Three Prongs for Prudent Climate Policy

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Abstract

For three decades, advocates for climate change policy have simultaneously emphasized the urgency of taking ambitious actions to mitigate greenhouse gas (GHG) emissions and provided false reassurances of the feasibility of doing so. The policy prescription has relied almost exclusively on a single approach: reduce emissions of carbon dioxide (CO_2) and other GHGs. Since 1990, global CO_2 emissions have increased 60 percent, atmospheric CO_2 concentrations have raced past 400 parts per million, and temperatures increased at an accelerating rate. The one-prong strategy has not worked. After reviewing emission mitigation's poor performance and low-probability of delivering on long-term climate goals, we evaluate a three-pronged strategy for mitigating climate change risks: adding adaptation and amelioration—through solar radiation management (SRM)—to the emission mitigation approach. We identify SRM's potential, at dramatically lower cost than emission mitigation, to play a key role in offsetting warming. We address the moral hazard reservation held by environmental advocates—that SRM would diminish emission mitigation incentives—and posit that SRM deployment might even serve as an "awful action alert" that galvanizes more ambitious emission mitigation. We conclude by assessing the value of an iterative act-learn-act policy framework that engages all three prongs for limiting climate change damages.

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Keywords: mitigation, geoengineering, adaptation, solar radiation management, carbon pricing, greenhouse gases, climate change, catastrophic risk, decision-making under uncertainty

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1. Introduction

Recent warnings from the Intergovernmental Panel on Climate Change (IPCC) provide clear guidance on the necessary timing and magnitude of actions required to combat climate change (IPCC 2018, 2019. “Today”—the next decade in climate terms—is the last clear chance to avoid the catastrophic impacts of climate change. Taking ambitious actions today could feasibly limit warming to 2°Centigrade above pre-industrial temperatures, barely avoiding catastrophic outcomes across much of the planet. Time is short, especially given the long lifetimes of greenhouse-gas-emitting capital (measured in decades), and the fact today’s global temperatures are already 1°C above pre-industrial levels.

Does this sound familiar? The urgency of the warnings and the call to limit warming to no more than 2°C has not shifted substantially in three decades. In 1990, the Advisory Group on Greenhouse Gases—created by the World Meteorological Organization, the International Council of Scientific Unions, and the UN Environment Programme and the effective predecessor to the IPCC—issued a report on targets and indicators for long-term, global climate action. The Advisory Group recommended two warming goals: to limit warming to 1°C and 2°C, coupled with a rate of change goal of 0.1°C per decade. They acknowledged that exceeding the lower target “may be unavoidable due to greenhouse gases already emitted,” but emphasized that “temperature increases beyond 1.0°C may elicit rapid, unpredictable, and non-linear responses that could lead to extensive ecosystem damage” (Rijsberman and Swart 1990, p. viii).

To date, environmental advocates, major international environmental agreements, and domestic policy programs have focused on one strategy to fight climate change: mitigation; that is, curbing the emission of greenhouse gases (GHGs).[1] That strategy has not been successful. Over the past sixty years, there has been a steep increase in the emissions of GHGs and their concentration in the atmosphere. Global surface temperatures have increased apace, and have accelerated more recently. The path that we are told can keep the warming of our planet to 2°C (see Figure 4) looks almost impossible to achieve. The costs are too high; the economic transformations required too extensive; and the political will too weak. And at slightly below 1°C of warming, our current status, the planet is encountering severe stresses such as major melts and super storms.

1 For example, refer to how Climate Action Network International (2018), a coalition of more than 1,200 civil society organizations addressing climate change from across the world, responded to the IPCC special report on 1.5°C. It called on countries to enhance their emission mitigation pledges under the Paris Agreement. This statement was silent on the issues of adaptation or solar radiation management, the latter of which Climate Action Network International (2019) explicitly criticized. Some environmental groups support adaptation, such as Environmental Defense Fund and The Nature Conservancy, and several groups support limited research and development for solar radiation management, including Environmental Defense Fund, Natural Resources Defense Council, and Union of Concerned Scientists.

Since the 1980s, policies and public discourse on climate change have focused on mitigation alone. Repeatedly, we have been told that there will be catastrophic consequences if we do not reduce the amount of carbon dioxide entering the atmosphere, and that we can do it. A primary finding of this essay is that the warnings seem accurate; the reassurances do not. A second downbeat finding is that the levels of emissions cuts advocates say are necessary, and often claim are feasible, are extremely unlikely to be achieved.

Given this dreary assessment, two prongs of action for reducing climate change risks in addition to mitigation merit policy attention. They are adaptation (limiting damages from whatever climate arises), and amelioration (reducing climate change given the level of GHG concentrations). Hence our title, "Three Prongs for Prudent Climate Policy." To illustrate, adaptation includes investments to offset of the damages associated with rising seas and changing weather such as sea walls and moving populations away from threatened areas. Amelioration includes investments to counteract the climate impacts induced by high CO_2 concentrations in the atmosphere. Such investments on a large scale are referred to as geoengineering. In this paper, we assess the case for solar radiation management (SRM), a geoengineering instrument, as an amelioration measure. The most promising SRM measure would inject aerosols into the upper atmosphere to reflect back incoming solar energy. This would lower the temperature for a given accumulation of atmospheric GHGs.

The paper proceeds as follows. Part 2 discusses the major errors along the path to the "climate emergency" of today. It addresses the information long ignored about climate change, and the more recent false reassurances, notably from the environmental community, about the ability of a mitigation-alone policy to control it. It then introduces the economics that underlie climate change. Part 3 broadens the policy palette. It presents the three prongs available for effective policy: mitigation, adaptation and amelioration. It then employs a wolf-based fable revealing how a society can go wrong by slighting adaptation and amelioration. Part 4 assesses our ability to limit warming to 2°C (or less), a goal specified in multiple international environmental agreements. It shows that goal is neither feasible nor sufficient to avoid catastrophic climate change. Part 5 discusses the economic costs associated with the use of the three prongs: mitigation, adaptation, and SRM prongs. Part 6 addresses the moral hazard issue among the three prongs, with a focus on solar radiation management. Part 7 analyzes how a three-prong strategy for coping with climate change might proceed. Part 8 summarizes the case for deploying all three prongs to combat climate change.

2. The Path to Today's Climate Emergency

The history of climate change policy is one where information has consistently been misused. Arrhenius, conducting research in the late nineteenth century, first demonstrated how human activity increased CO_2 concentrations in the atmosphere, which in turn increased temperature. These findings were largely ignored until the 1980s. Then followed a period of false denials and woefully inadequate policies at both the national and international level to control GHGs.

Present recognition is far different. Oxford Dictionaries declared its 2019 Word of the Year to be "climate emergency," which it defined as "a situation in which urgent action is required to reduce or halt climate change and avoid potentially irreversible environmental damage resulting from it" (Oxford University Press 2019).[2] Indeed, a group of 11,000 scientists published their warning that "planet Earth is facing a climate emergency" in November 2019 (Ripple et al. 2019).

The public is in accord. A strong majority of Americans, and far greater fractions of individuals in most other developed countries, believe that climate change is a significant problem and that the world is at a critical point (Leiserowitz et al. 2019; DG Communication 2019). They would broadly favor major efforts to cut our production of GHGs, but would argue about how vigorous we have to be in our efforts to curtail these gases, who would bear the burdens for reducing emissions, and what constitute desirable and feasible climate targets.

The international policy community, with scientists playing a major role, has been issuing urgent calls for action since the 1990s. The standard response to the climate emergency by policy advocates has highlighted the dire circumstances and the feasibility of preventing catastrophic climate change. In 2006, prominent climate scientist James Hansen stated that "we have at most ten years—not ten years to decide upon action, but ten years to alter fundamentally the trajectory of global greenhouse emissions" (Hansen 2006). In that year, former Vice President Al Gore gave a similar 10-year prognosis for undertaking drastic measures to reduce emissions (Germain 2006). A decade later, we hear similar reassurances—the climate crisis is serious but, if we take action now, we can prevent it. In 2018, Al Gore commented on the release of the IPCC's 2018 Special Report on Global Warming of 1.5°C (SR15) by noting that "time is running out, so we must capitalize and build upon solutions available today" (Gore 2018). In 2019, James Hansen stated that "Earth is not lost today, but time for action is short" (Hansen 2019).

2 Oxford found that the use of "climate emergency" in public discourse increased dramatically, citing a hundred-fold increase in the use of the term in September 2019 compared to a year earlier.

If in 2006 we had but 10 years to cut our emissions substantially, and emissions actually increased, then similar reassurances today ring false. What has led to the current moment? In this section, we survey a number of not surprising human failings, even within the expert community, that have so far prevented us from stabilizing our planet's climate. These include the considerable heterogeneity among economic analyses of the likely damages associated with climate change; the willingness of environmental experts to focus on unachievable means to reach unachievable goals as a political measure to motivate action; and the intentional inattention of such experts to adaptation and amelioration for fears of moral hazard. A summary assessment of these failings is that policy preferences led analyses, rather than the reverse.

2.1. Clashing Economic Models

Dating back to Cline (1991) and Nordhaus (1993), economists have employed integrated assessment models (IAMs) to characterize the relationships among economic activity, energy consumption, greenhouse gas emissions, and the global climate (Pizer et al. 2014). These IAMs estimate the marginal damage from an incremental ton of carbon dioxide emissions. The damage comes from reduced agricultural productivity, inundation of coastal areas by sea level rise, health impacts from vector-borne diseases and higher temperatures, increased energy demand for cooling, losses from extreme weather events such as flooding and hurricanes, and an array of other climate change impacts. As the understanding of climate change science and economics has improved, estimates of the social cost of carbon (SCC) have likewise evolved. Take two examples. First, the famed DICE model's estimate of the SCC has increased from about $14/ton in a 2008 estimate to nearly $36/ton in a 2017 analysis (Nordhaus 2008, 2017).[3] Second, the Interagency Working Group on the Social Cost of Carbon (2010) in the US government employed the three most prominent IAMs in the research literature to estimate the SCC for use in regulatory impact analyses. Over 2010-2016, this Interagency Working Group updated its preferred SCC estimates from $28/ton to $43/ton (Interagency Working Group on the Social Cost of Carbon 2010, 2016). This updating of the SCC increased the present value of economic damages from about $1 trillion to about $1.5 trillion for the carbon dioxide emitted globally in the year 2015.

Yet these models inadequately reflect our evolving understanding of climate impacts and mask key factors that influence the potential magnitude of climate change damages. Some scholars argue that IAMs' underlying damage functions do not adequately reflect the science and economics of climate change (Weitzman 2009; Pindyck 2013; Stern 2013; Heal 2017; Diaz and Moore 2017). Others have expanded the approach to enable a broad assessment of potential future states of the world. For example, Cai and Lontzek (2019) model stochastic economic growth and account for uncertainty in climate change impacts. They find that the standard deviation of the SCC increases faster than its mean, reflecting the potential for low-probability, large-magnitude climate damages. Daniel et al. (2019) find that uncertainty yields a higher

3 These SCCs are for the emission of a ton of carbon dioxide in the year 2015 expressed in 2018 US dollars.

initial social cost of carbon—in excess of $100/tCO_2$ today—then would result from an analysis ignoring uncertainty.

To address shortcomings in IAMs' damage functions, recent research has focused on identifying causal pathways of specific climate change-related impacts. In the past decade, an extensive literature has employed longitudinal data to exploit variations in weather (temperature, precipitation, and windstorms) to estimate the impacts of weather shocks on economic output, premature mortality, worker productivity, crime and conflict, and other outcomes (Dell et al. 2014). Burke et al. (2015) employ panel econometric methods to estimate how temperature influences economic output. They project that unabated climate change would reduce global incomes by about 23 percent by 2100 and exacerbate income inequality across countries. Carleton et al. (2018) develop the first global panel of mortality and temperature data, with extensive accounting for sub-national spatial coverage, for use in estimating how mortality risk responds to increases in temperature. They estimate that the mean willingness to pay to avoid increasing mortality risk under unabated climate change would be on the order of $40 per ton of carbon dioxide.

Pindyck (2019) employs an alternative approach, an expert elicitation survey focusing on economists and scientists active in the climate change literature. On average, these experts stated that unmitigated climate change would reduce world GDP by 12 percent in fifty years, and that there was about a 1 in 4 chance that the decline in output would exceed 20 percent. These estimates, albeit large, may significantly understate the risks. DeFries et al. (2019) documents the disconnect between the climate science risks and the economic monetization of these risks, reflecting the limitations and omissions of the economic models of climate change impacts.

2.2. Factors Undermining Effective Policy Responses

Policy responses, which often reflect political expediency, may amplify climate change damages. For example, Kahn (2005) documents that democracies and countries with higher-quality institutions experience less natural disaster-related mortality than other nations, conditional on the frequency and intensity of natural disasters. Poorly designed insurance policies—such as the US National Flood Insurance Program—may implicitly subsidize residential location in areas prone to climate-related flood risk (Michel-Kerjan 2010), and thus amplify damages. Large-scale climate-related migration, a likely prospect, would impose significant stresses on governments around the world. The resulting immigration policies, which respond to the politics of the moment, may rule out least-cost adaptation to a changing climate. While we have sufficient research evidence and experience to speculate on the major adverse impacts of climate change, impacts beyond our current understanding of science, economics and societal panics may dramatically affect human civilization in a period of rapidly changing climate. Recent experience with responses to a manageable, different global threat, COVID-19, is hardly reassuring.

2.3. False Reassurances on Manageability

In 2010, the UN Environment Programme (2010) estimated that the world would need to cut emissions by about 12 gigatons of CO_2-equivalent from a forecast ("business as usual") level of 56 gigatons in 2020 to limit warming to 2°C. Then–executive director of UNEP, Achim Steiner, notes in his introduction that "The Emissions Gap Report emphasizes that tackling climate change is still manageable, if leadership is shown" (UNEP 2010, p.3; italics added for emphasis). Five years later, after global carbon dioxide emissions had grown more than 7% since publication of the 2010 report, UNEP (2015) identifies 23 gigatons of emission cuts necessary to achieve the 2°C objective. Steiner optimistically opens the 2015 Emissions Gap Report by stating: "I firmly believe that if we act on the findings in this report, there is nothing to stop us closing the emissions gap" (UNEP 2015, p. xiii).

With global greenhouse emissions reaching 55.3 gigatons in 2018, the UN Environment Programme (2019) projects emission cuts for 2030 of at least 23 gigatons for a 2°C goal and 39 gigatons for 1.5°C goal. Inger Andersen, the Executive Director of UNEP, describes the emission-mitigation policy implication of this report:

> "Emissions must drop 7.6% per year from 2020 to 2030 for the 1.5°C goal and 2.7% per year for the 2°C goal. The size of these annual cuts may seem shocking, particularly for 1.5°C. They may also seem impossible, at least for next year. But we have to try…. We need quick wins or the 1.5°C goal of the Paris Agreement will slip out of reach" (UNEP 2019, p. xiii).

While Andersen acknowledges the "collective failure to act strongly and early" in this report (UNEP 2019, p. xiii), we are not told that given economic and political realities—both within and across nations—it is almost inconceivable that the world will reach either of these goals.

The almost universal commentary from the environmental community is that this decade is the last time to take action, but, if we do, we can stop disastrous warming. Greta Thunberg, the climate activist named Time's Person of the Year for 2019, has effectively emphasized the urgency of addressing the climate emergency: "We can't just continue living as if there was no tomorrow, because there is no tomorrow" (Alter et al. 2019).

However, Thunberg has fallen into the trap of issuing false reassurances about mitigation-only policies. In December 2019, Thunberg addressed the annual UN climate negotiations in Madrid, Spain and focused exclusively on the need to reduce emissions and keep fossil fuels in the ground in order to limit warming to 1.5°C. She closed her remarks by noting: "In an emergency, you change your behavior…. And without the sense of urgency, how can we, the people understand that we are facing a real crisis…. Right now we are desperate for any sign of hope. Well I'm telling you, there is hope. I have seen it but it does not come from the governments or corporations. It comes from the people" (Thunberg 2019). Similarly, Representative Alexandria Ocasio-Cortez (D-NY) has framed many younger voters' concerns as "the world is going to end in 12 years if we don't address climate change" (Cummings 2019) as part of her advocacy of the Green New Deal.[4] Christiana Figueres, the former head of the UNFCCC Secretariat, highlighted the findings of the IPCC's special report on 1.5°C in a recent op-ed, but noted that limiting warming to this level through emission mitigation is technically feasible if "there is political will" (Figueres 2018).

The environmental community merits plaudits for awakening us to the dangers of human-caused climate change. However, it merits blame for issuing false reassurances about the ability of a mitigation-only policy to cope with the problem. Time is late. Failure to recognize the dangers that loom is sure to lead to an insufficient and inappropriate mix of actions to cope with climate change.

2.4. Misunderstanding the Nature of the Problem: Flows and Stocks

In a model world, the control of pollution flows whose stocks impose costs can be modeled as an optimal control problem. A social planner could take appropriate account of all individuals living at present and into the future when choosing the settings for its control variables (Keeler, Spence and Zeckhauser, 1971). Almost all policy discussion on climate change addresses greenhouse gas flows into the atmosphere. Compare a polluted river and a polluted lake. Staunch the pollution flow into the river, and the problem is mostly solved as the pollutants flow away and become increasingly dilute. With the lake, the stock of pollutant remains. Climate change is a stock problem; the damages are due to the GHGs accumulated in the atmosphere. We need to focus on the impacts of higher concentration of GHGs in the atmosphere, and not merely on the rate at which we emit GHGs.

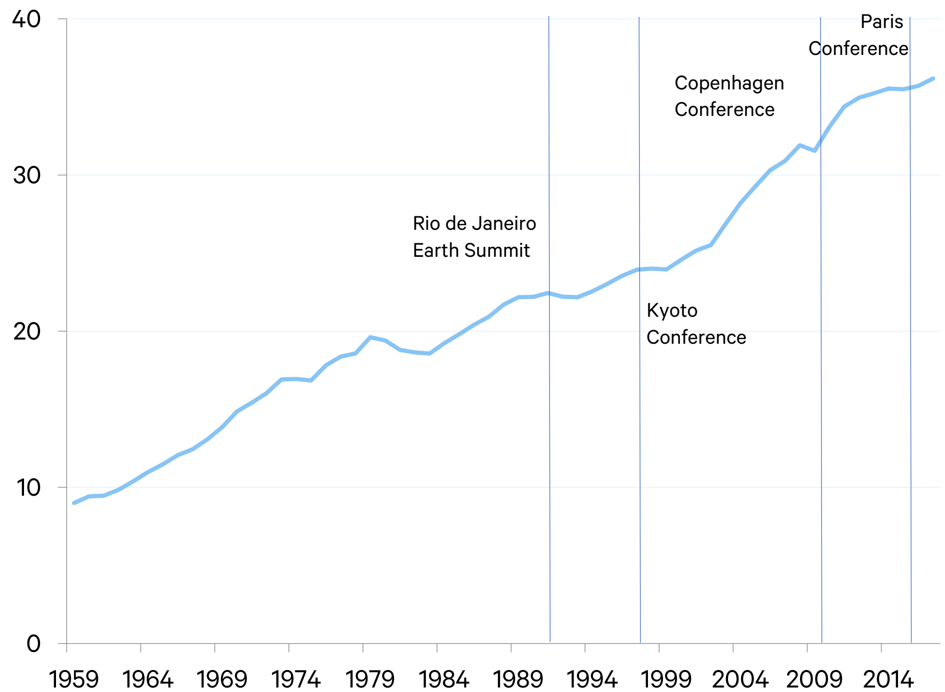
Since 1990, global carbon dioxide emissions from the combustion of fossil fuels have increased more than 60 percent, despite numerous international conferences calling for emission cuts (see Figure 1).[5] From the pre-industrial period through 1990, the atmospheric concentration of carbon dioxide increased by about 75 parts per million. Since 1990, the concentration has jumped another 55 parts per million, and the annual growth rate in concentrations is accelerating (Figure 2).

4 H. Res. 109, 116th Congress, "Recognizing the duty of the Federal Government to create a Green New Deal." **https://www.congress.gov/116/bills/hres109/BILLS-116hres109ih.pdf**.

5 Emissions of other greenhouse gas emissions, such as methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride also increased over this time period. We will focus on carbon dioxide emissions associated with fossil fuel combustion and industrial processes for illustrative purposes in this paper, although it should be noted that many of the other GHGs exhibit similar trends over time and in long-term projections. The 55 gigatons estimate discussed below in the 2015 Paris Agreement covers all greenhouse gas emissions.

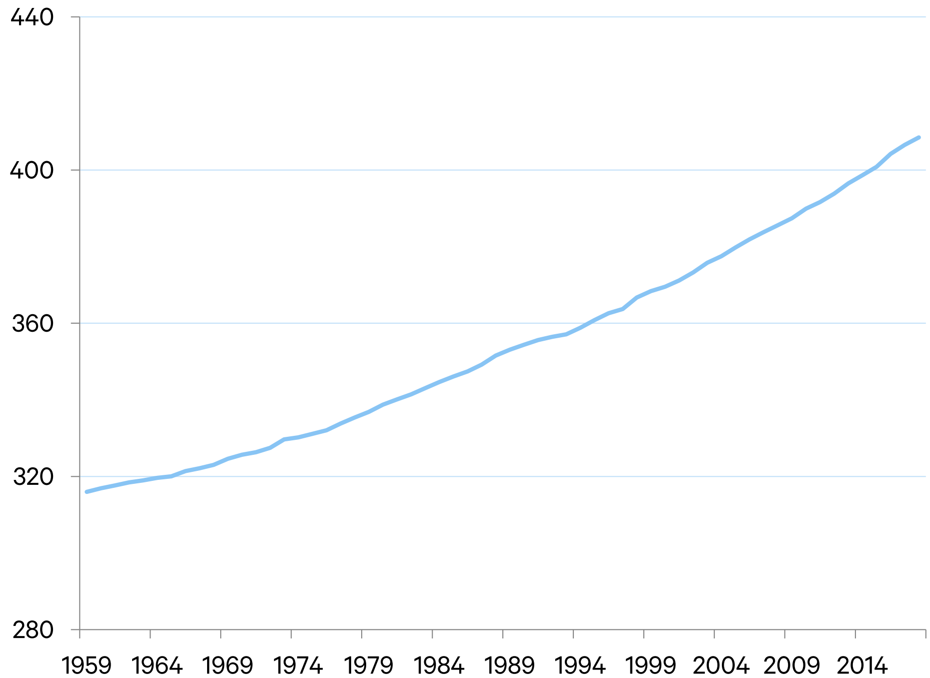
Global temperatures have increased on a near-linear basis by about 0.6°C over the past thirty years (Figure 3). In short, the record to date is extremely discouraging. Emissions and atmospheric concentrations show strong and consistent upward trends. Global temperatures show a strong and accelerating upward trend.

Figure 1. Global Carbon Dioxide Emissions (gigatons CO_2) and Major UN Climate Conferences, 1959-2017



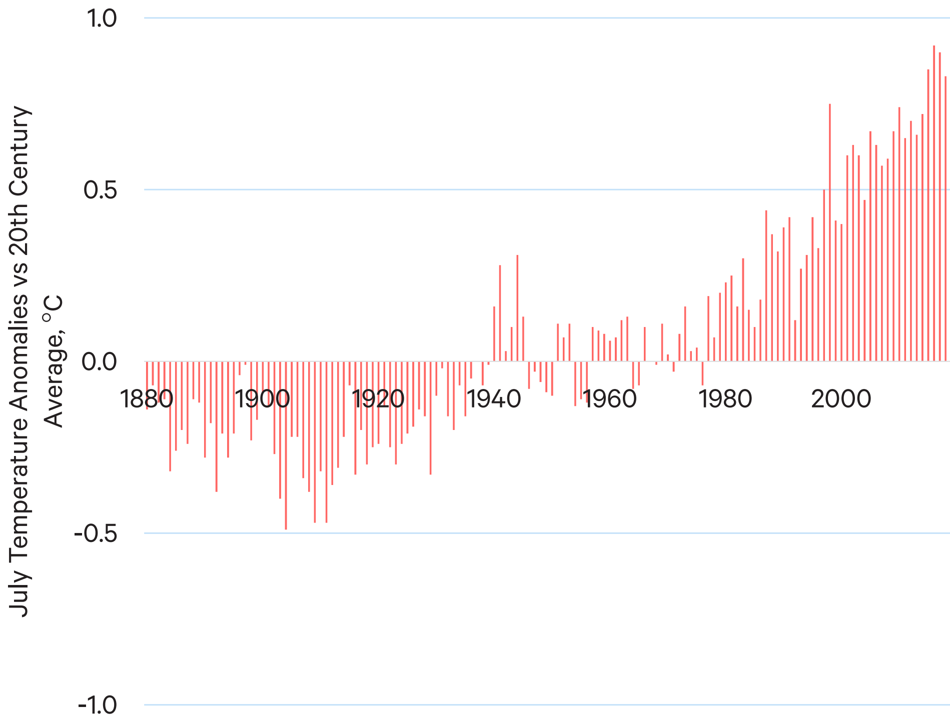
Notes: Figure represents carbon dioxide emissions from fossil fuel combustion and industrial processes. “Historic CO_2 Emissions” over 1959-2017 from the Global Carbon Project (2018).

Figure 2. Atmospheric Carbon Dioxide Concentrations, parts per million, 1959-2018



Notes: Data from Trends in Atmospheric Carbon Dioxide, Earth System Research Laboratory, NOAA. Figures presents the Mauna Loa annual mean carbon dioxide concentrations. **https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html**

Figure 3. Global Land and Ocean Surface Temperature Departure from Average, July, 1880-2019



Notes: Data from NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published September 2019, retrieved on October 1, 2019 from **https://www.ncdc.noaa.gov/cag/**.

2.5. Cheap Riding and Inadequate Coordination

The actual world does not have the social planner just mentioned. Rather, it has myriad decision makers including individuals, firms, and nations. These decision makers choose on the basis of their own welfares. Those welfares may include doses of altruism, but experience suggests that the welfare of others counts relatively little to one's own. Cheap riding—behavior just short of free riding—will persist, even if parties make pollution control agreements with others, as the nations of the world have done. It is a daunting task to craft durable, effective climate policy that accommodates disparate decision makers in multiple generations, both within and across political jurisdictions, and among many political jurisdictions with varied levels of development and vulnerability to climate change (Barrett 2003; Aldy 2016).

3. Broadening the Policy Palette: The Three Prongs for Policy

In a problem where a stock of a pollutant (GHGs in the atmosphere) creates impacts that in turn impose costs (losses of productivity, health, quality of life), what policy approaches are available to curb those costs? We identify three: limit the flows into the stock, reduce the impacts from the stock, and reduce the costs from any impacts. In the climate change context, these policies are respectively called mitigation (reducing greenhouse gas emissions), amelioration (SRM), and adaptation (e.g., building marshes and ocean barriers; reducing human activity near the oceans).

As we have seen, international groups, environmental organizations and most concerned political leaders have focused both discussion and action on the first policy prong, mitigation. Moreover, they have issued assurances that mitigation alone can keep losses within acceptable levels. As we have shown, this single-prong policy has been woefully inadequate to date. Assurances about the potential for mitigation alone to control losses are severely overstated. Given any realistic levels of emission reductions, the planet is on a path to almost surely exceed 2°C in a few decades and much more thereafter, hence to vast environmental damages. Given the massive looming losses from climate change, prudence requires that all three policy prongs—mitigation, amelioration, and adaptation—be employed to limit those losses.

Environmental advocates have downplayed discussion of adaptation measures, and fiercely opposed discussion and research on amelioration due to concerns about moral hazard. Indeed, adaptation and geoengineering, such as solar radiation management, were once forbidden terms in environmental and scientific circles. For example, Jake Jacoby of MIT noted in 2015 that "Earlier on, you wouldn't use the 'A' word in polite conversation. People thought you weren't serious about mitigation," where 'A' referred to adaptation (Helm 2015). Similarly, John Shepherd (2009), the chair of a 2009 Royal Society study on geoengineering, recommended that participants in climate policy debates get over their fears about mentioning "the 'G' word." The reasoning, often kept in the background, is that serious consideration of adaptation measures and geoengineering would undermine the policy argument for vigorous mitigation efforts. (We address this argument in Part 6 below.) However, even vigorous mitigation in the future would not stave off serious to catastrophic climate-change damages.

In this section, we look at how a mix of mitigation, adaptation, and amelioration will be needed, given the climate path we are on, to limit the catastrophic outcomes of climate change.

The academic literature as well as the media have dedicated significantly less attention to amelioration than to emission mitigation.[6] The most promising amelioration technology to date, in terms of feasibility and cost, as mentioned, is solar radiation management. It would inject aerosols, most likely sulfur particles delivered by airplane, into the upper atmosphere to reflect back incoming solar energy. This would lower the temperature for a given accumulation of atmospheric GHGs. This technology draws on research about the cooling impacts of introducing sulfur dioxide (SO_2) into the atmosphere—from volcanic eruptions as well as the combustion of sulfur-intensive coal and petroleum products (Crutzen 2006; Wigley et al. 1996). An SRM strategy would have side effects, perhaps extremely costly side effects.

Implementation of solar radiation management on a scale sufficient to cool the planet will take considerable time and money, though a slight fraction of the costs of climate change (see section five for a discussion of costs of various prongs of reducing climate change risks). While scientists are quite confident of its efficacy, experiments are still needed to demonstrate the feasibility of implementation. To deliver the SO_2 to the lower stratosphere will require a new type of plane, and planes take years to develop. Such change will require research on feasibility, safety and governance, and it could take many years to achieve grudging acceptance of this technology and then move to actual implementation at any scale.[7]

Adaptation will require considerable time and money as well. For example, if physical barriers are to be built to protect against rising sea levels and more intense storms, it will take years to figure out the engineering requirements, develop the plans, and secure the political will to produce the required resources. For example, the US Army Corps of Engineers (2019) has identified a six-mile long sea barrier with storm surge gates as a potential investment to protect New York City from climate change. It estimates that the wall would take 25 years to construct. Moving human activity away from the coasts will require decades and trillions of dollars. In short, the monies expended on adaptation will vastly exceed those required for solar radiation management. That is true even if political realities prevent many worthwhile protective projects from being undertaken.

6 We classify negative emission technologies within the mitigation prong. Some negative emission technologies, such as bioenergy power plants with carbon capture and storage technology, share similar incentives to high-cost emission mitigation technologies. Direct air capture of carbon dioxide, which has drawn recent attention but requires significantly more research and development, shares some characteristics with carbon capture and storage technology that could be applied to fossil power plants. Similarly, tree planting should be viewed as a mitigation strategy intended to cut the planet's emissions of GHGs.

7 Marine cloud brightening, which focuses on lower-altitude interventions to increase the reflectivity of clouds, also merits experimental research. If the costs prove modest and the interventions efficacious, it could become a part of the broader risk mitigation tool-kit.

Mitigation efforts, which will require immense efforts and vast expenditures, will likely take decades to even cut emissions in half. Large-scale renewable power, for example, would likely require years of innovation and commercialization of large-scale battery storage, and the hopeful development of nuclear fusion.)

In short, a three-prong strategy for climate policy will require political will, policy attention, and major expenditures over a period of many decades. The potential effort will be great, the potential savings in environmental costs far greater.

In the sections that follow, we explore the three prongs of an optimal climate change policy. We first look at the extreme shortcomings of our efforts toward mitigation: we have set a target that will not keep us safe, and we are extremely unlikely to meet it. We then explore the comparative costs of mitigation, adaptation, and solar radiation management; consider the moral hazard problems in choosing strategies, and then consider the first steps in determining the optimal mix of mitigation, adaptation, and SRM. First, we illustrate the choices we face with a fable.

3.1. Fable of the Wolf and the Three Prongs for Prudent Climate Policy

An extremely analytic boy lives in a village high in the mountains. The village used to have a traditional crop-based economy, with a few scraggly sheep on the side. However, outside technology produced hybrid sheep that yield ample wool and mutton and thrive at high altitudes. The village turned to mainly raising sheep, and ever more sheep.

When sheep were few, they could graze nearby the village. But when they became abundant, they had to graze well beyond where the villagers lived, namely in the outlands. The village had been warned that sheep without humans living nearby bring wolves.[8] The boy has seen wolves and noticed that sheep have disappeared in unusual numbers. The boy's pleas for a shift back toward a less-profitable crop economy have been ignored. Moreover, the boy is warning that more wolves are likely to take up residence nearby, and those wolves may reproduce. Changing the mix in the economy significantly back towards crops (a mitigation measure), will lower the wolf threat.[9] As the first prong of defense, he recommended a 50% cutback in sheep, thus significantly reducing their attracting smell and their presence in the outlands.

8 The boy, who had studied economics, labelled the cheap-rider situation that developed an outlands problem. The abundance of sheep outside the village attracted wolves, to the detriment of all.

9 Unfortunately, the wolf threat would not abate quickly once the hybrid sheep numbers is cut. It is the odor of the sheep that primarily attracts the wolves, and the odor persists in the environment for a long time. It is true that if sheep became much harder to catch in the village, wolves would drive elsewhere. Notice the parallel with GHGs, which degrade slowly, hence persist in the atmosphere for a long time.

The villagers heard the boy's message, and they responded, albeit in a woefully insufficient fashion. Whereas previously they had raised 20 sheep per family, they cut back to 18 and raised some vegetables. But evidently wolf numbers were still below equilibrium, and the losses to them increased.

Given the pace of sheep loss, and the unwillingness of the villagers to cut back sharply, the boy recommended that another layer of protective fencing (an adaptation technology) be erected in the outlands, even where the terrain is steep. This would be a second prong of the defense strategy. The village made a half-hearted effort; after all, fencing is expensive, particularly in rocky and hilly domains. Some new fences were built, but the wolves readily evaded most of them. After a minor dip, the losses continued to rise.

Finally, the boy in desperation recommended that the village raise a hunting posse to search out and kill or scare away the wolves (an amelioration strategy), a third prong of defense. The villagers are very reluctant. They are farmers turned shepherds, not hunters. There may be riding accidents or gun accidents; indeed, a wolf may even turn on the posse. The village council votes against raising a posse. A few more fences are built, and the council implores the villagers to cut their flocks, and return to agriculture, but few villagers follow that course. Raising large numbers of hybrid sheep, even with the current 20% annual loss rate, is more profitable than growing crops.

As the annual loss rate climbs to 25 percent, the boy cries: "Please, can't we move forward on all three fronts? Someday the wolves will come to snatch our children, and that will end the world as we know it."

And so it is with climate change. We've been told, correctly, that the world is running out of time to curb its emission-profligate ways. The world did little mitigation and ran out of the urgent time it was given. And matters have gotten worse, much worse. Emissions cutting, drastic emissions cutting, is still the recommended primary prong of our defense. Experience suggests, and economics reveals, that the magnitude of needed cutting will be almost impossible to achieve in the time available. Moreover, even if the prescribed level of mitigation is met, it may already be too late. A second prong of defense, adaptation, has received some discussion, but very little actual implementation. Adaptation would consist of such measures as building barriers to the ocean, restoring absorptive marshes, repositioning sensitive equipment from cellars to roofs, and preventing new construction in threatened areas. This analysis considers a third prong, amelioration through solar radiation management to complement mitigation and adaptation.

4. Why Mitigation Alone Will Not Control Climate Losses

In the 1992 UN Framework Convention on Climate Change, the global community agreed on the ultimate objective of "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (Article 2). The 2009 Copenhagen Accord represented the first meaningful elaboration of this goal; it recognized "the scientific view that the increase in global temperature should be below 2 degrees Celsius" (Paragraph 1). At the 2015 UN climate conference in Paris, the international community agreed on "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (Article 2, Paris Agreement).[10] As in previous negotiations, national emission goals served as the primary focus of efforts to mitigate climate change risk. In the Paris Agreement, these goals took the form of "nationally determined contributions"—voluntary emission pledges set by national governments. In this section we show that mitigation alone will not prevent catastrophic climate change impacts.

4.1. Catastrophic Outcomes Even if Temperatures are Kept to 2°C

Recent events demonstrate that catastrophic outcomes could arise even if temperature increases remain modest, particularly since current temperatures are well below the targeted threshold. Major ice melts in the Arctic, Antarctic, and Greenland are well above what scientific models had previously projected. The July 2019 ocean temperature was the highest ever recorded since records began in 1880 (see Figure 3 above). Moreover, the 9 highest ocean temperature readings are all since 2006.

Ocean temperatures are a primary factor in hurricane strength. Hurricane Dorian of 2019, which went on to tie with the 1935 Labor Day hurricane for the strongest ever Atlantic hurricane to make landfall, picked up strength from an extremely warm ocean. The increasing frequency of category five hurricanes in the Atlantic basin is further evidence of how climate change amplifies the risks of extreme storms. In 2019 alone, the world witnessed such dramatic weather events as catastrophic droughts in eastern and southern Africa, record monsoon floods in India, and monumental fires in Australia due to an unprecedented hot and dry summer.

10 UN Paris Agreement to the UNFCCC. **https://unfccc.int/sites/default/files/english_paris_agreement.pdf.**

Climate change may induce vast migrations. Myriad animal species have changed locales and migration patterns already. They provide a portent for massive movements of humans in response to warming temperatures and the droughts that come from shifting precipitation patterns. Human migrants can create tremendous social, economic, and political disruptions. Indeed, some have associated climate change with the Syrian drought that contributed to the civil war and millions of refugees (Kelley et al. 2015). This example illustrates a key characteristic of catastrophic impacts—they can be local, such as the drought in a nation or the swallowing up of a low-lying island state by rising seas, but their impacts will spill over to other peoples and countries.

In short, 2°C is not a safe harbor; it is an extremely hazardous location. Indeed, the 2018 IPCC Special Report on 1.5°C makes this point clearly across many dimensions of climate change impacts. That raises the question as to why the negotiators and heads of state at the 2009 Copenhagen Conference and the 2015 Paris Conference (among other UN gatherings), as well as many scientists and policy experts, would talk regularly as though this should be our target. The answer, we believe, was strategic: This is the lowest possible value that an expert could plausibly identify as an achievable level. If you want decision makers to get busy cutting emissions significantly, you had better tell them that a feasible target will do the trick.

4.2. Emission Reductions Will Fall Short

International agreements, including those where the United States refused to be a signatory, have been routinely failed to deliver sufficient emission abatement effort. The 1992 UN Framework Convention on Climate Change established a voluntary goal of returning greenhouse gas emissions to their 1990 levels by 2000 for industrialized nations—the members of the Organisation for Economic Co-operation and Development and much of the former Soviet bloc.[11] While some countries failed to meet this goal (e.g., the United States), others had emissions well below this aim (e.g., Russia), and overall these countries met the overall goal: emissions were 3 to 9 percent below 1990 levels in 2000.[12] The 1997 Kyoto Protocol imposed legally binding commitments for these industrialized nations that would reduce their emissions by at least 5 percent below their 1990 levels over the 2008-2012 period, but imposed no quantitative emission commitments on developing countries.[13] In aggregate, these industrialized nations met their 2008-2012 commitment, even when including the United States and Canada, which were not parties to the Kyoto Protocol by the end of its commitment period. The total industrialized countries' greenhouse gas emissions were 8 to 16 percent below 1990 levels over the 2008-2012 period. Nonetheless, global carbon dioxide emissions grew 57 percent over the 1990-2012 period (see Figure 1).

11 Article 4, UN Framework Convention on Climate Change. **https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf**

12 The range depends on the measure of emissions. The UNFCCC Secretariat reports four measures of emissions from these countries, and the decision of whether to include land use change related carbon dioxide emissions explains the variation in estimates.

13 Article 3, UN Kyoto Protocol to the UNFCCC. **https://unfccc.int/resource/docs/convkp/kpeng.pdf**.

The model of the 1990s—focusing on emission reductions among OECD and some former Soviet bloc countries—left too much of the world's emissions outside the goals and commitments; global emissions growth continued.

The Paris Agreement established a new policy architecture premised on a voluntary "pledge and review" approach, as opposed to a legally binding approach to national mitigation actions. The Agreement engages virtually every country in the world. The breadth of the Paris Agreement's initial pledges to mitigate emissions through 2030 are unlikely to be sufficiently ambitious—assuming every country delivers on its voluntary pledge—to prevent warming of more than 2°C. Assuming countries continue to decarbonize their economies at the same rate beyond 2030, as implied by their initial pledges through 2030, this would limit warming to 2°C with merely an 8 percent probability (Fawcett et al. 2015). This course of action—continuing the decarbonization rate of the Paris pledges through the rest of the century—translates into a 50 percent chance of reaching 2°C by 2061 (Rogelj 2019). By 2100, the expected temperature increase would be close to 3°C on average globally, contributing to significant risks across the planet. Climate Action Tracker, an independent group of analysts that publishes evaluations of countries' emission mitigation actions, reports that India is the only G20 country making progress consistent with a 2°C goal, and that Morocco and the Gambia are the only countries making progress consistent with a 1.5°C goal (Akpan 2019).

This is not a surprise to those who negotiated the Paris Agreement. The text of the agreement acknowledged that full implementation of the voluntary emission mitigation pledges through 2030 would lead to 55 gigatons of carbon dioxide, an emission level that does "not fall within least-cost 2°C scenarios" (Paragraph 17, Decision to Adopt the Paris Agreement).[14] These "least-cost 2°C scenarios" are integrated assessment modeling scenarios compiled by the Intergovernmental Panel on Climate Change for its fifth assessment report (Clarke et al. 2014).

The assessments reveal that current pledges to reduce emissions cannot hold back warming to the intended level, as four observations make clear. First, the voluntary emission pledges are simply inconsistent with the 2°C goal. Aldy et al. (2016) show that least-cost implementation of these pledges—through a globally harmonized carbon price (the approach taken in IAMs to model cost-minimizing emission mitigation)—deliver carbon prices of about $10 to $20 per ton of carbon dioxide. The average carbon price for 2030 among the IPCC Fifth Assessment Report (AR5) 2°C scenarios exceeds $100 per ton. To put this price in context, about 20 percent of global carbon emissions bear—or are scheduled to bear—a carbon price from either a carbon tax or a cap-and-trade program, and less than half of these emissions face a price of at least $10 per con carbon dioxide (World Bank 2019).

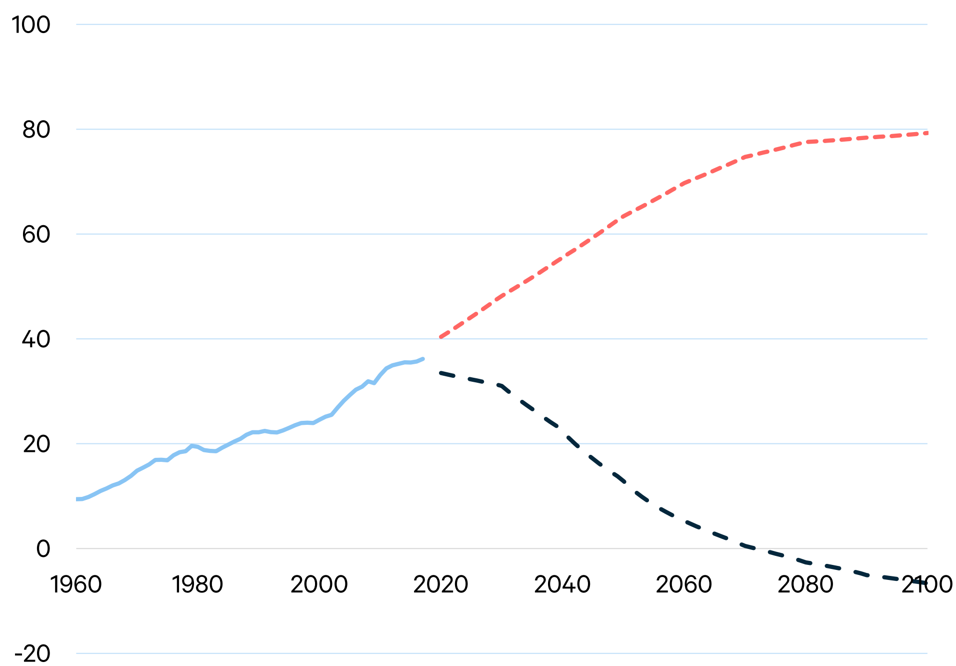
Second, none of the emission pathways in the IAMs prevent warming beyond 2°C with certainty. Typically, any reference to an emission pathway—and a global emission target for any given year along that pathway—corresponds to either limiting warming

14 Adoption of the Paris Agreement to the UNFCCC, **https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf.**

to 2°C to a 66 percent or 50 percent likelihood. (The latter is used for identifying the range of carbon prices for least-cost pathways to 2°C in Aldy et al. 2016.) As noted above, Fawcett et al. (2015) show that the probability is slim that warming will stay below 2°C without accelerating emissions cuts beyond the Paris pledges.

Third, the full suite of IAMs that have evaluated such ambitious temperature goals show that the challenge of limiting warming by transforming the energy foundation of the global economy is daunting. Figure 4 presents global carbon dioxide emissions from fossil fuel combustion and industrial processes over 1960 to 2017, as well as two projections of these emissions over 2020 through 2100. The historical series illustrates how, with few exceptions (most of which are associated with declines in economic activity), global carbon dioxide emissions have increased steadily over 50+ years. One projection of emissions reflects the average of the 100+ least-cost pathways in the IPCC AR5 database that limit warming to no more than 2°C with at least a 50 percent probability. Some pathways have higher emissions trajectories and others have lower trajectories, but the characteristics of this profile over the rest of the century are robust. Global emissions must peak immediately, fall precipitously, and eventually fall below zero.

Figure 4. Global Carbon Dioxide Emissions over 1960-2100, Gigatons CO_2



Notes: Figure represents carbon dioxide emissions from fossil fuel combustion and industrial processes. "Historic CO_2 Emissions" over 1960-2017 from the Global Carbon Project (2018). "Limiting Warming to 2°C Scenario CO_2 Emissions" represents the average global emissions in that year for all scenarios in the IPCC AR5 Modeling Database that limit warming to less than 2°C in the year 2100 by at least a probability of 0.5. "No New Climate Policy CO_2 Emissions" represents the average global emissions that year for all reference scenarios that are the no-policy (zero carbon price) analogs corresponding to each model's 2°C scenario in this database.

In these IAMs, negative global carbon dioxide emissions from the energy system is achieved with the near full electrification of transportation, buildings, and industry coupled with widespread generation of electricity from bioenergy-based power plants designed with carbon capture and storage technology. In these models, there can be no cumulative global carbon dioxide emissions from energy and industry over the second half of the 21st century. The complete transformation of the energy foundation of the modern economy must occur over a very short timeframe given the economic lifetimes of energy infrastructure. These "overshooting scenarios"—where global carbon dioxide emissions must be negative in the latter years of this century—require that a fully electrified planet (electric transport, electric heating, electric industrial processes, etc.) rely on zero-emitting sources, such as renewable and nuclear power, coupled with negative-emitting sources of energy (or direct air capture of carbon dioxide on a massive scale).

In contrast, the other projection reflects the average global emissions for all reference scenarios that are no-new-policy (effectively zero carbon price) analogues corresponding to each IAM's 2°C scenario used to construct the previous projection. While there is considerable variation across the individual scenarios represented by this average, they all forecast considerable growth in global emissions absent emission mitigation policies. The growth in global carbon dioxide emissions projected over the next 50 years is similar to the growth in global emissions over the first two decades of this century.

The 2°C scenarios permit only about 15 percent of the cumulative carbon dioxide emissions over the rest of this century that would occur in "business as usual" scenarios. This rather limited "carbon budget"—the allowable emissions of carbon dioxide consistent with a 2°C goal—requires dramatic energy system transformation. The energy intensity of economic output would need to decline 90 percent through 2100 to limit warming to 2°C and the carbon intensity of energy would need to become negative early in the second half of this century (Clarke et al. 2014).

The IAMs account for the long-lived nature of much of the energy-consuming capital in the economy. Cars and light trucks operate for 15 or more years, power plants operate for 40 to 60 years, and building shells may be used for a century or more. Thus, economic decisions today have long-term impacts on the global climate along two dimensions: first, burning fossil fuels results in the emissions of carbon dioxide that may reside in the atmosphere for centuries; and second, investing in fossil fuel consuming capital today may lock in emission-intensive activities for decades. Indeed, recent analyses based on industry- and sector-specific data suggest that using the already-built energy infrastructure around the world through the end of its economic lifetime would cause warming to exceed 1.5°C and exhaust at least two-thirds of the carbon budget of a 2°C scenario (Tong et al. 2019).

Fourth, all of these analyses are predicated on a strong assumption that national governments can overcome their strong incentives to ride cheaply on the emission mitigation efforts of other countries (Barrett 1990, 2003; Carraro and Siniscalco 1993). Some governments may pledge ambitious emission goals but undertake action that yields only a fraction of the necessary effort (Barrett and Dannenberg 2016). While countries may have a variety of domestic incentives for reducing such emissions, such as to deliver local air quality benefits, to reward specific industries, etc. (Ostrom 2010), national governments almost inevitably will significantly underweight the external benefits of their emission mitigation efforts. Accordingly, they will deliver less emission mitigation than would be in their collective self-interest, an amount well below what would be necessary to achieve an ambitious temperature goal.

For example, national governments have revealed little appetite for raising energy prices consistent with ambitious climate change policy programs. Most of the world's population lives in countries that subsidize transportation fuels and electricity. The design of carbon tax and cap-and-trade policies have often included mechanisms to offset energy price impacts, including: exempting energy-intensive industries from policy coverage (e.g., Denmark's carbon tax); using the revenue of allowances to minimize electricity price increases (e.g., California's cap-and-trade program); implementing a cap-and-trade program on power plants that sell electricity into markets with rates set by the state without regard to the carbon price (e.g., China's pilot cap-and-trade programs). The back-and-forth on carbon dioxide mitigation policies in Australia and the United States illustrates the fragile political support for durable climate change policy.

In short, the developments of recent years cast doubt on the prospects of reaching the emissions targets that will be necessary to hold temperature increases to 2°C. National politics, nations' cheap-riding incentives, and the time and vast expenditures required to transform the world's energy economy and economies more generally, are each a sufficient force for pessimism. It is hardly reassuring that countries are falling short of their Paris Agreement commitments, and that those commitments, even if met, are well below the emissions targets that would be required. These findings emphasize the importance of considering a multi-prong strategy that pursues multiple avenues to mitigating climate change risks, including mitigation, adaptation, and solar radiation management.

5. Comparative Costs of the Three Prongs

Posit that the world does move to a three-prong strategy. To determine an appropriate mix among them, will require careful consideration of their costs and risk-mitigation benefits. The resource needs for each of emission mitigation, adaptation, and solar radiation management strategies will vary, to some degree, with the extent of deployment of the other approaches, as well as with a better understanding of climate change damages over time (Aldy 2015; Heutel et al. 2018). Given the opportunities to substitute one strategy for another in reducing climate change risk, as well as the uncertainties associated with projecting resource costs through the end of this century and beyond, we focus on ranges of estimates and compare the general magnitudes of the costs of each approach.

5.1. Emission Mitigation Costs

The costs of mitigating emissions in line with ambitious temperature goals, such as limiting warming to 1.5°C or 2°C, have typically been estimated with integrated assessment models of the global energy economy over a century or more (Clarke et al. 2014). The integrated assessment models, which often include a detailed representation of energy generating technologies, their costs, and their potential to supply a range of quantities, show how investment in and subsequent generation from new natural gas, new nuclear, and new renewable power plants will likely respond to a specific carbon price. For example, they may model the potential to reduce petroleum consumption in transportation through substitution to biofuels, electric drivetrains, and other technologies. The assessment models also characterize how demand for energy responds to increasing energy prices under a carbon pricing regime, typically drawing on real-world energy system data and estimated elasticities. They typically assume a globally harmonized carbon tax, which creates a downward bias in estimated costs. These models often abstract away from other considerations, such as making technological change endogenous or revenue recycling to reduce the distortions in government tax codes. If so, they would exert an upward bias on estimated costs. Nonetheless, these models provide a sense of the relative scale of costs necessary to deliver on long-term temperature goals exclusively through emission mitigation.

The IPCC's fifth Assessment Report reviewed the integrated assessment literature and found that scenarios generally consistent with limiting warming to 2°C (or lower) required resources on the order of \$500 billion to \$2 trillion per year to mitigate emissions in 2030, increasing to \$1.5 to \$5 trillion per year in 2050 (Clarke et al. 2014 and authors' calculations based on the IPCC AR5 database). The globally harmonized carbon tax in 2020 would be about \$60/tCO_2 on average across modeling scenarios that limit warming to 2°C. The required price vastly exceeds today's implicit price. Nordhaus (2019) estimates that the current global carbon price—when applying existing carbon tax and cap-and-trade programs scaled to their scope of coverage—corresponds to no more than \$3/tCO_2.

5.2. Adaptation Costs

Adaptation can take a wide array of forms. Many adaptation investments will be made by individuals and businesses following their own interests. For example, households will respond to higher temperatures by increasing their use of air conditioning (Davis and Gertler 2015; Deschênes and Greenstone 2011). Farmers will alter the timing of planting and harvesting, the choice of seeds, and water, nutrient, and pesticide inputs (Schlenker et al. 2005). A second broad category of adaptation investments will have public good characteristics, and thus will likely require direct public procurement. This would include everything from sea walls to protect coastal cities from storm surge and sea level rise to enhanced public health efforts to counter vector-borne diseases. Much of the literature on adaptation focuses on specific types of adaptation investment or specific geographic areas.

The United Nations Environment Programme (UNEP) produces an "adaptation gap" report periodically, akin to its emission gap reports. The original 2014 report suggested that adaptation financing needs would increase over time given any temperature trajectory, but at a higher rate for higher-trajectory temperature profiles. By 2050, UNEP (2014) estimates that about ½ of 1 percent of gross world product would be used for climate adaptation under a scenario where temperatures stabilize at 2°C, but nearly double this estimate for warming of 4°C. The more recent estimates place annual adaptation financing needs for 2030 in the $140 to $300 billion range (UNEP 2018). The Global Commission on Adaptation (2019), co-chaired by former UN Secretary-General Ban Ki-moon, World Bank CEO Kristalina Georgieva, and Bill Gates, estimate the need for $1.8 trillion in adaptation and resilience spending over the 2020-2030 period. To put these magnitudes in context, UNEP (2018) identifies $23 billion in annual global public finance—resources transferred from developed countries and development banks to developing countries—currently dedicated to climate adaptation.

5.3. Amelioration Costs

The costs of amelioration are most speculative, given the absence of any full-scale amelioration intervention. The general premise that injecting sulfur particles into the atmosphere can deflect incoming sunlight and produce a net cooling effect on the planet reflects scientific understanding distilled from natural experiments (Crutzen 2006; Wigley et al. 1996).

The technology works. That eliminates a major uncertainty. But what would it cost? Researchers have developed preliminary engineering cost estimates for delivering sulfur particles (and other light-reflecting particles) into the stratosphere that would be sufficient to alter the global energy balance and offset (at least some of) the increase in warming due to increasing atmospheric GHG emissions. Smith and Wagner (2018) estimate the costs of deploying solar radiation management by injecting sulfate aerosols into the stratosphere. Offsetting all of the incremental warming associated with continued greenhouse gas emissions over 15 years would average about $4 billion per year.[15] Keith et al. (2017) suggest that an ambitious intervention of solar radiation management, that held radiative forcing at current levels as carbon dioxide emissions continue unabated through 2100, could offset about 100 gigatons of CO_2 emissions associated with changes in energy demand, permafrost melting, and carbon-cycle feedbacks. Keith et al. estimate that this would cost less than 50 cents per ton carbon dioxide.

This brief review of the global cost estimates suggests three key conclusions. First, costs being incurred today to mitigate emissions and to facilitate adaptation are an order of magnitude less than what is necessary for these two strategies to combat climate change on par with a 2°C goal. Second, the costs of emission mitigation and adaptation appear to be one to two orders of magnitude greater than the cost of solar radiation management in achieving the same targets. Third, emission mitigation and adaptation to climate change are likely characterized by increasing marginal costs, but solar radiation management—in terms of its direct costs of implementation—appear to be linear in the scale of deployment. Thus, each year of further inadequate action on emission mitigation would likely increase significantly the costs of lowering emissions consistent with long-term temperature goals and, as a result, improve the relative attractiveness on economic grounds of solar radiation management. A key outstanding question is whether the potential unintended consequences of solar radiation management are convex in its scale of application.

15 This assumes that the world's emissions trajectory is consistent with limiting warming to about 3.2°C above pre-industrial levels by 2100 (the so-called RCP 6.0 scenario). If emissions mitigation is more ambitious, the costs of this solar radiation management strategy would be lower to prevent incremental warming, but if the mitigation is less ambitious, then the costs would be higher.

6. Solar Radiation Management and Moral Hazard

There are many legitimate concerns about solar radiation management. Four stand out. First, dumping a chemical into the stratosphere on a continuing basis at unprecedented levels will affect the Earth's ecosystem in ways that science does not understand, and cannot predict. Second, it will be essential to curb GHG emissions; otherwise, as GHGs continue to increase in the atmosphere the pace of solar radiation management will have to increase alongside to keep temperatures at a roughly even level. Third, solar radiation management only targets the temperature dimension of climate change. It may do nothing for ocean acidification due to increased CO_2 concentrations; indeed, it could exacerbate acidification if sulfate is deposited in the oceans. Fourth, while initial discussions among scientists and policy experts conceive of a global governance regime, there is no assurance that one will emerge before some rogue nation undertakes solar radiation management on its own.[16] In short, there are significant dangers or shortcomings inherent in solar radiation management, or indeed in any geoengineering technique. They have been a source of hostility from scientists and environmentalists.

Moral hazard concerns have been a major second component of that hostility: If you tell citizens that there may be some technological corrective for climate change, they will be less willing to curb emissions (Keith 2000; Burns et al. 2016).

Yet moral hazard may go in the opposite direction: If observers are too tied to mitigation as our prime strategy for dealing with climate change, they will underplay the potential roles of adaptation and solar radiation management. There are three reasons to be concerned that moral hazard is flowing in this direction. First, the discussion in the scientific, environmental and public spheres has focused very heavily on mitigation in contrast to adaptation and SRM, as noted above.

Second, the world has expended extremely few resources on adaptation and solar radiation management. Even before consideration of deployment, there has been virtually no research and development undertaken on solar radiation management. Over 2008-2018, global R&D spending on solar radiation management never surpassed $10 million per year (Necheles et al. 2018). There are hints that the situation may be changing, that hostility may be dampening, and that SRM will get greater attention. In 2019, for the first time, the US Congress appropriated funds, the modest sum of $4 million (Temple 2019), to a federal agency to study climate interventions.

Third, although the overwhelming policy focus has been on mitigation, conditions in the environment have gotten far worse in the past few decades. This makes it evident that it is highly unlikely that a mitigation strategy alone will prove sufficient to

16 These problems are exacerbated because, as extensive work in psychology demonstrates, people are more concerned with errors of commission than errors of omission.

save the world from extreme expected damages. It also indicates that the returns to adaptation and solar radiation management efforts are far greater than they would be had mitigation proceeded at a much faster pace. It is too late to rely overwhelmingly on merely a single prong for climate policy.

A solar radiation management intervention may even spur additional emission mitigation, rather than substitute for it. In effect, solar radiation management could serve as an "awful action alert." If the general public does not sufficiently appreciate the current risks posed by climate change, then deploying solar radiation management—what some environmental advocates would label "an awful action"—would signal the extreme danger policymakers believe the world faces with climate change.

For a recent illustration of the phenomenon of an awful action alert, consider the response of financial markets to surprise news on policy actions taken to curb the COVID-19 pandemic. Equity markets melted down in March 2020 in response to the pandemic. The days with the two biggest drops were days with extremely surprising news about dramatic actions taken to curb the pandemic. Table 1 shows the dates with the largest daily declines in the S&P500 index and the text of the first three paragraphs of the lead story in the New York Times on those days.[17]

In an analogous manner, injecting sulfate particles in the stratosphere could highlight for the public the need for immediate, ambitious action on climate change and thus it could galvanize public support for more ambitious emission mitigation. Indeed, some preliminary investigation of this with focus groups that varied in the participants' concern about climate change suggests that solar radiation management would motivate individuals to find ways to reduce their carbon footprints (Shepherd 2009).

Burns et al. (2016) review the emerging social science literature on the link between learning about solar radiation management and individuals' decisions to pay voluntarily for emission offsets (i.e., contribute to emission mitigation). Merk et al. (2016), in an experiment find no impact. Mahajan et al. (2019) survey of American households and find that even respondents concerned about moral hazard were supportive of research on solar radiation management.

17 The day with the third biggest drop, - 7.6% on March 9, had an irrelevant lead story about Donald J. Trump taking over the Republican Party, and no stories about surprises on page 1.

Table 1. Financial Responses to Awful Action Alerts: Two Days with Greatest Losses in S&P 500 and Lead Stories from the New York Times

Data	S&P500 Percent Change from Previous Day's Close	*New York Times,* opening paragraphs from lead story on the awful action alerts
March 12, 2020	-9.51%	"President Trump on Wednesday night blocked most visitors from continental Europe to the United States and vowed emergency aid to workers and small businesses as the World Health Organization declared the coronavirus a global pandemic, stock markets plunged further and millions of people cut themselves off from their regular lives. "In a prime-time address from the Oval Office, Mr. Trump outlined a series of measures intended to tackle the virus and its economic impact as he sought to reassure Americans that he was taking the crisis seriously after previously playing down the scope of the outbreak. He said he would halt travelers from Europe other than Britain for 30 days and asked Congress to support measures like a payroll tax cut. "'The virus will not have a chance against us,' Mr. Trump declared in his 10-minute speech, reading from a teleprompter in an uncharacteristic monotone. 'We are all in this together'" (Baker 2020, p. A1).
March 16, 2020	-11.98%	"With the fast-spreading coronavirus posing a dire threat to economic growth, the Federal Reserve on Sunday night took the dramatic step of slashing interest rates to near zero and unveiled a sweeping set of programs in an effort to backstop the United States economy. "In addition to cutting its benchmark interest rate by a full percentage point, returning it to a range of 0 to 0.25 percent, the Fed said it would inject huge sums into the economy by snapping up at least $500 billion of Treasury securities and at least $200 billion of mortgage-backed debt 'over coming months.' "The remarkable Sunday afternoon action - a drastic move unlike any since the depths of the global financial crisis a dozen years ago - reflected the imminent peril facing the global economy as the virus shutters factories, quarantines workers and disrupts everyday life" (Smialek and Irwin 2020, p. A1).

7. Toward a Three-Prong Approach to Reducing Climate Change Risks

In recent years, as the world's disappointing record on emission control became clear and as some symptoms of climate change became more threatening, discussion of adaptation strategies became more acceptable. For example, after Hurricane Sandy hit New York, relatively inexpensive adaptation strategies, such as moving electrical equipment out of basements and developing coverings for subway entrances began to be contemplated and undertaken. Still, on an expected value cost-benefit basis they were woefully insufficient and considerable risks of a category 3 or higher hurricane persist for the greater New York area (Klinenberg 2017). Moreover, many vulnerable American cities have not even initiated modest-scale planning efforts on how they might make adaptation expenditures. The good news, however, is that adaptation expenditures have become a politically acceptable part of the conversation. Adaptation as a strategy to cope with climate change has at most modest moral hazard consequences with respect to curtailing emissions. While the need to control emissions is reduced through adaptation, it seems that only a small fraction of climate-change losses could be affordably controlled by adaptation. Moreover, consideration of expensive adaptation highlights the costs associated with the failure to effectively control emissions.

The risks posed by climate change are large and uncertain. The policy response to date—primarily efforts of emission mitigation—has not proved effective. A more comprehensive approach to climate risk mitigation holds potential to significantly improve outcomes as atmospheric greenhouse gas concentrations continue to increase. Figure 5 illustrates the various policy levers at the disposal of government. Policymakers may price carbon or employ other greenhouse gas mitigation policies to reduce emissions, i.e., to prevent the problem. They may employ geoengineering, such as solar radiation management to lower the solar energy reaching the earth's surface, to limit temperature increase, i.e., to ameliorate the problem. They may facilitate adaptation, such as the construction of sea walls, investment in new treatments for vector-borne diseases, etc., to reduce some of the adverse impacts of a changing climate. Research and development can influence the design and efficacy of policy levers across each of these dimensions, as well as on economic activity more generally and the emission intensity of economic output. Economic growth may influence greenhouse gas emissions as well as reflect the impacts from climate change.

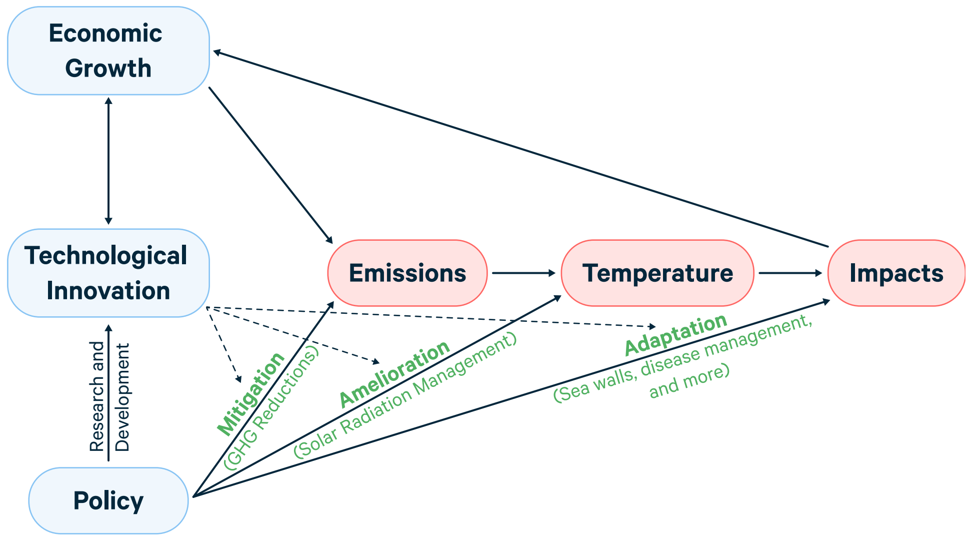
This figure is a stylized illustration and omits a variety of interactions and nuances of the policies. For example, adaptation efforts, such as air conditioning, may increase the costs of GHG mitigation by increasing energy demand. Conversely, higher energy prices due to carbon pricing would raise the marginal cost of air conditioning and hence the costs of adaptation. The change in temperature—and SRM's impact on temperature change—is not the only factor influencing the impacts of carbon dioxide emissions. For example, the acidification of oceans is largely unrelated to temperature changes, but instead reflects increased accumulation of carbon dioxide in the atmosphere and subsequent oceanic absorption. Solar radiation management may also impose adverse impacts unrelated to its direct effect on temperatures. While acknowledging these caveats, the diagram illustrates the potential for solar radiation management and adaptation to mitigate climate change risks when emission mitigation is insufficient.

Uncertainty is a prime characteristic of every arrow in this diagram. It is embedded in the relationship: between R&D and innovation and in turn with economic growth; between emissions mitigation and temperatures; between temperatures and impacts; between SRM and temperature; and between adaptation and impacts. These uncertainties suggest opportunities for policy learning to inform subsequent actions. They highlight the value of mitigating climate change risks through an act-learn-act approach (Manne and Richels 1992). This learning approach to policy would need to account for the irreversibilities in climate change, including those due to climate-risk-mitigation policies that have been long recognized in economics (e.g., Arrow and Fisher 1974).

This learning and subsequent execution of insights gained also requires time, a resource in short supply. Consider several examples. The City of Venice began constructing a flood barrier at the mouth of the Venetian lagoon in 2003, which may become fully operational by 2022. In the aftermath of the Northern California Camp Fire disaster and the prospects of future forest fire risk, Pacific Gas and Electric indicates that it may take a decade to fully replace its aging transmission infrastructure. In the interim, PG&E will implement "public safety power shutoffs"—cutting power to millions of customers for days at a time—to reduce the risk of another major fire. In 2006, the Southern Company initiated a permit application to build two new nuclear power generating units at its Vogtle power plant in Georgia. The units may enter into service by 2022. And, as we noted above, it may take more than a decade to develop a delivery system for SRM.

From a normative standpoint, the large potential adverse impacts of climate change—including the prospect of catastrophic impacts—suggest that further deployment of policies to promote solar radiation management and adaptation may be merited. While we do not want to dismiss adaptation, we recognize its limits. Climate change may pose existential risks to low-lying island nation-states and to populations living in already hot, arid climates. Even in large countries, such as the United States, sea level rise and storm surge may require those living in coastal communities, such as in Florida, to retreat to higher land. There are also private incentives for (at least limited) adaptation, such as air conditioning in homes and changes to agricultural practices by farmers. We prefer to focus on the economics of SRM to inform understanding of the potential policy steps on this policy lever.

Figure 5. Policy Levers for Mitigating Climate Change Risk



8. Summing Up: Dynamic Decision-Making and the Three Prongs

To date, climate change policy has followed an approach that entails extensive discussions of and promises on emissions reduction, and some modest efforts involving adaptation. Solar radiation management, which is strongly discouraged by many in the scientific and environmental communities, is at best in the early stages of R&D.

If civilization is to be saved from catastrophic losses through the end of this century, our current strategy has shown itself to be woefully insufficient. An effective strategy will require, at a minimum, three elements: a significant expenditure of resources, the effective use of all three prongs of climate policy, and significant technological advance within each prong. And those elements in turn will require time, time to get the nations of the world on board, and time to develop and implement the technologies that are required. Figure 5 illustrates.

It is controversial to recommend that solar radiation management be pursued on a serious basis. Even with significant research and experimentation, some of its major possible consequences will not be fully understood. The alternative would be to leave all efforts to control temperature increases to the single prong of reducing GHGs. The analysis above reveals that this one-prong strategy almost inevitably will lead to severe, possibly catastrophic, adverse consequences. Given that, ruling out solar radiation management as an instrument to control temperature would be imprudent.

To avoid possible misunderstanding, we should stress that however effective is solar radiation management, it will be essential to pursue emissions cuts with vigor. Absent significant curtailment, the world would be confronted with the increasingly perilous problem of conducting ever more extensive SRM efforts.

In closing, we should stress that there are massive uncertainties associated with each of the three policy prongs, and with their interplay, as well as with the consequences of a warming planet. Hence, pursuing effective policy will be a complex problem of optimizing dynamic decision making under uncertainty. We will learn as we go; the climate is not waiting.

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