



How to deal with **CLIMATE CHANGE**

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Climate change is a complex and contentious public issue, but the risk-management options available to us are straightforward and have well-characterized strengths and weaknesses.

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People are causing Earth's climate to change. Natural factors like solar variability and volcanoes may have also exerted a slight warming or cooling influence recently, but they are on top of the human contribution and small by comparison.^{1,2} That conclusion is extremely solid scientifically because it comes from multiple independent lines of evidence.

However, the societal consequences of climate change in the decades ahead are hard to predict. We simply don't know—and probably can't know—precisely how climate will change or how resilient our society will be to the impacts that result.

Even leading experts often reach very different conclusions about the seriousness of the risks we face. Some experts conclude that the consequences of climate change over the next several decades will most likely be small—perhaps a few percent of GDP.³ That conclusion might make sense if feedbacks in the climate system tend to stabilize climate rather than exacerbate changes. Or we might get lucky and find that physical systems, biological resources, and social institutions prove insensitive to climate change. Alternatively, rapid scientific and technological advances might give us the capacity to overcome the effects of climate change.



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Other experts see climate change as an extremely serious risk to society.⁴⁻⁶ That assessment might make sense since climate is projected to change over the next several decades faster than at any time in at least 10 000 years and would bring unprecedented climate conditions to human civilization. The physical characteristics of the planet, the biological resources on which society depends, and our social systems have developed over a long time in response to climate conditions we're quickly leaving behind.

Even setting aside disagreement among experts over the likely consequences—and the inescapable uncertainty that disagreement reveals—climate change represents a difficult risk-management challenge. Policy responses necessarily integrate both scientific information and subjective value judgments. Science can inform us about the climate system and our relationship with it. But it can't tell us whether to care more about our children and their children or about ourselves. Science can't decide what is fair for different nations and peoples. It can't resolve differences of opinion on the value of cultural heritage or nonhuman species. There is no clear path to agreement on any of those issues, and that lack of clarity sets up a complex and contentious policy debate.

Policies relating to climate change fall into the four broad categories illustrated in figure 1. We could reduce our greenhouse gas emissions, an approach that is typically called mitigation.⁷ We could increase society's capacity to cope with changes in climate, which is called adaptation.⁸ We could delib-

erately manipulate the Earth system in ways that might counteract at least some of the effects of increasing greenhouse gas concentrations. That kind of intervention is typically called geoengineering or climate engineering.⁹ We could also expand our knowledge base in ways that help us better understand the climate system, our sensitivity to climate change, and the other three risk-management strategies, which are more proactive.

Reducing emissions is somewhat like preventing disease—exercise, eat well, don’t smoke. Adaptation is more like managing illness—take medicine to cope with symptoms and alleviate problems. Geoengineering is a little like organ transplantation—best avoided if at all possible but potentially better than nothing.

Each category of response consists of a broad family of options. In some cases the boundaries between categories become a bit fuzzy—efforts to reduce emissions might increase adaptive capacity and vice versa. Indeed, many experts characterize geoengineering approaches as mitigation or adaptation^{7,8} rather than a separate category of risk management.

The three proactive risk-management options are not mutually exclusive; we could simultaneously mitigate, adapt, and geoengineer in a range of combinations. Comprehensive climate change risk management almost certainly includes a combination of solutions drawn from all three strategies.

Mitigation

By reducing emissions, mitigation reduces society’s future contributions to greenhouse gas concentrations in the atmosphere. That would reduce the amount that climate changes and thereby increase the chances that the resulting societal impacts are manageable. Mitigation might also confer secondary benefits unrelated to climate change risk management. For example, reducing emissions of greenhouse gases would likely also reduce oil consumption and some traditional forms of air pollution, which would lessen foreign oil dependence and improve public health.

But mitigation has potential downsides. It could cause excessive energy prices or the premature retirement of capital equipment. Similarly, some efforts to reduce emissions could lead to adverse secondary consequences. For example, policies to promote biofuel production could lead to inefficient uses of land, water, or agricultural crops. The use of biofuels can also exacerbate air pollution or degrade water quality.

Approaches to reducing emissions fall into several categories.¹ We could pass regulations that set minimum energy-efficiency standards for cars or appliances or that prohibit the use of inefficient products. Policies could encourage conservation of energy or forests through public awareness campaigns, or they could subsidize climate-friendly choices. Policies can fund the creation and deployment of low-emitting technologies like wind and solar energy or nuclear power (see figure 2 for an example). And policymakers could put a price on greenhouse gas emissions to encourage reductions.

Adding a price to greenhouse gas emissions is

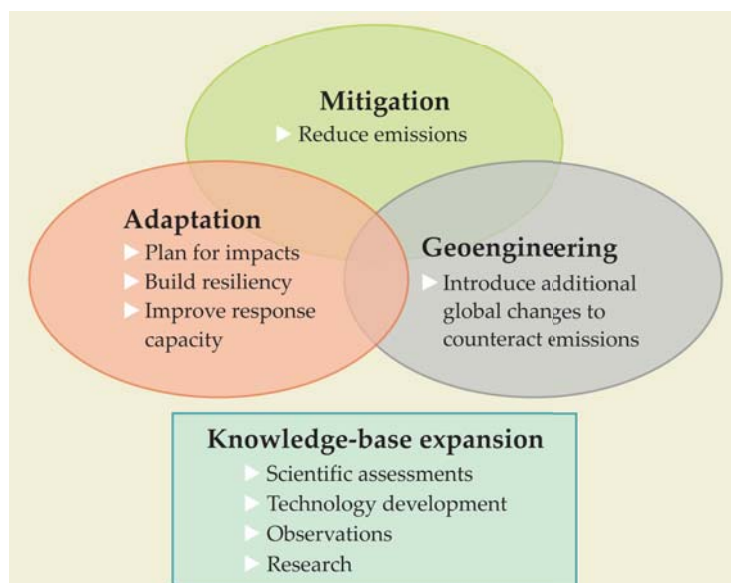


Figure 1. Climate change risk management consists of mitigation, adaptation, geoengineering, and knowledge-base expansion. Comprehensive risk management almost certainly includes a family of solutions drawn from all four approaches. (Adapted from ref. 1.)

a particularly noteworthy policy option because it would be expected to have a broad impact on emissions, it has received a great deal of attention from the research community, and it has been a focus of policy discussions since climate change emerged as a public issue.

There are several good economic reasons for the attention. As the cost of an activity increases, we engage in it less. We might find cheaper alternatives that give us the same benefit, or we might choose to spend our money on other activities. Either way, higher prices for emitting greenhouse gases will generally cause reductions to occur.¹⁰

Climate damage is an example of what economists call a negative externality. I decide whether to walk or drive to a friend’s place, whether to put on a sweater in winter or heat my house enough to wear shorts and a T-shirt. But what I pay at the fuel pump and on my monthly heating bill doesn’t include the damage I cause to the climate system. Instead everyone shares those costs, which amounts to an economically harmful subsidy to me from the broader society. As a result, I’m likely to choose the higher emission alternatives.

Having emitters pay the costs of climate damage would help ensure that they account more fully for the costs and benefits that result from their choices. Such accountability is a key requirement for maximizing economic well-being. In fact, incorporating the costs of climate change into the price of emitting greenhouse gases would increase overall economic well-being. That conclusion is the opposite of what we hear in public discussions, which invariably frame emission pricing as a choice between environmental protection and economic well-being. Unfortunately, that false framing feels so true that even some economists have it backward.

We can’t know what price on emissions would maximize economic well-being because the consequences of climate change are too difficult to know



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Figure 2. The Ivanpah Solar Electric Generating System, located in California's Mojave Desert, began commercial operation in 2013. The facility uses more than 300 000 tracking mirrors called heliostats to focus sunlight onto boilers atop three towers. The focused sunlight heats water in the boilers to generate steam, which in turn drives conventional turbines. The 377-MW-capacity plant was built with the help of a \$1.6 billion loan guarantee from the US Department of Energy.

ahead of time. Risk aversion to climate change implies erring on the side of a price that is more likely to be too high than too low. But aggressive mitigation through high emission prices could lead to overly costly energy and the early retiring of capital equipment. On the other hand, risk aversion to price increases for energy implies erring on a price that is more likely to be too low than too high. But weak mitigation through a low price on emissions would increase the chances of economic, social, and environmental harm from avoidable climate change impacts.

Adding a price to greenhouse gas emissions will have different effects on different people. Even with overall economic benefits, some people will likely be made worse off. Depending on the specific details of the policy design, the harm could be particularly significant for heavy emitters or some low-income families. Furthermore, losses will likely be narrowly distributed over a few economic sectors, like the coal industry and coal-fired electricity generation, whereas benefits will be broadly distributed among everyone.

In general, there are two market-based approaches for adding a price to emissions. Policymakers can set a limit on the quantity of emissions and allow emitters to buy and sell permits to emit. The approach, which is often called cap and trade, leaves it to the market to determine the price of emitting. Alternatively, policymakers can set the price of emissions by collecting a fee or a corrective tax. That approach leaves it to the market to determine the quantity of emissions.

Hybrids that combine elements of both approaches are also possible. For example, cap and trade can include a price ceiling at which additional permits are sold or a price floor at which permits are purchased. Similarly, a fee-based hybrid might include automatic increases in the price if emission quantities exceed an upper limit.¹¹

Notably, all the approaches have much in common because emission prices and quantities are linked through market transactions. In each case, policymakers must determine the initial price or

allowed quantity of emissions and how the price or quantity changes over time. Higher prices or lower quantities translate into larger, faster emission reductions but may trigger larger price increases for energy and transportation.

Adaptation

Adaptation involves planning, building resilience, and improving society's capacity to recover from climate impacts. It can help reduce damages and disruptions from climate change. Adaptation might also help with threats we already face from routine and severe weather events (see the article by Jane Lubchenco and Thomas Karl, *PHYSICS TODAY*, March 2012, page 31) or from other natural and human-induced hazards—an important side benefit of efforts to build adaptive capacity to climate change.

As with mitigation, adaptation also has limits or possible downsides. For example, some climate impacts could be too severe to manage through adaptation. And efforts to promote adaptive capacity could prove counterproductive if we get the details of climate change wrong or make poor choices about the best ways to prepare for its effects on physical systems, biological resources, and social institutions.

Regulations can promote adaptation by mandating practices that can decrease vulnerability. For example, improved land-use planning could help keep people away from flood-prone areas, and stronger building codes could help reduce the impact of extreme events.

Adaptation policies can also help establish planning and recovery procedures for dealing with climate impacts. For example, climate change impact assessments can identify vulnerabilities and protective measures for critical resources such as water, health care facilities, biological systems, agriculture, and infrastructure. Similarly, monitoring of key systems and resources can create early warning systems that enable rapid responses to extreme weather events, pest outbreaks, infectious diseases, and a wide range of other climate-related risks. In addition, efforts to minimize compounding stresses such as traditional air pollution, habitat loss and degradation, invasive species, and nitrogen deposition from fossil fuel combustion and agriculture could enhance resiliency to climate-related threats.

Implementing adaptation policies successfully may require detailed consideration of location-specific factors because climate change impacts will vary geographically and depend on the uneven distribution of societal resources and institutions. As a

result, more centralized policy responses—at the national or international level, for example—may be somewhat less effective for adaptation than for mitigation or geoengineering.

Nevertheless, centralized regulations have the potential to promote adaptive capacity by altering floodplain development, management of coastal zones, and insurance practices in ways that broadly account for climate change impacts. Similarly, more centralized approaches to disaster relief efforts, the establishment and design of wildlife reserves, and management of water and agricultural resources might be necessary for reducing some vulnerabilities to climate change.

Centralized adaptation policies can also support local and regional efforts. For example, a centralized repository could provide information and technical expertise about climate change vulnerabilities and response options. Alternatively, national and international policymakers could provide financial incentives for local adaptation planning and implementation. The goal of such efforts is to help ensure that decision makers who best understand the local context also benefit from lessons learned in other areas and have greater access to the resources they need to implement their decisions.

Geoengineering

Geoengineering refers to deliberate, often global-scale manipulations of the climate system. Geoengineering might help lower greenhouse gas concentrations in the atmosphere, partially counteract the warming influence of increasing greenhouse gas concentrations on the climate system, address specific climate change impacts, or offer desperation strategies in the event that abrupt, catastrophic, or otherwise unacceptable climate change impacts become evident.

But the complexity of the climate system makes it challenging for scientists to fully identify and quantify the potential consequences associated with geoengineering. As a result, the approach could cause unintended and adverse consequences. Some of them might even inadvertently compound rather than alleviate the dangers associated with climate change.

Even to the extent that the consequences of geoengineering could be well characterized, they would almost certainly differ among countries and individuals. That disparity raises complex legal, ethical, diplomatic, and national security concerns (see *PHYSICS TODAY*, November 2013, page 22). Furthermore, speculation on geoengineering's potential as a desperation strategy could distract from mitigation and adaptation efforts that may have a higher probability of contributing positively to risk management.

Nevertheless, two categories of geoengineering are most prevalent in scientific and policy discussions: solar radiation management and carbon removal and sequestration (see figure 3).

The goal of solar radiation management is to increase Earth's reflectivity to incoming solar energy (see *PHYSICS TODAY*, February 2013, page 17). For example, it might be possible to inject reflective particles into the atmosphere or increase the brightness

or distribution of certain types of clouds. The idea is to reflect incoming short-wave solar radiation by an amount that roughly matches the increased trapping of long-wave radiation by elevated greenhouse gas concentrations. Although short-wave and long-wave radiation are not interchangeable in all respects, the added reflection of sunlight might restore Earth's overall energy balance.

Solar radiation management might be a relatively fast-acting option for quickly reversing some of the warming associated with increasing greenhouse gas concentrations. However, solar radiation management represents a substantial global-scale manipulation of the Earth system that would likely have far-reaching impacts, some of which may be difficult to predict.

The goal of carbon removal and sequestration is to capture some of the increased atmospheric carbon from human activities and store it away, most

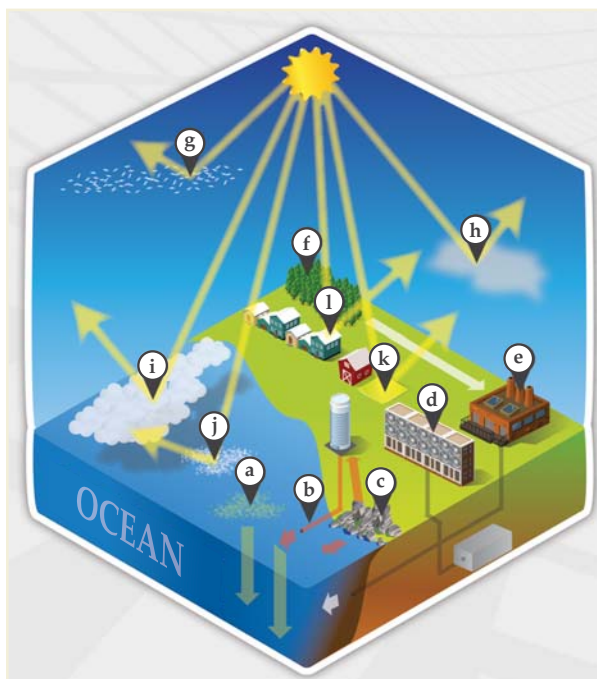


Figure 3. Overview of some proposed geoengineering methods. Proposals for carbon dioxide removal include (a) fertilizing the ocean, (b) adding minerals to increase the ocean's alkalinity and enhance its ability to dissolve carbon dioxide, (c) accelerating the weathering of silicate rocks that can draw in atmospheric CO_2 when they dissolve in water, (d) directly capturing CO_2 from the air by chemical means, (e) building biomass-based power plants with carbon capture and storage capabilities, and (f) reforestation or planting new forests. Solar radiation management aims to reflect more of the incoming sunlight back into space. Ideas include (g) deploying space mirrors, (h) injecting aerosols into the stratosphere, (i) seeding marine clouds to make them more reflective, (j) brightening the ocean surface with microbubbles, (k) growing more reflective crops, and (l) whitening rooftops. (Adapted from figure FAQ7.3-1 of ref. 2.)

likely either in the ocean or below ground. Carbon removal and sequestration would be challenging to do at a scale that matches current and expected greenhouse gas emissions. However, the risk of adverse effects associated with carbon sequestration is generally considered to be much lower than for solar radiation management.

Other large-scale interventions might be designed to reduce specific climate impacts. For example, the massive deployment of sea walls, efforts to protect continental ice sheets through snow-making or snow-preserving activities, or even relocating entire communities of plants and animals to areas where climate becomes favorable for them might all be conducted at a sufficiently large scale to be considered geoengineering.

Notably, geoengineering likely won't address all potential effects associated with greenhouse gas emissions. Solar radiation management, for example, will not reduce the amount of carbon dioxide in the air or the ocean and therefore would not stop ocean acidification or lessen the direct effects of carbon dioxide enrichment on biological systems.

Policymakers' options for geoengineering generally fall into five categories. They could fund research and analysis in order to develop or vet options. They could commission studies of geoengineering's impacts and potential unintended consequences. They could create punitive measures to discourage reckless or unilateral attempts to geoengineer. They could create policies that promote

cooperation and transparency or that help ensure governance issues are addressed appropriately. Of course, policymakers could also implement geoengineering approaches.

Knowledge-base expansion

Research, observations, scientific assessments, and technology development can help reveal risks and opportunities associated with the climate system and support decision making with respect to climate change risk management (see box 1). Expanding the knowledge base allows policymakers to understand, select, and refine specific risk-management strategies and to thereby increase the effectiveness of risk-management efforts.

Knowledge-base expansion could, in some cases, also reveal entirely new opportunities for protecting the climate system or reducing the risks of climate change impacts. As a result, policies to expand the knowledge base underpin and support mitigation, adaptation, and geoengineering.

Climate system research spans numerous disciplines and subdisciplines, including those in atmospheric sciences, oceanography, hydrology, biology, cryology, and paleoclimatology. Determining the societal consequences of climate variability and change likely requires insights from a broader range of disciplines, including economics, sociology, history, and political science. Each discipline has unique and sometimes contradictory insights on the potential for climate impacts and the effectiveness of risk management (see box 2).

Box 1. The need for better tools

Assessments of the societal consequences of climate change rely on a hierarchy of modeling approaches. Reduced form models, common in economic analysis, use relatively simple climate damage functions—usually a linear or quadratic equation—to assess economic consequences. That approach creates a relatively straightforward analytical framework for exploring how climate affects the economy, but it also constrains model output based on the assumptions the model developer uses when creating climate damage functions. Those assumptions can be hard to justify and easy to overprescribe.

More comprehensive modeling approaches seek to incorporate insights from numerous disciplines within a single framework. Such integrated assessment models (IAMs) often incorporate experimental results directly and, in some cases, allow model users to explore the implications of plausible assumptions.^{12,13} IAMs reduce the likelihood that risk-assessment efforts will depend on unrealistic assumptions. However, the models often still require key assumptions that are hard to constrain, and the technical detail needed to understand comprehensive IAMs can create a barrier to engagement for the uninitiated or become an obstacle to communication among experts unfamiliar with the specific model details.

Therefore, there is great need for new and complementary tools that are sufficiently intuitive to enable virtually anyone to understand, evaluate, and use; that keep necessary assumptions and choices explicit; that minimize the use of weakly supported assumptions; and that are easy to update and refine as new information becomes available. Such tools would enable both experts and nonexperts to explore the potential consequences of climate change given their own knowledge and based on their own values. Anyone could assess climate change risks for themselves.

Political landscape

There are several political obstacles to climate change risk management in general and to pricing greenhouse gas emissions in particular.

Policy deliberations and public debates about climate science are often at odds with the assessments of the relevant subject-matter experts. The complexity of the issue increases the potential for nonexperts to be unaware of expert assessments or more prone to believe rhetorical arguments that seem convincing, even when those arguments do not withstand the scrutiny of the expert community.

Furthermore, the businesses and people who might be hurt by a price on emissions often know it, care about a relatively small number of issues, and are politically powerful and well organized. In contrast, the constituency for climate protection is a relatively disorganized group that is politically weak because the resulting benefits are broadly distributed. Those who would benefit often take the climate system for granted and do not recognize the risks of climate change. Most people also tend to care about a wide range of issues—often more than climate change. The differences between those who stand to benefit and those who stand to lose from climate policy create significant political obstacles.

Climate change risk management can often be thought of as a constrained optimization problem. For example, the higher the price on greenhouse gases, the larger the reduction in emissions that will occur. Therefore, maximum climate protection comes

with the highest attainable price on emissions. But two political constraints limit how high emission prices can be.

First, there needs to be enough support among decision makers to enact policy. At the US federal level, there simply haven't been enough politicians who agree on establishing a price on emissions. Overcoming that constraint depends on increasing the number of policymakers who support the idea.

Opponents of emission pricing often share two somewhat unrelated views: They are more concerned about emission prices than they are about potential climate change impacts, and they tend to favor tax cuts on capital gains, corporate income, and the highest personal income-tax brackets. Therefore, some opponents might change their view if the revenue from an emission price were used, in part, to reduce taxes in the ways they care most about. Under such an agreement, proponents of climate policy would get the risk management they seek, while erstwhile opponents would get a significant tax victory.

Second, any policy must be sustained over time—the more the price of emissions increases, the greater the chance that energy and transportation costs will rise and the greater the likelihood that people will turn against climate policy. One potential solution is to return some of the revenue directly to the population on a per capita basis. The idea is that higher energy and transportation prices become more palatable—and therefore politically sustainable—when they are partly offset with regular payments through the equal sharing of revenues.

Of course, revenues used to reduce existing taxes can't be returned directly to the people on a per capita basis, and revenues returned directly to the people can't go toward reducing existing taxes. So achieving an optimal price on emissions would have to delicately balance the two constraints.

The global nature of climate change also creates challenges for climate policy. There is a genuine need for a global effort because atmospheric greenhouse gases are well mixed: Emissions from anywhere contribute to the problem everywhere. The need for shared participation makes unilateral action more difficult and less effective. It also creates a powerful rhetorical political argument against action. Why begin to reduce our emissions when other countries express no similar plan to do so?

Each of the challenges has policy solutions. For example, actions by one nation might include border tax adjustments to penalize those who do not incorporate climate damage into prices paid by their emitters. That would protect those who act unilaterally and encourage other countries to follow suit.

The key challenge is to close the gap between scientifically informed discussions of climate change and the increasingly contentious and often highly misleading public debate. The good news is that the basics of climate change risk management are well characterized and understood, at least among subject-matter experts. A wide range of policy options are available for meaningfully dealing with climate change—including options that align with virtually any political philosophy.

Box 2. Division by discipline

Experts don't always agree on the likely consequences of climate change. For example, some economists suggest that the consequences of climate change are most likely to be low over the next several decades,³ whereas physical and natural scientists often conclude that the consequences of climate change could be very high.^{4–6} The divergence in views arises in part from the different disciplinary background experts possess.¹⁴

Economists' experience suggests that substitutes for critical goods and services are widely available and easily developed. If steel becomes scarce, then we can switch to aluminum. If aluminum becomes hard to get, then we can use carbon fiber or invent a new material that will be cheaper and more effective. Thus climate impacts seem likely to be manageable because we should be able to find substitutes for key resources that disappear or become harder to find.

In contrast, biologists' experience suggests that the world is filled with complex and highly interdependent relationships, many of which are extremely sensitive to the conditions to which they are adapted. Removal of one seemingly insignificant species from a system can result in the rapid loss of dozens of other codependent species. Small changes in water availability or winter temperatures can allow pests to break free from their constraints and wreak havoc on the landscape.

At the same time, biological systems provide goods and services on a massive scale for free, which means that economic systems often do not account for them. Biological systems provide pollinators for crops, improve soil quality, and help purify the air and water. Forests soak up water and release it slowly over time, thereby reducing the potential for floods and droughts. Substitutes don't seem readily available for such basic life support services that get provided on a planetary scale. From that point of view, climate impacts appear likely to pose broad and dangerous risks to society, many of which cannot be predicted.

This work was supported in part by a grant from NASA (NNX13AM26G). Ira Greer, Peter Cowan, Shali Mohleji, Dick Hallgren, Bill Hooke, and Jonah Steinbuck provided valuable suggestions during the development of this article.

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