their use any time soon. Coal is cheap and abundant; it presents fewer geopolitical risks than oil. World consumption is expected to double by 2030. Indeed, even as these countries address their local pollution concerns they are doing so in ways that continue their reliance on coal—for example, by installing scrubbers and other pollution control equipment and buying more efficient coal plants rather than abandoning coal altogether.

In the mature, highly industrialized countries, emissions are flat, and in many coal consumption is on the decline. However, these trends are modest and are unfolding slowly. They reflect, for the most part, underlying concerns about air pollution and the side effects of economic restructuring rather than any particular, major effort to control warming emissions. Modifying the present course will require political, market, or regulatory incentives, globally applied, that stimulate technological innovation, promote efficiency across society, and change how energy is produced and used. None of that is likely soon. Even talking about these changes has proven exceptionally difficult.

Since the UNFCCC entered into force in 1995, there have been eighteen UNFCCC "Conference of Parties" meetings. These meetings, increasingly large and chaotic, have achieved little in concrete agreements or actions. Some ascribe the lack of timely action to a generalized hostility to climate change or lack of U.S. leadership, but this is too simplistic. The negotiations are not structured to make timely progress. The annual meetings are too big and the issues too complex to be resolved by consensus. The negotiations have been made harder to manage by the diverging interests of key countries. Nations have different political and social systems and economies, and thus different interests related to climate change. There are nations deeply worried about climate change and keen to devote their own resources to controlling emissions (e.g., Europe, Japan); others are more reluctant (e.g., China, the U.S.). While most countries think they will be harmed by climate change, a few see potential benefits in at least some warming (e.g., Russia). The costs of controlling emissions are immediately visible to most governments and pressure groups, while the benefits of avoiding unchecked climate change are unknown and abstract—a structure that often leads to policy inaction.[8] The countries most acutely aware of the harms that will befall them in a warmer world—the small island nations—are unfortunately among the smallest emitters and have the least leverage on the underlying problem.

Even if the world's nations agreed tomorrow to reduce CO_2 emissions, it would still be decades before the global energy system could accomplish the task. Some of the technologies that might play major roles—such as carbon capture and storage (CCS) on coal plants—are not yet widely tested. Large-scale deployment of renewable technologies is promising to many analysts, but the technologies needed to allow these systems to work at scale are not yet viable. While rapidly growing, renewable energy sources still provide a small faction of today's power production, and it will be difficult for them to replace fossil fuels in the next few decades. Indeed, they are not yet poised to do so, since all of today's renewable technologies require subsidies to make them competitive. This makes them politically vulnerable, especially in democratic market economies.

Here is the most fundamental reason why CO_2 is so hard to deal with. The inertia built into the global carbon cycle and the oceans means that the climate effects of what we do about energy will be delayed for decades. CO_2's long atmospheric lifetime is also the most fundamental reason why CO_2 mitigation is so important, even though it cannot have much impact in the short term.[9] CO_2 remains in the atmosphere about a hundred years, long enough to spread uniformly around the world. Of every 100 CO_2 molecules added to the atmosphere today, about 55 will soon be absorbed by the oceans or taken up by the world's forests. Of the remaining 45, about a third will be in the atmosphere at the end of the century. The oceans also take up a major fraction of the energy added to the climate system by greenhouse warming. Some of the heat and CO_2 molecules the oceans take up today will still be in the process of being released a thousand years from now. Because of this, there will still be 20 CO_2 molecules in the atmosphere, still contributing to climate warming. If and when we reduce atmospheric CO_2 concentrations, the reduced rate of greenhouse warming will be offset by release of the heat and CO_2 deposited earlier in the oceans, so that the atmospheric temperature will remain elevated for a thousand years. The oceans, right now our friend, are storing up problems.[10] This is the fundamental reason why continuing to emit carbon dioxide is so risky.[11]

Part 2. Air Pollution's Role in Climate Change

Air pollution and greenhouse gases compete with one another to affect the climate. The radiatively active aerosol particles in pollution include sulfates, organics, and nitrates (SONs); the sulfates may be familiar since they are responsible for acid rain. SONs reflect visible light back into space whereas GHGs retain infrared radiation in the atmosphere that otherwise would escape to space. At the earth's surface, there is competition between warming by enhanced infrared radiation and cooling by reduced visible light.

Sulfate air pollution has been offsetting greenhouse warming. Air pollution is concentrated where human activity is intense, but winds carry it over intercontinental distances.[12] Because pollution is now spread wide and far, it is affecting the total energy balance of the atmosphere. From the 1950s through the 1980s, increasing SON pollution from the rapidly growing economies of North America and Europe almost completely counteracted greenhouse warming. When North America and Europe brought their pollution under control in the 1980s, aerosol cooling diminished, and the global temperature responded by increasing more rapidly. Atmospheric brightness followed a pattern consistent with that observed in global temperature; long-term records of visible light intensity show dimming from the 1950s to the 1980s, indicating increasing SON pollution, followed by brightening, indicating a decrease in pollution.[13]

Black carbon particles in air pollution—essentially soot—add to warming, rather than subtracting from it. The name "atmospheric brown clouds," or ABCs, has been given to the plumes of black carbon mixed with other man-made pollutants (notably SONs) carried away from their sources by the winds.[14] Black carbon aerosols are produced in many regions of the developing world by biomass burning, open cooking fires, inefficient diesel engines, and industrial processes.[15] The soot particles are suspended below three kilometers in altitude; dark in color, they absorb sunlight and warm the atmosphere where they are. The aerosols from industrial sources are black, while those from biomass burning are brownish because they contain organic substances. The black carbon from industrial sources is about 100% more efficient a warming agent than that from biomass burning.[16] We use the term black carbon for both types. The regional mix determines the color of air pollution;[17] each region's plume has a distinctive composition.

While atmospheric black carbon is produced regionally, prevailing winds soon disperse it around the globe. Asia is presently the largest source; black carbon produced in East Asia arrives over the American West Coast in about seven days; about 25% of the particles at altitudes above 1 km over Los Angeles come from Asia. Similarly, America passes on the unwanted products of its combustion to Europe, and Europe's go to Asia.

Let us compare black carbon warming and sulfate cooling using illustrative figures.[18] Sulfate-organic-nitrate pollution by itself reflects about 2.1 watts/m^2 back into space. Black carbon is invariably internally mixed with sulfates[19] and its solar absorption rate is amplified by the presence of sulfates in the pollution plumes;[20] its local warming rate is clearly situationally dependent. Ramanathan and Carmichael[21] calculated from observational data that atmospheric black carbon adds about 0.5 to 0.9 watts/m^2 warming averaged over the globe. At the time (2008), this result was thought to be an outlier; however, a 2013 re-assessment[22] supports an even larger best estimate, 1.1 W/m^2 warming. Black carbon now makes the second largest human contribution to climate change, after CO_2.

How much warming should we have gotten from greenhouse gases acting alone? By 2005, CO_2 (1.65 watts/m^2) and the other GHGs taken together (1.35 watts/m^2) had added 3 watts/m^2[23] of infrared energy flow to the climate system since pre-industrial times.[24] According to simple energy balance models, 2005's GHG concentrations should lead to warming of 2.4 (1.4–4.3)[25] °C above the pre-industrial level. Without aerosol cooling, we would have realized about 1.9°C today with 0.5°C to be released later from the oceans (all figures approximate). We have experienced 0.75°C. Air pollution, it seems, has protected us from 60% of the warming expected from today's concentrations of greenhouse gases.

What would happen to the climate if all humanity suddenly stopped polluting its air? Black carbon particles would disappear in a few weeks. The SONs in the lower atmosphere would be removed by weather processes in months, whereas those that make it to the stratosphere, like those from volcanic eruptions, would disappear in one or two years. After all this, we would have removed pollution cooling, but the climate forcing due to greenhouse gases would continue, and the embedded greenhouse warming would reemerge. Suppose also we could actually hold today's concentrations of greenhouse gases constant as pollution cooling is eliminated. We would eventually get the full 2.4 (1.4–4.3) °C warming that our present GHG concentrations are exposing us to;[25] we might already be experiencing "dangerous anthropogenic interference in the climate system."

In solving their pollution problems, developing nations could exacerbate climate change. Extension of current air pollution controls to all regions around the world might reduce sulfate pollution by as much as 60% by 2050, but this would uncover some of the embedded greenhouse warming. Allowing pollution to increase—a climate solution that depends on tolerating human harm—is not sustainable. Nor is tolerating pollution politically viable, since people, knowing that places like London, Los Angeles, and Mexico City have brought it under control in about twenty-five years, will demand that it be done away with.

Part 3. Slowing Climate Change While Reducing Air Pollution

This section focuses on what we should do in the next few decades when CO_2 mitigation has yet to come to fruition, yet the changing climate is creating adaptation risks that must be dealt with.

The moral and economic passions evoked by CO_2 may have blinded the public discussion to other options we have to offset adaptation risk. One is to reduce the emissions of the other greenhouse gases of human origin. In the aggregate, non-CO_2 anthropogenic greenhouse gases are responsible for 40%–45% of the present infrared energy flux driving climate warming, so working with them can have a material impact. Moreover, there will be a shorter lag between mitigation action and climate response because their atmospheric residence times are much shorter than that of CO_2.

The seemingly harmless synthetic gases called hydrofluorocarbons (HFCs) are the fastest growing climate-forcing agent in many countries.[26,27] HFCs, organic molecules containing fluorine atoms, have replaced chlorofluorocarbons (CFCs), whose use was banned by the 1988 Montreal Protocol on Substances That Deplete the Ozone Layer. Because of their similarities to CFCs in chemical properties and uses, HFCs should eventually be included in the Montreal Protocol[28] or a similar treaty. The Montreal Protocol has been successful; since 1988, 98% of nearly 100 chemicals similar to HFCs and CFCs have been phased out. The chlorofluorocarbons, CFC-11 and CFC-12, per molecule, are about 10,000[29] times as potent as greenhouse gases, as is CO_2. Had they not been regulated by the protocol, they would have added 0.6–1.6 watts/m^2 warming by now, comparable in magnitude to the warming produced by CO_2 emissions since the protocol went into effect. This unanticipated benefit of the Montreal Protocol shows that management of non-CO_2 GHGs can materially reduce short-term climate risk.

Methane is the most important anthropogenic greenhouse gas after carbon dioxide. It is 23 times more potent per molecule than carbon dioxide as a greenhouse gas, and despite lower concentrations drives 18% of greenhouse warming, or 0.48 watts/m^2. Microbes in anaerobic environments release methane to the atmosphere.[30] Natural environments where anaerobic production occurs include wetlands, tundra, soils, and ruminant animals. The managed environments include landfills, rice paddies, and cattle ranges. Other sources include incomplete burning of biomass and fossil fuels, and the geological processes that create natural gas. The atmospheric concentration of methane has nearly tripled since pre-industrial times, and is higher than in the past 650,000 years. Human activities are now responsible for 55%–70%[31]

of all the methane released to the atmosphere, so managing methane can have a non-trivial effect.[32] Since its atmospheric lifetime is about eight years, decision makers can begin to see reductions in concentration during their tenures in office.

Cutting the emissions of the most important short-lived climate pollutants to 30% of present levels (methane), 70% (black carbon), and 100% for HFCs (by using replacement compounds) could cut the rate of warming from 2010 to 2050 by as much as 50%.[21] Technical solutions are at hand; Shindell et al. (2012)[33] identified fourteen actionable measures targeting methane and black carbon that could reduce warming in 2050 by about 0.5°C. One of the more significant is reducing the emissions of black carbon from hundreds of millions of open cooking fires in Asia.

HFCs excepted, dealing with short-lived climate pollutants and managing air quality go hand in hand.[34] Because methane, ozone, and aerosols interact with one another chemically, a change in the concentration of one changes all the others. Air quality managers already model the interactions in the soup of air pollution that hangs over their air-sheds and could begin also to account for their air-shed's impact on climate change. As we saw in section 2, what they do about pollution affects the rate of climate change, not only in their regions, but globally.

A policy focus on short-lived climate pollutants can have important ramifications.[35] People will see the co-benefits[36] in their lifetimes, including improvements in human health,[37] agricultural productivity,[38] and aesthetics;[39] progress will literally be visible. Some nations reluctant to tackle CO_2 have made similar calculations—such as the U.S., which has done little at the federal level to control CO_2 emissions but already has active and growing efforts to control its short-lived pollutants.

Doing what can be done right away also gives a sense of forward motion to the stalled climate negotiations.[40] That should make it easier for governments to justify further action on CO_2. Developing countries, most of which have been reluctant to engage in CO_2 mitigation discussions, are major emitters of short-lived climate pollutants and stand to realize many co-benefits of pollution control. Opening this second front in mitigation policy may also be a way to enlist them in CO_2 mitigation efforts, which is important since they will be the principal sources in the future.

On 16 February 2012, Secretary of State Hillary Clinton announced the formation of a Climate and Clean Air Coalition (CCAC)—Bangladesh, Canada, Ghana, Mexico, Sweden, the United States, and the UN Environmental Programme—to promote practical ways to limit emissions of short-lived climate pollutants. These substances are not currently regulated within the Kyoto Protocol or its parent treaty, the

1992 UN Framework Convention on Climate Change. As a result, their levels or actions to reduce them are not formally discussed as part of the annual climate negotiations. However, at the Doha UNFCCC conference in December 2012, the CCAC coalition, which had grown to twenty-five participants since February, announced the actions it is beginning to take.

Part 4. Adaptation

If we do everything—meet the CO_2 emission targets for stabilization, act on short-lived warming agents, *and* reduce cooling air pollution—how long can net warming be held below 2°C? Ramanathan and Xu (2010)[41] modeled what it would take to hold warming in 2050 to 2°C. The major CO_2-emitting nations would have to meet goals like California's. In 2050, carbon dioxide concentrations should be on the path to stabilization at 441 ppm by the end of the twenty-first century; by contrast, the business as usual scenario of IPCC 2007 predicts about 600 ppm by 2100. The short-lived GHGs (methane, ozone precursors such as methane, carbon monoxide, and nitrous oxides) should be reduced at the rates calculated by two groups that have systematically analyzed the options.[42,43] Air pollution reduction could go forward as fast as is feasible, but should be made as climate-neutral as possible by matching the removals of cooling SON aerosols and warming black carbon particles.[44] Finally, to keep warming below 2°C in 2050, total GHG emissions would have to start declining by 2015 at the latest. Emissions in 2012 are increasing, not declining, and there is no evidence that they are starting to come down. The 2°C threshold will likely be crossed before 2050.

Until very recently, it was unfashionable to bring up adaptation[45] because the advocates of action on CO_2 feared that talk of adaptation would reduce the will to mitigate and reward miscreants. Now we have no choice. Prudent risk management demands we anticipate 2°C warming and prepare for more over the coming decades. In other words, we should prepare our children for three times the warming we have experienced thus far. They will experience impacts on natural disasters, coastal infrastructure, food security, water availability, ecosystems, and the oceans (through acidification)[46] that will put the well-being of billions at risk, especially in the developing world.

There has been a vast outpouring of scientific studies of the present and future impacts of climate change on both natural and human systems. While predicting global climate change is difficult enough, the task of understanding the many different kinds of impacts expected at local and regional levels has proven far more complex. Nonetheless, in the past half-decade especially there have been efforts to bring this knowledge to bear on decision making. It is now urgent to strengthen and expand these efforts.[47] Much remains to be done.

Sea level rise is the most comprehensible impact of climate change; dozens of coastal areas are now formally assessing their risks, and a few—notably the Netherlands and Venice—are strengthening their coastal defenses. Today's science can identify many other adaptation risks, but cannot say precisely when they become urgent. Science can forecast the occurrence of large-scale geophysical events—the melting of mountain glaciers, snows, polar sea ice, and the Greenland and Antarctic ice sheets—but the local and social impacts have not been articulated well enough to prompt local action. Science can advise that extreme events—floods, storms, droughts—may intensify, but it cannot link any single extreme event to global climate change. Ecologists can map how plants and animals shift pole-ward or upward to stay in their comfort zone, or document the changing timing of biological events,[48] but can give only general advice about land use, agriculture, ecosystem management, or conservation.

Science has greater difficulty still with cascades of interrelated effects,[49] such as when the climate, itself a complex system, interacts with other interacting complex systems like water and ecosystems. General experience tells us that surprises are possible when complex systems interact nonlinearly,[50] but we will not know, until one is near, whether a tipping point is approaching. Finally, it is even harder to predict society's response to climate change than to predict climate change itself. Until we can, we will not know at what point adaptation costs become intolerable.[51] In short, today's science knows enough to warn decision makers that the past is not a guide to the future, but it cannot yet advise them reliably when, where, and how much to act on that knowledge. This is an urgent task for the future.

A visible commitment to adaptation could create greater motivation to mitigate. Most people do not live day in and day out with the images and data that fill the mental worlds of the scientists who study the earth. A majority of climate scientists may be convinced, but at today's 0.75°C, the impacts of climate change have not been compelling enough socially to motivate reduction in GHG emissions. Science can help develop the social motivation to mitigate by identifying local adaptation risks and what needs to be done to counter them. People will not appreciate the abstract benefits of mitigation until they can see the risks to the things they care about in their communities.

Science is not speaking clearly enough to the people who will make local mitigation and adaptation decisions.[52] Many decisions about energy, air pollution, and short-lived GHG emissions will be made by regional and local leaders who will be influenced more by the future welfare of the people around them than by the pronouncements of the international scientific community. These leaders will be preoccupied with issues of social and economic development as they ponder whether and how much to invest in reducing climate and pollution risk. They will have to find their own balance between mitigation and adaptation, and they will need to know how their mitigation actions affect their adaptation risks.[53] We in the scientific community need to learn how to speak to these local leaders.

The scientific community will need to adapt its assessments of climate change to the economic, environmental, and cultural concerns of each region.[54] Already, there is a growing convergence of methodologies for assessing the vulnerabilities of regional ecosystems, populations, and infrastructure;[55] recognition that each region must develop its own adaptation strategy; and a beginning sense of how to manage the regional adaptation process. The declaration (quoted below) of the Special Session on Regional Climate Change of the 2010 Kyoto Forum on Science and Technology in Society[56] proposes a new management tool that employs both social and informational networking:

> Knowledge Action Networks[57] create a two-way flow of information, knowledge and methods between local communities, scientists, opinion leaders and decision makers, and their regional, national and global counterparts. . . . Their functions should include
>
> - Understanding ongoing natural and social impacts of climate change
> - Characterizing the risks of future climate change to the things local communities care about
> - Leveraging existing resources and programs
> - Providing information flows to ensure that interrelated decisions can be made at the global, regional, and local levels
> - Building capacity, by filling gaps in available information, by stimulating local analytical capabilities, by providing models and observations generated elsewhere, by sharing best practices, and by promoting general social resilience
> - Translating scientific knowledge and data into locally understandable and usable form
> - Communicating the need for and nature of adaptation actions in culturally appropriate ways
> - Promoting the development by the international community of technical systems that can be applied to or operated at the local level
> - Relaying local knowledge to the regional, national, and international communities
> - Supporting local leaders as they implement adaptation actions

These *desiderata* raise questions about how scientific assessments for climate change adaptation purposes should be conducted. When adaptation joins greenhouse gas mitigation as a major assessment goal, it becomes essential to grapple with the regional specificity of climate change impacts, and to focus on local communities—the front lines of adaptation. This leaves us with an important question. There are hundreds of regions and thousands of communities that will have to decide how to adapt to climate change; how can the relatively small science, policy, and technology community develop the capacity to serve the different needs of millions of decision-makers in thousands of communities with individual cultural, economic, and environmental characteristics?[58]

Part of the answer to the capacity problem is a planned deployment of modern information, communications, bibliometric, and social technologies to support the assessment process. Present trends and anticipated future developments look promising in this regard. It is possible to visualize a time when comprehensive documentation of the state of the earth system will be made widely available in near-real time. In other words, a kind of continuous awareness of the state of the earth system and its interactions with human society could be communicated to decision makers and the public. By blending technologies, policies, and institutions, we could create a knowledge-dense cyber-infrastructure that takes advantage of scientific continuous awareness and can turn assessment from an expert document that appears periodically into an always-on knowledge management service.

In a world in which information technology and the climate are both evolving, it is better to plan by looking forward than by looking back. Scientific vision becomes technical reality faster than we can make policy and institutional innovations. Thus, the first issue is not to create cyber-infrastructure, but to agree on what it should do and who should do it, and to start building the social understandings that define the attributes of the knowledge management systems that are needed. Shouldn't we start to prepare the social infrastructure—policies, governance, institutions, financing—needed to knit climate knowledge and adaptation action together?

At the 2011 UNFCCC meeting in Durban, the nations agreed to provide a US $100B fund for adaptation by 2020. We suggest that a fraction of these funds be used to develop a twenty-first-century climate assessment infrastructure.

Acknowledgments

It is a pleasure to acknowledge the many discussions we have had with colleagues: Kristin Blackler, Dan Cayan, Paul Crutzen, Mike Dettinger, Dick Fenner, Dan Goldin, Julian Hunt, Jim Falk, Sam Iacobellis, John

Kennel, Matthew Kennel, Paul Linden, Gordon McBean, Kim McIntyre, Cristina Nasci, Naomi Oreskes, Martin Rees, Ismail Serageldin, Larry Smarr, and Alexander Zehnder. We are indebted to two reviewers who made useful suggestions about the organization of this paper.

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1. For an earlier review, see V. Ramanathan and Tim P. Barnett. Experimenting with Earth. *The Wilson Quarterly* (1976–) 27.2 (Spring 2003): 78–84, URLhttp://www.jstor.org/stable/40261187.
2. Global temperature is a term only a scientist could love. It is computed by averaging temperature measurements taken at thousands of locations around the earth. The recent Berkeley reanalysis of more than a billion thermometer measurements illustrates the great variability in space and time that underlies this one number. Nonetheless, the global temperature increase since the beginning of the industrial era may be thought of as an index of the energy being added to the climate system by human activities. This increase has been 0.75°C. Thus 2°C amounts to 2.67 times the increase we have experienced thus far. The "business as usual" scenario of the Intergovernmental Panel on Climate Change (IPCC) forecasts an increase of 4.75°C by the end of the twenty-first century. To put this in context, the difference between an ice age and an interglacial warm period like the one we are in is 5°C.
3. IEA Energy Perspectives. 2008.
4. J.C.S. Long, M. John et al. *California's Energy Future—The View to 2050,* summary report, California Council on Science and Technology, 56 pp. May 2011.
5. California does not have available to it a mitigation tool that is important to countries like Brazil and Indonesia: reduction in the rate of deforestation. At present, deforestation produces the equivalent of about 10% of global CO_2 emissions.
6. The arguments in this section are based on D. G. Victor, *Global Warming Gridlock* (Cambridge University Press, 2011), 358 pp., and D. G. Victor and R. K. Morse. Living with coal; climate change's most inconvenient truth. *Boston Review* Sept./Oct. 2009, 7–14.
7. Coal, oil, and natural gas contribute 41%, 39%, and 20% respectively to fossil fuel carbon dioxide emissions. Replacing coal and oil with natural gas where possible would produce significant greenhouse gas benefits.
8. These challenges are large but not insurmountable. Indeed, these challenges in managing the problem of climate change are similar to those that have arisen in international diplomacy on trade and in other areas of international economic regulation. One lesson from the experience with international trade is that progress will occur in fits and starts. Another is the benefit of working in smaller groups of important countries—"clubs"—that can band together and focus on practical solutions. Already consortia are forming around deforestation. The major emerging countries—Brazil, China, India, and South Africa—have started their own club. It may seem paradoxical, but a more distributed negotiating arena could make decision-making more efficient because it would allow countries to concentrate on actions and promises that are credible. By contrast, negotiations that involve all 185 countries that are UNFCCC members are prone to gridlock.
9. The global distribution and long response time of carbon dioxide to mitigation actions give rise to the chief intergenerational ethical issues in climate change. Things we do today change the climate and conditions for life in unknown ways for thousands of years. The CO_2 emissions each of us causes today change the climate for everyone on earth for generations. Put differently, present generations pass on environmental risk to future generations as well as assets such as knowledge

and infrastructure. The intergenerational challenge is to strike a balance between future debt and present investment for the future. Beyond these ethical issues there are practical problems. Decision makers today face certain costs for controlling emissions, yet cannot expect to see the benefits of their action for many years—long beyond the tenure of politicians, CEOs, leaders of environmental groups, and even citizens. The incentives to temporize are strong. Yet for future generations the consequences of inaction are costly.

10. They have already done so; even if greenhouse gas concentrations were held fixed by magic, the climate will still change; see G. A. Meehl, W. M. Washington, W. D. Collins, J. M. Arblaster, A. Hu, L. E. Buja, W. G. Strand, and H. Teng. How much more global warming and sea level rise? *Science* 307 (2005): 1769–72.
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