DO GLOBAL WARMING AND CLIMATE CHANGE REPRESENT A SERIOUS THREAT TO OUR WELFARE AND ENVIRONMENT?

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I. INTRODUCTION

The subjects of "global warming" and "climate change" have become parts of both the popular lexicon and the public discourse. Discussions of global warming often evoke passionate responses and fierce debate between adherents to different views of the threat posed. Yet there are many nuances regarding global warming, climate change, and the threats they represent that are not well understood by the public. The public's conceptual understanding hinges largely on images and paradigms within the popular culture that are often little more than caricatures of the actual, underlying scientific concepts. To appreciate the potential threat that climate change and global warming represent to human society, living things, and our environment, it is necessary that we first understand the true science underlying these phenomena.

The purpose of this essay is to assess the implications of climate change for the welfare of human society and our environment. I will first discuss the science underlying global warming, climate change, and the connections between these two phenomena (Section II). I will then explore what climate changes are projected for the future under various plausible scenarios of future human behavior (Section III), and what impacts these changes are likely to have on society, ecosystems, and our environment (Section IV). Finally, I will consider the economic, security, and ethical considerations relevant to evaluating the threat of climate change (Section V) and the steps that should arguably be taken to mitigate climate change and its impacts (Section VI). I will summarize my conclusions Section VII.

II. Scientific Background

Global warming refers to the phenomenon of increasing average surface temperatures of the Earth over the past one to two centuries. The concept is related to the more general phenomenon of *climate change*, which refers to changes in the totality of attributes that define climate—not only surface temperatures, but also precipitation patterns, winds, ocean currents, and other measures of the Earth's climate. For this reason, I will favor the

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use of the more general term 'climate change' throughout this essay, recognizing that global warming is simply one of the attributes of climate change. Climate change can be viewed as consisting of two components, one of which is human (i.e., anthropogenic) in origin and coincides in timing with the industrial period of the past two centuries, and the other of which is natural and has played a role in both past and current climate variability. Global warming generally refers to the anthropogenic component of climate change alone, and only the surface warming associated with it. The key scientific issues required to understand the behavior of the Earth's climate system are discussed below, and include the notion of energy balance, which governs how the climate system works, the greenhouse effect (including the special case of the enhanced or human greenhouse effect), which is necessary to understanding surface temperatures on Earth, and so-called *feedbacks*, which can amplify the magnitude of climate changes. Other essential aspects of the science of climate change are the construction and use of theoretical *climate models* to investigate the behavior of the climate system, an understanding of the factors that have governed past climate, and, finally, the inferences that can be drawn through a comparison of model simulation predictions and available observations in the assessment of the human impact on climate.

A. Energy balance

The average surface temperature of the Earth is maintained by a balance between incoming and outgoing sources of energy or radiation. The incoming energy is in the form of solar radiation, some of which takes the form of the visible light that we see from the sun, but much of which is in invisible forms of electromagnetic radiation such as ultraviolet radiation. Some of the incoming radiation scatters off the molecules of our atmosphere, giving us, for example, the blue skies of Earth rather than the stark black skies of the moon or planets without an atmosphere such as Mercury. The outgoing radiation is of a very different form than the incoming radiation. The wavelengths of radiation produced by the relatively cool Earth are longer than those produced by the relatively hot sun, and such radiation is invisible, falling outside the frequency band of visible light. This radiation is primarily in the form of so-called infrared energy, which we typically associate with heat.

For every 100 units of incoming solar radiation, roughly 30 parts are reflected back to space by either clouds, the atmosphere, or reflective areas on the Earth's surface. This reflective capacity can vary over time as changes occur in the spatial extent and distribution of reflective surfaces such as clouds and ice cover. The remaining 70 units that are not reflected are absorbed by either the atmosphere, clouds, or the surface. To maintain a steady temperature or equilibrium, the Earth's surface and atmosphere must emit the same amount of radiation that they receive from the sun. Thus, the Earth must emit that same quantity of 70 units of radiation back out to space, but this time in the form of invisible, infrared radiation as discussed above.

Because the amount of radiation produced by a body, such as the Earth's surface, increases as a function of the temperature of the body, that 70 units of radiation determines, in turn, the surface temperature of the Earth. This relationship constitutes a sort of natural thermostat wherein the average surface temperature on Earth is predetermined by the requirement that it radiate the same amount of radiation to space that it absorbs from the sun.

B. The greenhouse effect

If the only considerations determining the Earth's surface temperature were those described above, the Earth would be a frozen (and likely lifeless) planet. There is an additional factor, the so-called greenhouse effect, which leads to a warming of the lower atmosphere. The existence of the greenhouse effect is not controversial; in fact, without it, the Earth likely would not be habitable. Trace gases with certain chemical properties (the so-called greenhouse gases) absorb some of the infrared radiation produced by the Earth's surface. Due to this absorption, some fraction of the original 70 units does not directly escape to space, but is instead absorbed by these gases. Because greenhouse gases emit the same amount of radiation they have absorbed, but equally in all directions (i.e., as much downward as upward), the net effect of absorption by greenhouse gases is to increase the total amount of radiation downward toward the Earth's surface and lower atmosphere. To maintain equilibrium, the Earth must therefore emit more than the original 70 units of radiation, which in turn means that surface temperature must increase. This is the atmospheric greenhouse effect. The analogy with how a true greenhouse works is loose-the precise processes involved are actually different. However, the end effect is similar. The presence of greenhouse gases leads to a warming of the Earth's lower atmosphere. The Earth's surface temperature is about 60° F warmer (60° F) than it would otherwise be (0° F).

C. The human greenhouse effect

It is essential to distinguish the *human* greenhouse effect from the *natural* greenhouse effect described above. The natural greenhouse effect results from the natural presence of greenhouse gases such as carbon dioxide, methane, and nitrous oxide in the atmosphere. Their presence in our atmosphere is a result of the balance between natural biological and geochemical processes which maintain modest background levels of these gases in our atmosphere. In addition to these background greenhouse gas concentrations, human beings have been increasing greenhouse gas concentrations, principally in the form of carbon dioxide and methane, through industrial activity, primarily in the form of fossil fuel burning and agriculture, respectively. It is this *enhanced* or *human* greenhouse effect which is primarily responsible for human-caused (anthropogenic) climate change.

D. Feedbacks

There are a number of so-called feedback processes within the climate system that act to either diminish or magnify the response to any external perturbation of the climate system (which could include a change in solar output, or a change in atmospheric greenhouse gas concentrations). On the whole, the feedbacks average out to be positive, which means that the response to the perturbation tends to be larger than one would expect in the absence of feedbacks. In particular, this means that the response to an increase in greenhouse gas concentrations arising from human activity is larger than one would expect without considering feedback processes. One important positive feedback is the so-called water vapor feedback. This feedback derives from the fact that water vapor is also a potent greenhouse gas, but its presence in the atmosphere is controlled by surface temperatures themselves through the control they have on relative humidity levels. Hence, a given initial amount of warming leads to even more warming because of the increased evaporation of water vapor into the atmosphere caused by warming. Another important positive feedback is the so-called ice albedo feedback. This feedback derives from the fact that warmer surface temperatures over the Earth in general are associated with decreased global ice cover, reducing the reflectivity of the Earth's surface and allowing more solar radiation to be absorbed by the Earth. The one significant feedback in the climate system which may be a negative, rather than a positive, feedback is the cloud feedback. The best current scientific thinking suggests that a warmer Earth will lead to greater cloud cover, and the main impact of the increased cloud cover is increased reflection of solar radiation back to space from cloud tops, a cooling impact. This feedback is more uncertain than the water vapor and ice albedo feedbacks, because of the complexity of representing the behavior of clouds in theoretical climate models. The net effect of all the feedbacks is a positive feedback that roughly doubles the amount of warming that is expected from increasing greenhouse gas concentrations in the absence of feedbacks.

E. Theoretical climate models

Theoretical models of the Earth's climate system can be used to study the behavior of the Earth's climate, and to investigate the response of the climate to imposed "forcing," including the buildup of greenhouse gases in the atmosphere due to fossil fuel burning. These models are based on applying the laws of physics (fluid dynamics and radiation balance) and principles of chemistry and biology to describe the behavior of the components of the climate system (the ocean, the atmosphere, ice sheets, and the terrestrial and marine biosphere) and the interactions between them. These models vary in their complexity, from the simplest "energy balance" models, which treat the Earth's surface as a globally uniform layer whose temperature is determined by a balance of incoming and outgoing radiation, to the fully three-dimensional global climate models which solve for not only the global radiation balance, but also the physical equations of motion governing the atmosphere, the ocean, and ice, and also solve for the exchanges of energy and momentum both within and between the different components of the climate. In many cases, such models also include a dynamic representation of the Earth's biosphere and carbon cycle.

These models must divide the atmosphere and ocean into discrete grid cells or "boxes" which are typically several hundred kilometers or more in length and width. The models therefore cannot explicitly resolve all of the processes that are important in the atmosphere and ocean, including individual clouds or winds and ocean currents that are smaller in scale than the grid spacing. Instead, such "sub-grid-scale" processes must be represented through statistical "parameterizations" that relate the properties of the atmosphere and the ocean at scales smaller than the grid spacing to properties that are explicitly resolved by the model. For example, the average fraction of cloud cover over a grid box can be related to the average relative humidity and vertical temperature profile for the grid cell. Variations in the behavior of different climate models, such as how much warming is realized for a given increase in greenhouse concentrations, are typically due to differences in the parameterizations of subgrid-scale processes, and clouds in particular.

Despite the numerous simplifications that are required to construct a theoretical model of the climate system, these models have proven quite successful in reproducing basic features of the Earth's climate. These features include the seasonal cycle of temperature and precipitation over the Earth, and wind patterns such as jet streams. These features also include the pattern of atmospheric circulation known as the "Hadley Cell" circulation, which is associated with the tendency for rising, moist, rainfall-producing air currents in equatorial regions which descend as dry, desert-producing air currents in subtropical regions. The models also successfully reproduce key features of the oceans such as the Gulf Stream in the North Atlantic Ocean. The models have also proven increasingly successful in reproducing important features in the natural variability of the climate system such as the El Nino/Southern Oscillation (ENSO) phenomenon.

Finally, climate models have been tested in their ability to reproduce key aspects of observed climate change. In 1987, Dr. James Hansen and his team

at the NASA Goddard Institute for Space Studies predicted the warming expected for the next two decades. The predictions turn out to have matched the observed warming since that time remarkably well.¹ In a later study published just after the 1991 Mount Pinatubo volcanic eruption in the Philippines, Hansen and his collaborators also used a climate model to successfully predict that global surface temperatures would cool by roughly one half degree Celsius for the two years following the eruption.²

F. Earth's climate history

The Earth's climate varies on a wide range of timescales. Over tens of millions of years, geological processes such as plate tectonics have driven substantial changes in the composition of the atmosphere, impacting the levels of natural greenhouse gases. During the early Cretaceous period (roughly 100 million years ago), for example, it is believed that carbon dioxide levels were several times higher than they are at present, and global temperatures several degrees warmer than today, warm enough that the poles were ice-free. As long-term geological processes slowly drove down greenhouse gas concentrations, the Earth's climate entered the so-called Pleistocene climate epoch approximately two million years ago. The Pleistocene was characterized by oscillations between widespread glacial conditions (ice ages) and more moderate, relatively ice-free interglacial periods, driven by natural, multi-millennial cycles in the geometry of the Earth's orbit around the sun. The most recent ice age culminated roughly twenty thousand years ago in what is often termed the "Last Glacial Maximum." At that time, continental ice sheets extended well into the mid-latitude regions of Europe and North America, covering what is now New York City in the United States, and much of southern England. Assessments of geological and other paleoclimate data suggest that year-round global temperatures were about 4 to 5° Celsius colder than the twentieth-century average, with the greatest cooling observed at polar latitudes, and little cooling over large parts of the tropical oceans. This glacial interval terminated roughly twelve thousand years ago, giving rise to the current, relatively ice-free interglacial period known as the Holocene. With human activity over the past two centuries having now driven greenhouse gas concentrations to levels higher than at least the past 700,000 years, and perhaps the past several million years, many scientists have argued that human beings have now pushed the climate into a new, unprecedented regime billed as the "anthropocene."³

¹ See James Hansen et al., "Global Temperature Change," *Proceedings of the National Academy of Sciences* 103 (2006): 14288–293.

² See James Hansen et al., "Potential Climate Impact of the Mount Pinatubo Eruption," *Geophysical Research Letters* 19 (1992): 215–18.

³ This term was first coined by Nobel Prize winning scientist Paul Crutzen. See, e.g., P. J. Crutzen and E. F. Stoermer, "The 'Anthropocene,' " *Global Change Newsletter* 41 (2000): 12–13.

Over this latter period of the past one to two centuries, we know that there are substantial trends consistent with a warming Earth, with global surface temperatures rising, global sea level rising accordingly (as seawater expands with ocean heating and land ice melts and runs off to the sea), and snow cover decreasing (as warmer temperatures favor an increasingly short season of snow cover). Paleoclimate evidence based on "proxy" climate data such as tree-rings, corals, ice cores, and marine sediments indicates that the warmth of the most recent decades likely exceeds that for at least the past thirteen hundred years, and perhaps longer.⁴ Mountain glaciers which have existed for many thousands of years throughout North America, the European Alps, the Andes, the Himalayas, and even the ice caps that comprise the "Snows of Kilimanjaro" immortalized in Ernest Hemingway's short story of the same title, are disappearing now or projected to disappear within decades. Such evidence hints at the likelihood that the climate changes we are now witnessing may have no precedent in many thousands of years.

G. Anthropogenic impact on climate

The primary influence of anthropogenic activity on the Earth's climate has been the alteration of the planetary energy balance associated with the elevation of concentrations of greenhouse gases in the Earth's atmosphere due to fossil fuel burning and other industrial, agricultural, or land-use practices. A less-discussed but nonetheless influential secondary anthropogenic impact on climate is the industrial production of so-called aerosol, particulate matter that also alters the energy balance of the Earth's surface and atmosphere through the reflection and/or absorption of incoming solar radiation. Most prominent among these is sulfate aerosol, which derives from industrial sulfur dioxide emissions associated with the burning of coal and oil. Also important is nitrate aerosol, produced from smog that comes out of the tailpipes of automobiles, from the burning of oil, or from ammonia used in fertilizers. Both sulfate and nitrate aerosols primarily reflect incoming solar radiation, reducing the amount of sunlight reaching the Earth's surface, and hence producing a regional cooling impact. Unlike greenhouse gases, however, anthropogenic aerosols only reside in the lower atmosphere, and for a relatively short amount of time. Thus, the cooling impact is restricted to regions where they are continually produced, such as eastern North America and parts of Eurasia. The cooling effect has therefore primarily been confined to the Northern Hemi-

⁴ This conclusion is drawn in the Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change. See, e.g., chapter 6 of the Working Group I report by E. J. Jansen et al., "Paleoclimate," in S. Solomon, et al., eds., *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge and New York: Cambridge University Press, 2007).

sphere. The time history of aerosol emissions is also somewhat different from that of greenhouse gases, with aerosol production having increased sharply during the early and mid-twentieth century, but tailing off thereafter due to antipollution measures, in particular the various Clean Air Acts passed in recent decades by countries such as the United States, Canada, and the United Kingdom. The regional cooling impact of anthropogenic aerosols consequently appears to have been at least partially responsible for the cessation of Northern Hemisphere warming from the 1940s through the 1970s, and the accelerated warming of recent decades now that aerosol production has decreased.

The observed changes in climate can be compared with the predictions of theoretical climate models to assess whether or not human impacts on the climate can indeed be detected in the observational record. So-called detection and attribution studies comparing the predicted and observed spatiotemporal patterns of climate change over the past century have shown that the observed patterns of warming of the Earth's surface and the upper oceans, and the changes in prevailing winds and rainfall patterns, are consistent with the model-predicted patterns of human-caused climate change. Moreover, the observed patterns, including the anomalous recent warming, cannot be explained by the models in terms of natural factors. For this reason, the scientific community largely accepts the main predictions of future climate change expected in response to various possible future emissions scenarios. These scenarios are explored below.

III. PROJECTED FUTURE CLIMATE CHANGES

Projections of future climate change suffer from at least two basic uncertainties. One of these, and arguably the more fundamental, is that we cannot predict the future course of human behavior. At one extreme is a scenario wherein society chooses to take immediate action to curb fossil fuel burning (turning to alternative carbon-free or carbon-neutral sources of energy to meet its energy demands), dramatically increases its energy efficiency, and stabilizes the growing global population within one or two decades. In such a scenario, it is likely that greenhouse gas concentrations can be kept below twice their pre-industrial level. This is the level which many scientists believe constitutes the threshold for "dangerous anthropogenic interference with the climate system,"⁵ that is, the limit beyond which human-caused climate change likely poses a serious threat to society and the environment. At the other extreme is the scenario wherein we continue to accelerate further the rate of our burning of fossil fuels, and greenhouse gas concentrations rise at an ever-accelerating rate. In this

⁵ The stated objective of the Kyoto Protocol, which was agreed upon at a summit in Kyoto as a followup to the United Nations Framework Convention on Climate Change (UNFCCC), was to achieve "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

scenario, we will likely breach the aforementioned threshold by mid century.

Climate modelers have investigated both of these extreme scenarios, and a variety of other scenarios that fall in between, including a so-called business-as-usual scenario, which is somewhat of a middle ground between the two extremes. The climate impacts of these various emissions scenarios are explored by taking state-of-the-art theoretical climate models and driving them with the various possible future human-caused greenhouse gas concentration increases. Even for a given emissions scenario, however, not all climate models predict the same future climate changes. Different models, instead, project a spread of possible future climate changes for a given scenario because of the differences in the way that different physical processes are represented among the different models. For example, as discussed earlier, different models differ in how they represent the properties of clouds and how clouds response to changes in various other climate variables. This leads to differences in the magnitude of climate feedbacks related to clouds, and, thus, differences in the net amount of warming that results from a given increase in greenhouse gas concentrations. Such differences are often summarized in terms of "climate sensitivity," which is the amount of surface warming that is expected in response to a doubling of greenhouse gas concentrations from their pre-industrial levels (which will occur roughly midway through this century if we follow the current trajectory). State-of-the-art climate models typically vary in their climate sensitivity over a range of roughly 2 to 5°C for such a greenhouse gas concentration doubling. Of course, surface warming is just one of many projected responses of the climate to future emissions. Other responses include changes in patterns of precipitation and soil moisture, regional climate changes, ice melt and rising sea levels, and changes in the intensity of tropical cyclones. I discuss each of these below.

A. Surface warming

The projected increase in global surface temperature from 2000 to 2100 ranges from roughly 1 to 6°C, depending on which of the emissions scenarios (discussed above) is assumed, and on the climate sensitivity of the particular model used.⁶ The scenario that most closely corresponds to "business as usual" (i.e., in which there are no significant departures over the next century from the historical pattern of increasing fossil fuel burning) is the so-called A1B scenario,⁷ a mid-range scenario that would result

⁶ S. Solomon et al., "Summary for Policymakers," in *Climate Change 2007: The Physical Science Basis.*

⁷ N. Nakicenovic and R. Swart, *Special Report of the Intergovernmental Panel on Climate Change on Emissions Scenarios* (Cambridge: Cambridge University Press, 2000).

in more than a doubling of carbon dioxide levels, raising these levels from their pre-industrial level of roughly 280 parts per million in the atmosphere by mass (ppm) to about 700 ppm. Such an increase in greenhouse gas concentrations would, in turn, lead to a warming of between 2 and 4°C, depending on the model.

The lower-end emissions scenarios (such as the B1 scenario)⁸ on average hold additional global surface warming by 2100 to below 2°C, which is considered by many scientists to be the threshold that defines "dangerous anthropogenic interference" with the climate. However, it is noteworthy that even in this most conservative of scenarios, some models do predict a breaching of the 2°C warming threshold by 2100. This observation underscores how uncertainty impacts decision-making in the context of future climate change. While contrarians in the climate change debate often argue that scientific uncertainty constitutes a reason not to act on the problem, it is likely that precisely the opposite is true. If we are to reduce the risk of dangerous changes in climate to an acceptable level, we must consider not just those changes which are very likely given a particular course of action, but also those even more dramatic changes that, even if not likely, are nonetheless plausible, and, if they occur, would have truly calamitous consequences.9 In this particular example, we see that even adopting a very stringent emissions policy in the decades ahead does not insure that we will avoid dangerous interference with the climate system.

It is also important to note that the projected warming will not be globally uniform. Greater warming is predicted over land than over ocean, implying that, on average, human civilization will experience more warming than would be inferred from the simple global average surface temperature change typically depicted (which combines the more rapidly warming land regions with the more slowly warming oceans). Among land regions, the greatest warming is projected over the polar region of the Northern Hemisphere, due primarily to the melting of sea ice. This means that civilizations and ecosystems in these regions, some of which are quite fragile, could be subject to especially large amounts of warming. Other regional variations in predicted warming arise from changes in wind patterns and ocean currents that themselves are a result of climate change. Such changes include alterations in the pattern of the jet stream, and changes in the paths of warm ocean currents, both of which are discussed later in this essay in more detail. Another key issue is so-called committed warming. Because of the long response timescales intrinsic to the climate-in particular, the slow nature of the warming of the deep oceans-we are committed to many decades of additional surface warm-

⁸ Ibid.

⁹ An example of fallacious support for near-term inaction based on a neglect of lowprobability, high-cost outcomes can be found in popular contrarian writings such as Bjørn Lomborg, *Cool It* (New York: Knopf, 2007).

ing even if we hold greenhouse gas concentrations fixed at current levels (which would require us to suddenly cease all burning of fossil fuels today). The committed warming predicted by the models is, on average, estimated at about 0.6°C by 2100. The issue of committed warming highlights how our decision-making today holds future implications for decades to come, and illustrates the so-called procrastination penalty of failing to act on climate change.¹⁰

B. Patterns of precipitation and soil moisture

As patterns of winds and atmospheric circulation change with a warming climate, changes are also predicted in the large-scale patterns of rainfall and precipitation which depend on these wind and circulation patterns. Increased precipitation is generally predicted in the subpolar latitudes of the world, especially during winter, due to a poleward shift in the jet streams. By contrast, many mid-latitude regions, such as large parts of Europe and North America, are likely to experience decreased rainfall, particularly in summer, due to a poleward expansion of the subtropical high-pressure centers. Counterintuitively, extreme precipitation events and flooding may actually increase in regions where there is a decrease in total rainfall, because the precipitation that does occur is more likely to be concentrated in a smaller number of heavier rainfall events. This latter effect is due to the existence of a more vigorous hydrological cycle in a warmer world. Decreased summer precipitation in the extratropics, combined with greater rates of evaporation over large parts of the globe due to warmer surface temperatures, leads to a tendency for decreased soil moisture and drought over much of each of the major continents.

C. Regional climate changes

Precise projections of future regional climate change are hampered by uncertainties in the details of how wind and ocean circulation patterns will change in response to human impacts on the climate. Of particular relevance in this context is the potential for changes in the ENSO phenomenon. While current-generation climate models perform reasonably well in reproducing El Nino-like behavior, they do not reproduce certain important features of the phenomenon, such as the detailed pattern of trade winds in the equatorial Pacific. Because the interaction between the trade winds and the ocean surface is an important component of El Nino, this means that these features, and in particular how they might respond to anthropogenic impacts on climate, are uncertain. The various state-ofthe-art climate models used in the IPCC's Fourth Assessment Report

¹⁰ This use of the phrase 'procrastination penalty' appears, for example, in Bill McKibben, "Warning on Warming," *The New York Review of Books*, March 15, 2007.

differ significantly¹¹ in their predictions of the expected future changes in the frequency and intensity of El Nino events in association with anthropogenic climate change. Indeed, there is no consensus as to whether or not El Nino events will be more frequent and of greater magnitude in the future. If this were to be the case, such a change would lead to increased winter precipitation in certain regions, such as the southwestern United States, which are currently predicted to suffer from increased drought, and decreased precipitation (and thus worsened drought conditions) in other regions, such as southern Africa.

Similar uncertainties exist in other climate phenomena influencing regional temperature and precipitation patterns, such as the so-called North Atlantic Oscillation or NAO, which is characterized by a fluctuation from year to year in the pattern of the jet stream over the North Atlantic ocean, primarily during winter. In its positive phase, the NAO brings relatively warm and rainy conditions to Europe, cold conditions to the northeastern United States, and dry conditions to the Middle East. The opposite, negative phase brings the opposite conditions in those regions. While it is currently not known with confidence how climate change will impact the NAO, some models indicate an increased tendency for the NAO to reside in its positive phase. If such predictions hold true, water resources could be further diminished in the already waterstarved Middle East.

It is also possible that changes in large-scale ocean circulation patterns such as the so-called ocean conveyor belt could impact regional climate, though in ways that cannot yet be confidently determined. The conveyorbelt circulation drives the poleward flow of warm, subtropical North Atlantic waters, providing a warming influence on Iceland and coastal regions of Europe. This circulation is driven by the sinking of cold saline waters in the subpolar regions of the North Atlantic ocean. In some simulations of the climatic response to anthropogenic greenhouse gas increases, the freshwater runoff to the ocean produced by melting polar ice leads to a significant weakening or even a shutdown of this ocean current system, since fresh water is less dense than saline water and inhibits the sinking motion that drives the conveyor-belt circulation. It has been speculated that such changes could, counterintuitively, trigger cooling in regions surrounding the North Atlantic (such as Europe) in response to global warming. Indeed, such speculation has fostered fictional popular accounts of the threat of another ice age as a result of anthropogenic influence on climate.¹² However, experiments with current-generation climate models

¹¹ See section 10.3.5.3 of chapter 10 of the Working Group I report: G. A. Meehl et al., "Global Climate Projections," in Solomon et al., eds., *Climate Change 2007: The Physical Science Basis.*

¹² It is this (flawed) scientific premise that provides the basis for the plot of the disaster movie *The Day After Tomorrow*, released by Twentieth Century Fox in 2004, written and directed by Roland Emmerich.

do not support such a scenario. Such experiments indicate, at most, only a moderate weakening of the ocean conveyor belt, damping but not erasing the warming predicted for Europe or other regions neighboring the North Atlantic as a result of increased greenhouse gas concentrations. It is nonetheless possible that a weakening of the conveyor-belt ocean circulation could have negative environmental or economic implications, threatening, for example, marine ecosystems and commercial fishing. Moreover, this is one of several examples where the changes could take place abruptly in response to gradual warming, because of "tipping points" in the way ocean circulation may respond to larger-scale climate changes. Such tipping points are of particular concern in evaluating the potential societal and environmental threat posed by future climate change. (See, for example, Section V below.)

D. Ice melt and rising sea levels

Among the most significant potential impacts of a warming climate are prospects for significant melting of the polar ice caps, and the related phenomenon of rising global sea levels. Even if we ceased fossil fuel burning today, the Earth's surface would continue to warm for decades, and the deep ocean would continue to warm for centuries due to the "committed warming" phenomenon referred to in Section III.A above. It is predicted that a combination of the thermal expansion of seawater and the melting of mountain glaciers associated with this warming will lead to between a third and a full meter of global sea-level rise by 2100 under the "business as usual" emissions scenario.¹³ It is possible, however, that the sea-level rise could be considerably greater.

The Greenland and Antarctic ice sheets, for example, may melt more rapidly than is currently projected by global climate models. Even stateof-the-art climate models typically employ a fairly primitive representation of ice sheet behavior. Recent observations reveal that there are a number of processes that appear to be active in actual ice sheet behavior but are not included in current models—processes which could lead to a more rapid collapse of ice sheets than those models predict. These processes include the formation of deep fractures called "moulins" that allow meltwater to penetrate to the base of the ice sheet, where they

¹³ This estimate is taken from a recent peer-reviewed study published in *Science* (S. Rahmstorf, "A Semi-Empirical Approach to Projecting Future Sea-Level Rise," *Science* 315 [2007]: 368-70), which was published too late for inclusion in the IPCC Fourth Assessment Report. This recent work suggests sea-level-rise estimates that are moderately higher than suggested in the IPCC report. While the IPCC report is widely recognized as the most comprehensive assessment of the peer-reviewed climate change research, one shortcoming of the report was that the contribution to sea level from melting continental ice sheets was ignored, simply because its contribution is uncertain. This decision insured that the magnitude of sea-level rise would be systematically underestimated in the IPCC report, and more recent work supports modestly higher estimates, as cited above.

encourage rapid sliding of the ice in the form of ice streams, and can lead to accelerated collapse of the continental ice sheet. Another such process is the buttressing effect of ice shelves. When ice shelves—thick sea ice flowing from inland glaciers out onto the ocean surface collapse, as did a large part of the famous Larsen Ice Shelf in February 2002, they can destabilize the inland glaciers, allowing them to break up and flow out to sea, also potentially accelerating the collapse of the continental ice sheet. If recent observations of such phenomena are indicative of a larger-scale pattern of changes in ice sheet behavior, it is possible that the ice sheets could collapse far more rapidly than predicted by current models (which project their collapse over a period of multiple centuries).

Paleoclimatic evidence suggests than most of the Greenland ice sheet, and some fraction of the Antarctic ice sheet, were absent roughly 120,000 years ago, when the Earth was perhaps only slightly warmer than at present. The destruction of the Greenland ice sheet would lead to roughly five meters of sea-level rise, enough to submerge substantial lowland and island regions of the world, including major parts of the U.S. Gulf and East coasts, roughly the lower third of Florida, large parts of the Netherlands and Belgium, and populated tropical low-lying regions such as Bangladesh. If, in addition, the west Antarctic ice sheet were to collapse (which recent observations indicate might indeed now be underway),¹⁴ the eventual sea-level rise could be closer to ten meters, submerging major U.S. coastal cities such as New York. While state-of-the-art coupled climate/ice sheet models currently predict that such sea-level rises might take several centuries to occur, it is possible that the rate could be considerably faster than those models predict due to processes such as those discussed above, which are currently not incorporated in the models. Moreover, because of the complex nature of these processes, it is possible that ice sheet collapse (and associated sea-level rise) could occur suddenly and irreversibly in response to smooth, steady warming-another possible climate-change tipping point.

E. Tropical cyclones

Climate change is likely to impact the characteristics of tropical cyclones (the strongest of which are known as "hurricanes" in the Atlantic ocean). Warming tropical ocean temperatures associated with global warming increase the maximum possible intensity, and thus the destructive potential, of tropical cyclones. In the Atlantic, where long-term data are available, a close relationship is observed between warming ocean temperatures

¹⁴ E. Rignot, "Recent Antarctic Ice Mass Loss from Radar Interferometry and Regional Climate Modelling," *Nature Geoscience* 1 (2008): 106–10.

in recent decades and the increased powerfulness of hurricanes.¹⁵ Though there appears to be a consensus that warmer ocean surface temperatures will favor increased tropical cyclone intensities, there is less agreement with regard to whether tropical cyclones will become less or more frequent in response to future climate change. Additional factors such as alterations in the large-scale atmospheric circulation can also influence the environmental favorability for tropical cyclone development. Increased wind shear (that is, winds of opposing directions or different strengths at different levels in the atmosphere), for example, can serve to create an unfavorable environment for the development of tropical cyclones because they interfere with the highly organized vertical circulation pattern required to maintain a tropical cyclone. Thus, even if warmer oceans tend to favor tropical cyclone development, if climate change also leads to an increase in the amount of wind shear in the atmosphere in a given region, fewer tropical cyclones may form. However, future changes in wind patterns are uncertain, due (for example) to the uncertainties in how climate change will impact ENSO, as discussed earlier.

IV. IMPACTS ON OUR ENVIRONMENT AND SOCIETY

The projected climate changes due to anthropogenic impact on the Earth's climate, as I have noted, include warmer surface temperatures, shifting patterns of rainfall, more widespread drought, rising sea levels, and more extreme meteorological conditions including flooding and intense tropical cyclones. These changes in climate are likely to have profound impacts on ecosystems, human health, water resources, agriculture, and the basic infrastructure that supports modern civilization. On balance, impacts are likely to be harmful, rather than beneficial, and include a greater tendency for drought and loss of water resources in some regions, widespread extinction of animal species, decreases in global food production, loss of coastline and coastal wetlands, increased severity of storm damage and flooding in many regions, and increased spread of infectious disease. These additional stresses on society could, in turn, lead to greater conflict. The extent of any such impacts will depend on the rate and amount of future warming, and on the nature of adaptations that are undertaken. In what follows, I will consider each of the various impacts in more detail.

A. Ecosystems

Climate change is likely to influence the functioning of ecosystems and to impact biodiversity. Plants and animals have established their current

¹⁵ K. Emanuel, "Increasing Destructiveness of Tropical Cyclones over the Past 30 Years," *Nature* 436 (2005): 686–88.

geographic ranges through long-term adaptation to seasonal climate patterns. Anthropogenic climate change is likely to alter those seasonal patterns on a timescale far more rapid than has occurred naturally over past millennia. It is this rapid rate of climate change which is likely to challenge the natural adaptive capacity of living things.

It has been estimated that anywhere from a fifth to a third of all plant and animal species are likely to be at an increased risk of extinction for an additional warming between 1.5 and 2.5°C,¹⁶ the range of warming predicted by 2100 in even the lower-range emissions scenarios. For warming in excess of 4.5°C, which is projected by some models for the higher-end emissions scenarios (e.g., in the aforementioned A1B scenario), as much as 40 percent of species would be at risk of extinction. Such widespread extinctions would, in turn, likely threaten the delicate balance and trophic structures of ecosystems, posing a wider threat to ecosystem function and services and biodiversity.

There are a number of mechanisms by which climate change is predicted to lead to species loss. In temperate regions, warming and shifts in seasonal patterns of precipitation are likely to confuse the seasonal cues controlling the timing of leaf-out of trees, egg-laying and hatching by birds and insects, and the seasonal migration patterns of birds, fish, and other migratory species. For high-latitude ecosystems, continued warming may threaten many of the so-called charismatic megafauna at the top of the food chain which rely on broken sea ice for hunting, such as polar bears and walruses. A number of climate-change impacts, such as warming oceans, decreased sea ice, and changes in ocean current systems and salinity patterns, are likely to impact algae and plankton populations, and therefore may threaten fish and other organisms which forage upon them. The second largest of all penguin species, the Antarctic King penguins, for example, may be threatened by continued warming of the ocean, which appears to be decreasing the populations of the small fish they feed on in their region of winter foraging at the northern edge of the Antarctic continent.17

Climate change is likely to cause the destruction of rare and fragile habitats that are home to "specialist species" unable to thrive in other environments. For example, the coastal wetlands, salt marshes, and mangrove swamps that are home to many rare species are threatened by rising sea levels. Certain amphibian species such as the golden toad,¹⁸ whose habitats are limited to certain isolated tropical cloud forests, have

¹⁶ M. L. Parry et al., "Summary for Policymakers," in *Climate Change* 2007: *Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge and New York: Cambridge University Press, 2007).

¹⁷ C. Le Bohec et al., "King Penguin Population Threatened by Southern Ocean Warming," *Proceedings of the National Academy of Sciences* (2008): 10.1073/pnas.0712031105.

¹⁸ See J. Alan Pounds et al., "Widespread Amphibian Extinctions from Epidemic Disease Driven by Global Warming," *Nature* 439 (2006): 161–67.

either met or are meeting their demise as these environments literally disappear in response to warming atmospheric temperatures.

In many cases, the combined stresses of climate-change impacts and other anthropogenic disturbances to the environment, such as changing land-use patterns and pollution of the atmosphere and oceans, pose a significantly greater threat to ecosystems than does any one of these stresses alone. Nowhere else is this phenomenon better illustrated than with coral reef systems, which contain much of the ocean's biodiversity.¹⁹ Threats to the viability of coral reefs include increased incidence of "bleaching" (a loss of symbiotic algae at high water temperatures) due to warming oceans, and damage to reefs by increasingly destructive tropical cyclones. These effects are likely to add to stresses from increased ocean acidification (also a result of anthropogenic increases in atmospheric carbon dioxide concentrations) and marine pollution. Another example of the confluence of multiple stresses is the threat to migratory animals that are likely to encounter physical impediments from human constructions, such as highways and fences, as they attempt to migrate away from increasingly inhospitable climatic conditions. Destruction of coastal wetlands and other habitats due to human development also compound the stresses on ecosystems.

B. Human health

Human health will likely be detrimentally impacted by climate change in a number of different ways, including through greater spread of infectious disease, increased incidence of environment-related health afflictions (including heat stress), and more widespread malnutrition.

Infectious disease is likely to become more widespread as the geographical ranges and seasonal windows of activity of disease vectors such as insects and rodents widen with warmer temperatures. For example, the unusually warm winter of 1999 in New York State led to an outbreak of the West Nile virus.²⁰ In the southwestern United States, alternations between drought and floods related to ENSO have created conditions favorable for the rodent-spread hantavirus,²¹ while the spread of mosquitoborne Rift Valley fever in equatorial east Africa was related to wet conditions associated with ENSO.²² To the extent that climate change leads to

¹⁹ O. Hoegh-Guldberg et al., "Coral Reefs Under Rapid Climate Change and Ocean Acidification," *Science* 318 (2007): 1737–42.

²⁰ D. S. Asnis et al., "The West Nile Virus Encephalitis Outbreak in the United States (1999–2000)," Annals of the New York Academy of Sciences 951 (2001): 161–71.

²¹ B. Hjelle, and G. E. Glass, "Outbreak of Hantavirus Infection in the Four Corners Region of the United States in the Wake of the 1997–1998 El Niño–Southern Oscillation," *Journal of Infectious Diseases* 181 (2000): 1569–73.

²² K. J. Linthicum et al., "Climate and Satellite Indicators to Forecast Rift Valley Fever Epidemics in Kenya," *Science* 285 (1999): 397-400.

a greater number of large ENSO events, climate change could increase the spread of infectious disease indirectly through its impacts on ENSO.

Among other afflictions which may be worsened by climate change are diarrhea, cardio-respiratory illness, and allergic reactions to increased levels of pollen in extratropical regions experiencing longer growing seasons.²³ Moreover, global warming may also worsen air pollution by increasing concentrations of ozone, which in the lower atmosphere is a pollutant that irritates the human lung. Warming air temperatures both increase ozone production and promote stagnant atmospheric conditions, which favors the accumulation of high levels of ozone in the lower atmosphere. Urban areas, already suffering under increased pollution, are likely to experience especially large increases in pollution. One recent study, for example, estimated the potential for an increase of 1,000 pollution-related deaths in the United States and 20,000 worldwide (and an increase in nonfatal respiratory illnesses) for each degree Celsius of additional warming.²⁴

Heat stress represents an additional climate-change health threat. Heat waves represent a significant threat, particularly in regions where air conditioning is not widely available, and for the very young or elderly, who are least physiologically able to tolerate extreme warmth. During the European heat wave of 2003, for example, European fatalities neared 35,000.²⁵ Most of those who perished were elderly people who were unable to escape the persistent and oppressive heat. It is highly likely that heat waves will become more common and more intense with global warming.²⁶ For example, heat waves that previously might have been considered one-in-one-hundred-year events could in many regions become one-in-two-year events, because of the dramatic impact that surface warming of even one or two degrees Celsius has on the probability of short-term periods of extreme warmth.

Finally, worsened malnutrition is a likely consequence of climate change, due to reduced agricultural and livestock yields in many underdeveloped countries already afflicted by food shortages. The impacts of climate change on agriculture and farming are discussed in more detail below.

C. Agriculture and farming

Agricultural productivity may increase modestly overall in extratropical regions in response to a local warming of 1 to 3°C.²⁷ Similar increases

²³ U. Confalonieri et al., "Human Health," in M. L. Parry, et al., eds., *Climate Change* 2007: *Impacts, Adaptation, and Vulnerability*, 391–431.

²⁴ M. Z. Jacobson, "On the Causal Link between Carbon Dioxide and Air Pollution Mortality," *Geophysical Research Letters* 35 (2008): L03809, doi:10.1029/2007GL031101.

²⁵ See, e.g., S. Bhattacharya, "European Heatwave Caused 35,000 Deaths," *New Scientist*, October 10, 2003.

²⁶ Ibid., 11.

²⁷ W. E. Easterling et al., "Food, Fibre and Forest Products," in Parry et al., eds., *Climate Change* 2007: *Impacts, Adaptation, and Vulnerability*, 273–313.

are expected for livestock productivity, since this relies on feed stocks which are themselves agricultural products. These increases are primarily a result of the lengthening of growing seasons in temperate regions associated with large-scale warming. However, for even greater amounts of warming, agricultural productivity begins to fall off, since such warming begins to rise above the optimal temperature levels for photosynthetic activity that plants have evolved through long-term evolution. In tropical and subtropical regions, crop productivity is projected to decrease for even weak local warming because essentially any warming exceeds these optimal temperature levels. Increased incidence of droughts and flood events may lead to further declines in agricultural and farming productivity, with the impacts influencing subsistence farmers most severely. In regions such as the African Sahel, decreases in agricultural productivity have already been observed due to a reduced growing season resulting from warmer and drier conditions. One problematic aspect of the projected trends in agricultural productivity is that they differentially threaten the tropical regions and, thus, the developing world, while (at least in the near term) benefiting the extratropics and, hence, the developed world. In this sense, climate change represents a redistribution of resources from the poor to the well off, a troubling ethical implication that I will discuss in more detail later (in Section V.C).

D. Water resources

Water resources are also likely to be substantially impacted by climate change. At current rates of warming, by the middle of this century a 10 to 40 percent increase in average river runoff and water availability has been projected in higher latitudes and in certain wet regions in the tropics, while decreases of similar magnitude are expected in other parts of the tropics, and in the dry regions of the subtropics, particularly in summer.²⁸ In many cases, water availability is decreasing or expected to decrease in regions that are already stressed for water resources, such as the African Sahel, western North America, southern Africa, and western Australia. In those regions, drought is likely to increase in magnitude and extent, with negative impacts (see above) on agriculture and the raising of livestock. Increased and earlier spring runoff is already being observed in extratropical regions with glacial or snow-fed streams and rivers, such as western North America. Fresh water currently stored by mountain glaciers and snow in both the tropics and the extratropics is projected to decline, reducing fresh water availability for more than 15 percent of the world's population which relies upon these freshwater sources. It is also likely that warming temperatures, through their impact on biological

²⁸ Z. W. Kundzewicz et al., "Freshwater Resources and Their Management," in Parry et al., eds., *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, 173–210.

activity in lakes and rivers, may have an adverse impact on water quality, further diminishing access to safe water sources for drinking or farming. Risk-management procedures are already being taken by some countries in response to expected changes in water availability.

E. Energy

Energy availability and use will both be impacted by climate change. Warmer conditions will almost certainly fuel increased energy demand for air conditioning. This will be partially offset by decreased energy demand for winter heating in extratropical regions. Any such changes in energy demand will be superimposed on a continually increasing percapita demand for energy as the underdeveloped world industrializes, and a global population likely to increase for at least the next few decades.

Climate change will not only influence energy resources through its impact on energy demand. There are also ways in which climate change could impact energy supply. Shifting water resources as a result of the changing patterns of rainfall discussed earlier could impair energy production. Most current methods of energy generation require water either directly, such as hydroelectric and hydrothermal energy generation, or indirectly by steam turbines in coal-fired power plants, or as a coolant in nuclear power plants. Such energy sources are therefore likely to be diminished in regions with reduced water supplies. Increasing use of certain other methods of energy generation could both ameliorate this threat and contribute toward the mitigation of the greenhouse gas emissions responsible for projected climate changes. I discuss such issues below in Section VI.

F. Societal infrastructure

Projected climate changes pose numerous threats to societal infrastructure. As is true with many other climate-change impacts, poor communities and nations, with their limited adaptive capacities, are likely to be disproportionately impacted.²⁹ Among the more damaging impacts are possible increases in certain types of severe weather (e.g., hailstorms, tornadoes, and tropical cyclones), the predicted tendency in some highly populated regions for increased frequency of heavy flooding, and the likely increase in wildfire threats over regions such as western North America, as a result of dryer conditions, decreased snow-pack, and thus decreased summer ground moisture, all favoring a longer fire season.³⁰ Such increases will threaten homes, dams, and other human infrastructure. In high-latitude and mountain regions, melting permafrost is likely

²⁹ T. J. Wilbanks et al., "Industry, Settlement, and Society," in Parry et al., eds., *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, 357–90.

³⁰ Å. L. Westerling et al., "Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity," *Science* 313 (2006): 940–43.

to lead to ground instability or rock avalanches, further threatening structures in those regions. Increased coastal vulnerability due to sea-level rise and the potential for increased severity of tropical cyclones and hurricanes represents a heightened threat to coastal infrastructure throughout the world. An additional warming of 1 to 3°C, it has been estimated, will threaten millions more people with the risk of annual flooding. Densely populated poor low-lying regions in Africa, Asia, and island nations will be most vulnerable due to their limited adaptive capacity, but regions of developed nations such as the low countries of Europe and the East and Gulf coasts of the United States will also be vulnerable in higher-end sea-level rise scenarios. Adaptive steps are already being taken by some governments through the building of dams and drainage works in response to the increased coastal vulnerability expected from projected future climate changes.

V. EVALUATION OF THE THREAT

One of the challenges faced by society involves how to weigh the potential costs and benefits of dealing with the climate-change threat. It is useful in this context to focus on three key kinds of considerations. The first of these—and perhaps the more straightforward—are the economic considerations, which weigh the potential financial costs of adaptation and mitigation against the benefits of thwarting the various threats to our environment and societal infrastructure associated with climate change. The second of these, the potential threat to our security, is somewhat more speculative but no less significant. The third of these are ethical considerations, which are more fundamentally philosophical, yet equally if not more important than the other two kinds of considerations. Ethical considerations focus on issues such as justice and equity that are central to human civilization as it struggles to deal with the challenges of climate change. I discuss each of these considerations in more detail below.

A. Economic considerations

Obviously, any analysis of the economic implications of climate change and climate-change mitigation must weigh the costs of combating climate change against the benefits of doing so (alternatively viewed as the costs of *inaction*). For example, the immediate costs of dramatic reductions in fossil fuel burning are known to potentially be quite large. However, only recently have there been systematic analyses of the benefits of taking action. Such costs and benefits are typically evaluated through a type of cost-benefit analysis known as "integrated assessment." In this context, integrated assessments are performed by coupling climate model projections to economic models.³¹ The impacts are typically quantified in terms of the fractional change of gross domestic product (GDP) that can be expected given a particular climate-change scenario. By driving the climate models with a range of possible emissions scenarios, both the costs and the benefits for a given scenario can be estimated in terms of a projected change in GDP. (This is typically expressed in current dollars, i.e., adjusting for future assumed inflation.) There are a number of implicit assumptions in these estimates, some of which are potentially limiting and arguably quite problematic.

One of the primary limitations of these analyses is the use of very crude "energy balance" climate models (see Section II.E above) to generate climate-change projections. When such simple climate models are used, impacts must be based solely on estimated changes in global average temperature, the single variable predicted by the models. Yet, as we have seen (see Sections III.C and III.D), many of the most significant potential climate-change impacts, such as the potential for rapid sea-level rise or possible abrupt changes in ocean circulation, represent possible tipping points that cannot simply be linked to the smoothly evolving long-term changes in global temperature, and for which both the probability and timing of occurrence is unknown. Perhaps even more problematic, the economic estimates do not take into account so-called externalities-that is, the intrinsic value of natural ecosystems and our environment, which are under threat from climate change as detailed in Section IV of this essay. This oversight is, of course, a special case of the well-known "tragedy of the commons." 32 Finally, there are deep ethical considerations, which are not incorporated at all in traditional economic cost-benefit analyses (see subsection C below for a more detailed discussion).

The cost-benefit calculations typically involve an estimate of the so-called social cost of carbon (SCC), which is defined as the marginal benefit at some point in time of reducing carbon emissions, often evaluated in U.S. dollars per ton of atmospheric carbon produced. The SCC depends on several factors, including the projected costs of climate-change damages caused by rising carbon dioxide concentrations. A complicating factor is the so-called social discount rate, which measures the degree to which consumption now is preferred to consumption at some time in the future (with prices held fixed, but assuming that incomes rise at the same rate as per-capita GDP).

There is no common agreement upon what the social discount rate should be in the context of climate-change mitigation. Unlike standard

³¹ See, e.g., W. D. Nordhaus, "To Slow or Not to Slow: The Economics of the Greenhouse Effect," *The Economic Journal* 101 (1991): 920–37; and W. D. Nordhaus, "Economic Approaches to Greenhouse Warming," in *Global Warming: Economic Policy Responses*, ed. R. Dornbusch and J. M. Poterba (Cambridge, MA: MIT Press, 1991).

³² This concept was first described by W. F. Lloyd, *Two Lectures on the Checks to Population* (Oxford: Oxford University Press, 1833).

financial discounting, there are substantial uncertainties in climatechange impacts that make it difficult and, perhaps, impossible to predict the precise impacts that will result from a given pattern of greenhouse gas emissions. Such uncertainties render standard economic discounting approaches (e.g., setting the rate equal to the return on treasury bills)³³ invalid, because the choice of discount rate reflects the level of confidence that society will be able to solve environmental problems as they arise. Yet these levels of confidence may have no underlying scientific foundation where there are tipping points such as those discussed above that could lead to unpredictable, dramatic, and irreversible changes in climate with potentially catastrophic damage costs. For example, if we cross a threshold wherein we set in motion the irreversible melting of the major ice sheets, we could be faced with an inevitable sea-level rise of ten meters or more, which would insure the destruction of a large number of major cities throughout the world, including New York. While perhaps unlikely given our best current scientific assessments, it is conceivable that this rise could take place over the course of a century. If so, the damages would be essentially incalculable and, for all intents and purposes, the costs can be considered infinite. There is a disaggregation between those primarily causing climate change (i.e., emitters from industrialized nations) and those most likely to suffer the damages of climate change (in large part, the poorest people in the developing world). Climate-change mitigation also involves an intergenerational transfer of wealth and utility, since current generations gain (e.g., from access to cheap energy) at the expense (e.g., from a degraded environment) of future generations. Aside from introducing some troubling ethical implications (which I will discuss later), such issues pose a major challenge to conventional cost-benefit approaches, which are ill-equipped to deal with the complications introduced by such disaggregation or intergenerational transfer issues.

The net result of these complications is that economic models are relatively unconstrained with regard to the social discount rates they employ. Coupled with the fact that the choice of which strategies are more optimal (e.g., little versus major near-term investment in mitigation of greenhouse gas emissions) is highly sensitive to the discount rate used, this lack of constraint means that conclusions as to whether or not to mitigate climate change from economic models are not especially robust. Some of the earlier economic studies by leading researcher William Nordhaus assumed a fairly high discount rate of 6 percent.³⁴ At such high levels of discounting, the economic models tend to favor a delay in the mitigation of greenhouse gas emissions in favor of near-term gains of higher GDP. More

³³ Most serious economists would not advocate such a choice for the social discount rate. Nonetheless, libertarian activists sometimes do. See, e.g., J. Taylor, "Nordhaus vs. Stern," http://www.cato-at-liberty.org/2006/11/28/nordhaus-vs-stern/.

³⁴ See, e.g., W. D. Nordhaus, ed., *Economics and Policy Issues in Climate Change* (Washington, DC: Resources for the Future, 1998).

recent studies by Nordhaus have assumed a considerably more stringent 3 percent discount rate.³⁵ (Notably, some advocates against greenhouse gas mitigation continue to misrepresent Nordhaus's work by citing the higher rates from his older work and ignoring the considerably lower rates he has favored in his more recent work).³⁶ Other researchers have argued for even lower rates. Most notably, Sir Nicholas Stern, head of the Government Economic Service in Great Britain, argues for a 1.4 percent social discount rate based on ethical principles (in particular, that it is wrong to discount the utility of future generations who will suffer the consequences of our actions today).³⁷

Whether one adopts the very low (1.4 percent) rate advocated by Stern (which amounts to an SCC in the range of \$160/ton of atmospheric carbon, according to one estimate), or the modestly higher (3 percent) rate advocated by Nordhaus (which amounts to an SCC of roughly \$60/ton), the economic model calculations generally indicate that we should invest significantly in the mitigation of greenhouse gas emissions to forestall the damages posed by the higher-end emissions scenarios. In the low-range (B1 and B2) through "business as usual" (A1B) emissions scenarios, which collectively are likely to lead to a 1 to 4°C overall warming of the globe (see Section III.A above), losses are likely in certain, but not all, economic sectors. Losses are predicted to be especially great in tropical and high-latitude regions, while other regions could potentially benefit.³⁸ For warming in excess of 4°C, costs are estimated to clearly exceed benefits overall, with aggregate global economic losses estimated to be between 1 and 5 percent of the global gross domestic product (GDP).

Though scientific uncertainty is sometimes argued as a reason to delay taking action to mitigate climate change, incorporation of uncertainty into the economic models actually leads to the conclusion that an even greater near-term investment should be made.³⁹ This feature arises from the "heavy-tailed" nature of the statistical distribution of climate-change damages, that is, from the fact that uncertainty leads to the existence of low-probability, but extremely high-cost scenarios (e.g., the tipping-point example of abrupt and irreversible sea-level rise discussed above). Indeed, such considerations can be argued to motivate—even within the context of standard cost-benefit analysis—the so-called precautionary principle,⁴⁰

³⁵ W. D. Nordhaus, "Critical Assumptions in the Stern Review on Climate Change," *Science* 317 (2007): 201–2.

³⁶ See, e.g., Lomborg, *Cool It.*

³⁷ N. Stern, *The Economics of Climate Change: The Stern Review* (Cambridge: Cambridge University Press, 2007).

³⁸ S. H. Schneider et al., "Impacts, Adaptation, and Vulnerability," in Parry et al., eds., *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, 779–810.

 ³⁹ See, e.g., David Biello's interview of economist Gary Yohe of Wesleyan University, in D.
Biello, "Clash: Gary Yohe," *Scientific American*, November 26, 2007.
⁴⁰ C. Raffensberger and J. Tickner, eds., *Protecting Public Health and the Environment: Imple-*

⁴⁰ C. Raffensberger and J. Tickner, eds., *Protecting Public Health and the Environment: Implementing the Precautionary Principle* (Washington, DC: Island Press, 1999).

that is, the principle that the burden of proof in policymaking, in the presence of significant scientific uncertainty, falls upon those advocating inaction, where such inaction has the potential to cause extreme and/or irreversible societal or environmental harm. In essence, the finite probability of catastrophic damages imposes an essentially infinite expected cost on inaction. In the presence of such infinite expected costs, cost-benefit analysis will indicate taking whatever mitigation measures are available, short of those which might incur essentially infinite costs themselves.

Standard economic considerations dictate that society will act to reduce carbon emissions as long as the SCC exceeds the costs associated with emissions reduction. This means that the SCC can be regulated by governments (e.g., through taxes on carbon, or through tradable carbonemission credits) in such a way as to insure that net carbon emissions are kept below some level, e.g., the level perceived to constitute "dangerous anthropogenic interference" with the climate (see the discussion at the beginning of Section III). Indeed, a carbon trading scheme has already been initiated in Europe.⁴¹

B. Security considerations

There is a popular misconception that concern over climate-change impacts is confined to political progressives. Yet, quite to the contrary, a constituency typically more thought of as being aligned with the conservative end of the political spectrum—the national defense community—has increasingly become concerned with the threats that climate change may increasingly pose to national security in the future.⁴²

Irrespective of climate change itself, reliance on fossil fuels naturally threatens the national security of nations such as the United States by placing them at the mercy of volatile foreign regimes in satisfying their energy needs. There are also direct threats of climate change itself to national security. Paramount among these threats is the defense of national borders. A case in point relates to the dramatic melt-back of Arctic sea ice

⁴¹ The European Union Carbon Emission Trading scheme covers slightly less than half of the EU's energy- and industry-related greenhouse gas emissions. Emission allowances or "permits" are apportioned to major emitters for a period of several years at a time. The scheme requires emitters to monitor and report their emissions, and to return to the government a number of permits that is equivalent to their emissions on an annual basis. Permits can be bought from other emitters or the government as needed, or sold when they are available in excess of what is required by the emitter, thus creating a tradable emissions market. Upon instituting this scheme in 2005, the price of carbon credits began near the low end of the range of SCC estimates cited in the text, but then rose to around US\$100/ton, close to the mid-range of estimates, before falling in 2006 (because the credits were believed to have been too generous). These fluctuations all fall within the range of SCC estimates cited in the text.

⁴² K. K. Campbell et al., *The Age of Consequences: The Foreign Policy and National Security Implications of Global Climate Change* (Washington, DC: Center for Strategic and International Studies, 2007).

witnessed during the summer of 2007. Sea ice retreated to a record minimum of under 3.5 million square kilometers (for comparison, the longterm average annual minimum is roughly 6 million square kilometers). With this dramatic retreat came the opening of the Northwest Passage, an ice-free path through the Arctic ocean connecting the Atlantic and Pacific ocean basins that had remained elusive in modern history, though its fleeting existence in the past had been anecdotally reported. While the record 2007 melt-back might have represented an isolated anomaly, the summer of 2008 has also witnessed anomalous Arctic sea ice melt. Indeed, in the "business as usual" climate-change projections, an open Arctic ocean is forecast to be commonplace in a matter of decades. Such an open Arctic ocean would pose obvious national defense challenges. Nations in North America and Eurasia would have to defend new Arctic coastlines against the threat of potential military attack and/or illegal immigration.

Climate change also represents a security threat through the increased competition it may create among nations for diminished basic resources such as food, water, and energy. Historically, increased stress for resources has favored sociopolitical instability: for example, the election of populist demagogic leaders. Climate change, of course, threatens to introduce precisely such threats. Decreased or unreliable precipitation and runoff patterns are likely to create increased competition for available freshwater resources. In regions such as the Middle East, where there is a history of sociopolitical conflict over religious differences and valuable oil rights, the tentative climate model projections of decreased freshwater resources can only add to the volatile mix of factors underlying sociopolitical conflict.

Sea-level rise and other factors that make currently inhabited regions inhospitable to human societies (e.g., expanded patterns of drought, and conditions unfavorable for agriculture and farming) are likely to create increased competition for the remaining habitable land. Indeed, the term 'environmental refugee' has been coined to describe individuals fleeing their homelands because of drought, desertification, and other environmental factors placing stress on essential resources. An estimated 25 million people were classified in 1995 as environmental refugees,⁴³ more than the number of refugees due to civil war or religious persecution. Among these 25 million were roughly 5 million who have fled the recent droughts in the African Sahel (the 10 million who left minus the 5 million who returned), and at least another 7 million who have fled other parts of Sub-Saharan Africa in order to obtain relief food.⁴⁴

When added to the pressures of a considerably expanded global population by the mid twenty-first century (projected at roughly 9 billion, a 33 percent increase above the 2008 level of just under 7 billion), the stresses

⁴³ N. Myers and J. Kent, *Environmental Exodus: An Emergent Crisis in the Global Arena* (Washington, DC: The Climate Institute, 1995).

⁴⁴ N. Myers, "Environmental Refugees: Our Latest Understanding," *Philosophical Transactions of the Royal Society B* 356 (2001): 16.1–16.5.

on available water, land, and food resources created by climate change could foster an environment that is rife for heightened global conflict. As nations around the world exceed their capacity to adapt to the changing climate, competition for dwindling resources could lead to increased violence and potentially even societal destabilization. A combination of worsened drought, oppressive temperatures, and rising sea levels could, by the mid twenty-first century in some scenarios, displace a large enough number of environmental refugees to challenge the ability of surrounding nations to accept them. A possible scenario threatening the United States is one in which drought and decreased river runoff in the desert Southwest place further stress on water- and resource-starved northern Mexico, leading to increased migration to the U.S. and placing further stress on already delicate diplomatic relations between the governments of the U.S. and Mexico. Security experts have described worst-case scenarios that are not so unlike those depicted in post-apocalyptic theatrical productions.

C. Ethical considerations

While much attention in the popular discourse on climate change has been given to the economic considerations discussed in Section V.A, disappointingly little attention has been given by comparison to the equally important ethical considerations. Such considerations are intrinsic even to interpreting the objective of the Kyoto Protocol, which is to insure the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." This objective begs a number of ethical questions. How do we define what constitutes "dangerous"? And "dangerous" to whom? To answer such questions, we must consider political, cultural, and philosophical principles that are fundamentally ethical in nature.

In some cases, the relevant ethical principles are rooted in religious precepts and the words of the Bible. A widely accepted religious principle is that mankind should serve as "stewards of the Earth," and "protectors of creation." As such, this principle holds that we are bound by a moral covenant to protect the Earth, its environment, and all its creatures. In support of these principles, evangelical leaders in the United States have recently engaged in a campaign to raise awareness of major environmental threats, including climate change, among their followers.⁴⁵

Another key ethical principle that comes into play in the context of climate change is equity. Issues of equity include distribution of the risks,

⁴⁵ Press Release (National Association of Evangelicals): "Evangelical, Scientific Leaders Launch Effort to Protect Creation" (January 17, 2007). The coalition released an "Urgent Call to Action" statement signed by twenty-eight evangelical and scientific leaders, describing a joint effort to protect the environment against human-caused threats to Creation—including climate change, habitat destruction, pollution, species extinction, the spread of human infectious diseases, and other dangers to the well-being of societies.

benefits, responsibilities, and costs of climate change in a way that is fair to both developed and developing nations. Climate change is likely to lead to substantial regional redistributions of wealth and resources, due to impacts on food production, freshwater availability, and health. In this redistribution, there will be winners and losers. Unfortunately, in most cases, negative climate-change impacts, including decreased freshwater supply, decreased food production, and disease and loss of land, appear likely to disproportionately impact the tropical, largely developing world. By contrast, at least in the short run, extratropical regions dominated by the developed nations may actually benefit from climate change, through longer growing seasons and associated benefits for agricultural productivity. Further exaggerating this inequity is the fact that the developing world, by virtue of its relative poverty and lack of technological infrastructure, is more vulnerable to the threats posed by climate change. For these reasons, it is often argued on ethical principles that the developed world has a responsibility to assist developing nations both in adapting to inevitable climate changes and in minimizing future detrimental climate change and its impacts.

There are other implications of justice considerations that come into play involving fossil fuel burning itself. The developed world has already had an opportunity to benefit from more than a century of inexpensive energy in the form of fossil fuels. It might therefore seem somewhat of an injustice to mandate that developing nations, who are just now beginning to build their energy infrastructures, should not also get such an opportunity. This challenging ethical dilemma complicates any determination of the appropriate burden of mitigation efforts, and the appropriate distribution of emissions rights among nations.

There are additional problematic ethical issues that arise from the generational transfer of the benefits and costs of fossil fuel burning. These issues are often hidden in seemingly objective economic cost-benefit analyses such those discussed above in Section V.A, which implicitly make key ethical judgments in the determination of an appropriate social discount rate. Discounting places a greater value on benefits today at the expense of costs to subsequent generations, under the assumption that those generations will have access to technology that enables them to deal with any of the resulting environmental threats and dangers. If this assumption leads us to posit high social discount rates, we essentially insure that a policy of inaction will be chosen. Yet such high discount rates neglect the impact of uncertainty and, in particular, the potential looming threats associated with abrupt and irreversible changes in climate. A valid argument holds that it is simply unfair-and indeed unethical-to take the gamble that we will be able to solve the future environmental problems caused by our patterns of behavior today. If we lose out in that gamble, it is subsequent generations, rather than us, who will bear the brunt of the ensuing damages.

Further ethical complications, as discussed earlier, arise from the disaggregation of the costs and benefits of fossil fuel burning. Simply put, the individuals who gain from current fossil fuel burning in the form of cheap energy are not the same as the individuals who stand to lose due to the negative impacts of the resulting climate changes. It is questionable whether or not we can assign meaningful costs to human mortality due to starvation and other ill health impacts of climate change. Such impacts will be disproportionately felt by the poor and disadvantaged citizens of developing countries. It is unclear that the value of their lives can be meaningfully incorporated in standard economic cost-benefit calculations.

Finally, there are ethical dilemmas which arise when considering options for mitigation of climate change (the subject of Section VI below). For example, how do we go about incentivizing compliance with international emissions agreements and penalizing noncompliance? Is there a role for punitive actions in the latter case? Addressing such issues in a satisfactory manner will require delicate international negotiations.

VI. Adaptation and Mitigation of Climate-Change Impacts

As I discussed in the previous section, economic, security, and ethical considerations all seem to point toward taking precautions to protect society and the environment against the threats posed by major climate changes. Yet there is still fierce debate over precisely how we go about achieving such protection. In fact, there are a number of different approaches that have been articulated for how society should go about confronting climate change. In one approach—"adaptation"—we accept at least some amount of climate change as inevitable, and find ways to deal with the challenges and solve the problems created by climate change. In the other approaches, each of which constitute some form of "mitigation," we seek to either prevent or offset the climate changes which constitute a threat. Each of the approaches possesses potential weaknesses or obstacles for implementation. The approaches in general are not mutually exclusive, and it is thus likely that we will need to consider a combination of approaches if we are to protect ourselves and our environment from the threats posed by climate change.

A. Adaptation

As we have seen above (see Section III.A), even the most optimistic scenarios for the future path of fossil fuel burning might still lead to dangerous climate change. It is thus arguable that society will be faced with required adaptation in any plausible scenario. The problem with adaptation as a sole strategy is that, in most if not all realistic future emissions scenarios, many of the predicted climate-change impacts are also likely to exceed the capacity for humans (or ecosystems, for that matter) to adapt. These considerations lead us to the inevitable conclusion that we will have to combine elements of both adaptation *and* mitigation (see below), perhaps combined with technological innovations (see Section VI.D below), to cope with the challenges posed by climate change.

Vulnerability to climate change is related to adaptive capacity, namely, the ability to respond (either through behavior changes or the development and use of appropriate technology) to climate variability and change in a way that mitigates the negative impacts of that change or variability. Yet, as I discussed in Section V.C, there is great variability in this capacity among different societies, with wealthier developed nations such as the United States possessing significantly greater adaptive capacity (and thus, less vulnerability) than the developing world (e.g., Africa). While there are many examples, particularly salient examples can be found in the potential adaptive responses to sea-level rise and agriculture. In the case of sealevel rise, wealthy nations (e.g., the low countries of Europe) have the technology and financial resources to build coastal defenses, while poor tropical regions that find themselves similarly threatened, such as Bangladesh, do not. With regard to agriculture, wealthy extratropical nations such as the United States have the resources (e.g., access to a large force of inexpensive farm workers) to take advantage of longer growing seasons while limiting the downside of more widespread drought through sophisticated irrigation and water-management schemes. By contrast, nations in tropical west Africa which are almost certain to see less favorable growing seasons do not have access to sophisticated irrigation systems or other technology that might help to mitigate deleterious climate-change impacts.

"Business as usual" climate-change projections for 2100 indicate that the adaptive capacities of even the developed world are likely to be exceeded.⁴⁶ Analyses indicate that strategies for increasing adaptive capacities over time (that is, "learning") can reduce, but not eliminate, vulnerability for most regions and nations. Coupled with substantial mitigation efforts, however, it may be possible for most nations to avoid breaching the limits of their adaptive capacity (though the developing world and, in particular, Africa, China, and much of South America, are likely to remain vulnerable to climate-change impacts). While mitigation strategies may largely benefit the developing world in the short run, the developed world too will benefit significantly in the long run (e.g., by the end of the current century) based on comparisons of climate-change projections between the lower-end and mid-range emissions scenarios.

B. Mitigation: Reducing energy demand

The simplest approach to decreasing global greenhouse emissions is to decrease the demand for energy which drives these emissions. This task

⁴⁶ W. N. Adger et al., "Adaptation Practices, Options, Constraints, and Capacity," in Parry et al., eds., *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, 717–43.

is, alas, not a simple one, as energy demand underlies nearly all aspects of modern life and major sectors of the world economy such as transportation, agriculture, forestry, and waste management.

First and foremost, there are changes we can make in our personal lifestyles that can greatly reduce our personal energy demand, and thus our "carbon footprints." In many cases, these are "no regrets" changes that have side benefits that make them worth doing irrespective of the reduction in energy use, benefits including improved health and quality of life, conservation of natural resources, and smaller energy expenses.

Examples of "no regrets" domestic strategies include home improvements that decrease required winter heating and summer cooling. These improvements include better insulation, use of passive solar heating in cold months, and substituting window fans and opening windows in place of using air conditioning in warm months. Another measure that can be taken involves replacing older and inefficient incandescent lightbulbs with far less power-consuming compact fluorescent bulbs. Since a significant amount of energy is used in the manufacturing sector to process new raw materials, there is substantial opportunity for saving energy by recycling disposable items such as newspaper and waste paper, cans, bottles, plastic containers, and cardboard boxes. Appliances that are not used frequently can be unplugged, reducing "leakage" of unused, dissipated power.

Altering our personal transportation patterns can provide tremendous potential energy savings while yielding other benefits. Commuting to work by bicycle or by foot combines personal fitness and commuting activities. Such measures, or other transportation choices such as public transport and carpooling, have the desirable added benefit of reducing traffic congestion and improving air quality. Reduced gasoline consumption has the added national security benefit of reducing our collective reliance upon volatile foreign regimes for energy. Reduced personal use of gasoline also leads to lower gasoline bills.

While individuals can accomplish many of the energy reductions outlined above, there is also an important role for companies, governments, and nongovernmental organizations. Companies can establish training and reward systems that encourage employees to reduce energy consumption. Governments and nongovernmental organizations can provide educational programs aimed at teaching energy-conservation principles, and campaigns aimed at encouraging individuals to make environmentally conscious decisions in their daily lives.

C. Mitigation: Moving away from a carbon-based energy infrastructure

Mitigation of greenhouse gas emissions can go only so far based solely on attempts at increased energy efficiency such as those described above. To prevent greenhouse gas concentrations from reaching levels that may threaten to cause dangerous interference with the climate, it will be necessary to move toward practices that do not pollute the atmosphere with increased greenhouse gases such as carbon dioxide and methane (as well as other secondary greenhouse gases such as nitrous oxide).

Given the global scope of anthropogenic greenhouse gas emissions, it is generally agreed that widespread observance of international negotiated treaties such as the Kyoto Accord is necessary to achieve the required reductions in carbon emissions. However, while many nations have indeed signed on to the Kyoto Accord, and are prepared to sign on to even more stringent fossil fuel emissions treaties, the two largest emitters of greenhouse gases-the United States and China⁴⁷-have not. In the absence of these major emitters agreeing to reduce their emissions, it is unlikely that any significant progress can be made in the mitigation of global greenhouse gas emissions. This is because there are few economic incentives for reducing emissions, especially in the two largest emitting nations, the United States and China, whose very large economies are currently essentially fossil fuel dependent. It is arguable that these nations will only sign on to global greenhouse gas reductions if forced to do so based on economic considerations and, specifically (see Section V.A), when the social cost of carbon (SCC) becomes prohibitively expensive. Consequently, it is necessary to internalize the SCC into economic decision-making by industries across the various sectors responsible for fossil fuel emissions.

Two methods that have been widely considered are the "carbon tax," which places a surcharge on carbon at the point of origin (e.g., on the greenhouse gases emitted by the tailpipes of automobiles or the smokestacks of factories), and tradable carbon emission permits ("cap and trade"), which are instead aimed at "end use" (e.g., the automobile industry). Under a cap-and-trade system, a limit is placed on the level of emissions (the "cap") for a particular industry, and emissions rights are determined through a system of permits which are initially assigned based on some set of criteria, but which can subsequently be traded. Vigorous arguments have been made for and against the two alternatives. Those favoring carbon taxes typically point to the fact⁴⁸ that they are a more natural market-based mechanism for leveraging behavior, that they avoid the bureaucracy, volatility, and potential arbitrariness of the cap-and-trade system, and that they can be used to raise revenue, or, alternatively, can be made revenue-neutral though the use of offsetting reductions in other taxes. Advocates of tradable emissions rights, in contrast, typically note⁴⁹ that, unlike a carbon tax, the cap-and-trade approach allows for emissions to be kept below some predetermined desired level, which is important if

⁴⁷ China recently overtook the United States as the world's single largest emitter of greenhouse gases. See, e.g., "China Overtakes U.S. in Greenhouse Gas Emissions," *International Herald Tribute*, June 20, 2007.

 ⁴⁸ See, e.g., "Doffing the Cap," *The Economist*, June 14, 2007.
⁴⁹ Eileen Claussen and Judith Greenwald, "Handling Climate Change" (op-ed), *Miami* Herald, July 12, 2007.

there are dangerous climate "tipping points" (as discussed earlier). Moreover, proponents argue that the cap-and-trade approach has historical precedents that have demonstrated its viability in dealing with large-scale environmental threats (e.g., acid rain in the United States), as well as more recent demonstrated success for carbon emissions specifically in restricted markets (e.g., in the European Union, which has developed a system along the lines of what was originally suggested by the Kyoto Accord).

The only barrier to implementation of mitigation strategies is establishing an acceptable system of incentives, whether it be in the form of a carbon tax or a cap-and-trade system. The technology to achieve mitigation is already in place. Anthropogenic greenhouse emissions can be reduced by eliminating fossil fuel burning and other human emissions of greenhouse gases such as methane and nitrous oxide produced by certain types of agricultural practices. In addition, carbon dioxide emissions produced by power plants or industrial activity can be scrubbed from smokestacks before they have the opportunity to enter the atmosphere (see subsection D below).

The largest contributor to current global greenhouse emissions is the global energy supply sector, which is responsible for nearly 6.4 Gigatons of CO₂ equivalent annually.⁵⁰ Increases in the use of alternative carbon-free energy sources such as wind, solar, geothermal, and nuclear, or in the use of carbon-neutral energy sources such as biofuels, provide substantial opportunities for the mitigation of greenhouse gas emissions in the energy supply sector. Emissions from other sectors, such as forestry and agriculture, have been increasing as rapidly or more so than emissions from the energy sector in recent decades. Cleary, mitigation efforts must target these sectors as well. In the agricultural sector, for example, alternative methods of rice cultivation that minimize methane production, feeds that minimize methane production by ruminants, and alternative fertilizers that minimize nitrous oxide production can contribute significantly to mitigation efforts. There is also substantial room for mitigation in the transportation sector, either through the widespread use of more fuel efficient vehicles such as hybrid cars, or through the increased use of biofuels, especially those currently under development (including cellulosic ethanol, which is considered to be a more efficient alternative to the currently available cornbased ethanol). Increased efficiency could also be achieved in aviation transport through the use of more efficient fuels. It is likely that further technological innovation in areas such as hydrogen fuel cell technology and electric vehicles will yield even greater opportunities for future greenhouse gas mitigation.

⁵⁰ To make comparisons across sectors, it is necessary to define a consistent unit of measurement that takes into account the impact of emissions of different types of greenhouse gases with different warming impacts. The preferred unit is the "CO₂ equivalent," which expresses the combined impact of multiple greenhouse gases (i.e., carbon dioxide, methane, nitrous oxide, etc.) in terms of the impact of an equivalent amount of carbon dioxide (CO₂). The CO₂ equivalent is typically measured in Gigatons (billions of metric tons) CO₂, abbreviated as "Gt CO₂ eq."

The developed world is currently responsible for the bulk of worldwide greenhouse gas emissions. However emission rates are increasing most rapidly in the developing world, underscoring the fact that measures aimed at mitigating greenhouse emissions must take into account current trends as well as historical patterns of emissions.

D. Mitigation: Geoengineering

One alternative to conventional mitigation approaches involves "geoengineering,"⁵¹ that is, efforts to offset human impacts on climate either at the source level (i.e., preventing greenhouse gas emissions from building up in the atmosphere) or at the impact level (i.e., offsetting the climate changes caused by greenhouse gas emissions through some measure). In either case, the approaches in question involve planetary-scale engineering of our global environment unlike anything yet witnessed.

One source-level geoengineering scheme that has been proposed involves "iron fertilization," the deliberate addition of iron to the upper ocean. The principle behind this scheme is fairly straightforward. Iron is a key nutrient that is often of limited abundance in the upper ocean. The limited availability of this nutrient consequently places limits on the productivity of marine plants that live near the surface of the ocean. Since these marine plants take carbon dioxide from the surface waters which, in turn, take their carbon dioxide from the atmosphere, an increase in marine plant productivity could, in principle, increase the rate at which carbon dioxide is taken from the atmosphere, thus depleting the levels of carbon dioxide in the atmosphere. However, the limited experiments that have been performed indicate that the main effect of iron fertilization appears to be simply a faster cycling of oceanic carbon between the atmosphere and the upper ocean, with little or no burial in the deep ocean.⁵² Without such deep ocean burial, the processes in question are unlikely to slow the long-term carbon dioxide increase in the atmosphere. Moreover, there could be negative side-effects of interfering with the complex and potentially delicate ecology of the marine biosphere in this way.

Other source-level geoengineering approaches include attempts to increase the efficiency of natural terrestrial processes that take carbon dioxide out of the air. A simple example is the reforestation of areas, particularly in the tropics, that have been deforested in recent centuries. While this approach is in certain respects more environmentally friendly than many other proposed geoengineering approaches, it is not clear that it could be implemented on the massive, planetary scale that would be necessary to significantly counteract the effect of human carbon emis-

⁵¹ An excellent summary of the topic is provided by D. W. Keith, "Geoengineering," *Nature* 409 (2001): 420.

⁵² K. O. Buesseler et al., "The Effects of Iron Fertilization on Carbon Sequestration in the Southern Ocean," *Science* 304 (2004): 414–17.

sions. Related to this approach are so-called carbon capture and sequestration (CCS) approaches. With CCS, carbon is extracted from fossil fuels as they are burned, preventing their escape to the atmosphere. The captured carbon is buried well beneath the Earth's surface, or injected into the deep ocean where it is likely to reside for centuries. One scheme that has been proposed involves using scrubbers to remove carbon dioxide from smokestacks, and reacting the captured carbon dioxide with particular types of rocks to yield limestone. Such a sequence of processes mimics the natural processes that remove carbon dioxide from the atmosphere on geological timescales, but more efficiently and more quickly.⁵³ Klaus Lackner, a scientist at Columbia University, has argued for a related alternative in which massive arrays of artificial "trees" would be built from synthetic materials. They would consist of a pillar resembling a goal post, with slats covered in a solution of carbon-absorbing limewater. Like trees, these structures would take carbon directly out of the air. The captured carbon would then be sequestered.⁵⁴

One of the most commonly proposed impact-level geoengineering approaches involves deliberately decreasing the amount of sunlight that reaches the Earth's surface. In principle, incoming sunlight can be reduced to a level where the decreased warming impact of solar radiation at the surface offsets the surface greenhouse warming. One scheme that has been proposed involves deploying "solar shields" in space that reflect sunlight away from the Earth.⁵⁵ It is unclear that such a scheme could be implemented in an economically viable manner. An alternative, potentially far less expensive approach involves injecting sulfate aerosols into the stratosphere. This approach mimics the cooling impact of volcanic eruptions.⁵⁶ In principle, such a procedure could be implemented as often as necessary, to offset surface warming by greenhouse gas emissions. However, there are a number of potential pitfalls of such an approach. First, the chemistry of sulfate aerosols is such that a massive sudden injection of them on a sustained basis is likely to worsen the problem of stratospheric ozone depletion. In addition, simply offsetting the surface warming effect of greenhouse gas emissions does nothing to solve the problem of ocean acidification, which is also caused by accumulating carbon dioxide in the atmosphere. Moreover, modeling studies indicate that reducing incoming solar radiation, though it might offset the average surface warming of the globe, would not coun-

⁵³ F. Goff and K. S. Lackner, "Carbon Dioxide Sequestering Using Ultramafic Rocks," *Environmental Geoscience* 5 (1998): 89–101.

⁵⁴ M. Bentley, BBC (online), "Synthetic Trees Could Purify Air," http://news.bbc.co.uk/ 2/hi/science/nature/2784227.stm (February 21, 2003).

⁵⁵ R. Angel, "Feasibility of Cooling the Earth with a Cloud of Small Spacecraft Near the Inner Lagrange Point (L1)," *Proceedings of the National Academy of Sciences* 103 (2006): 17184–189.

⁵⁶ See, e.g., P. J. Crutzen, "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma," *Climatic Change* 77 (2006): 211–20; and T. M. L. Wigley, "A Combined Mitigation/Geoengineering Approach to Climate Stabilization," *Science* 314 (2006): 452–54.

teract the regional climate impacts of increased greenhouse gas concentrations. Some regions (including Greenland) might warm at even greater rates. Regional patterns of rainfall and drought might be significantly altered, perhaps to the further detriment of regions already suffering increased drought due to climate change.

All of the proposed geoengineering schemes suffer from possible shortcomings and pose potential dangers. While some advocates maintain that we may need to resort to these schemes at least as a partial solution if faced with the prospect of irreversible and dangerous climate change, many feel it imprudent to tamper with a system as complex and potentially fragile as our global climate in this manner. Finally, geoengineering is saddled with problematic ethical considerations. One of the more troubling problems is that certain nations could stand to benefit from interfering with the climate system in a particular manner, at the expense of nations elsewhere who stand to suffer from the resulting climate changes. It is unclear how such potential conflicts could be resolved.

VII. CONCLUSIONS

The Kyoto Protocol compelled the nations of the world to take whatever actions are required to avoid breaching the threshold of "dangerous anthropogenic interference" with the Earth's climate. Few would argue with the logic of this imperative. As we have seen, however, it is a challenge to define just what is meant by "dangerous anthropogenic interference," let alone how close we might be to it, and what is necessary to avoid it. Such uncertainty complicates the objective prescription of policy solutions for combating the problem of global climate change. Indeed, uncertainty abounds for those looking to it as an excuse for inaction. Yet if anything, as we have seen, uncertainty will likely work against us rather than for us, given the potential "tipping points" that may accelerate future climate changes and their impacts. Uncertainty is not an excuse for inaction. Quite the contrary, as I noted earlier, uncertainty places an even greater burden of proof upon those advocating inaction, given the possibility it introduces for even more severe and irreversible harm to society and the environment than is currently envisioned.

If the remaining uncertainties in the science are not a valid argument against taking immediate action to slow climate change, then it is worth asking: What is? As discussed earlier, some have argued that taking actions to mitigate greenhouse gas emissions, such as the imposition of carbon taxes or a cap-and-trade system, could threaten to harm the economy. Yet this argument does not appear to withstand scrutiny, as economic analyses tend to point to the opposite conclusion: that the economic harm of inaction would be far greater than the cost of mitigation. Some contrarians argue that climate change might be beneficial to humankind. Yet, as we have already seen, an objective assessment of the science underlying projected climate-change impacts strongly suggests otherwise. Others argue that we can engineer our way out of the problem with emerging and future technology (i.e., geoengineering). However, I have explored the numerous pitfalls associated with that approach in Section VI.D.

Others who are opposed to taking action to mitigate climate change concede that climate change represents a potential threat to society, but that it is only one of many problems facing society, and that focusing on the climate-change problem might take away attention and resources that would be better focused on more pressing problems.⁵⁷ Such reasoning, however, is premised upon a false dichotomy. The assumption that society must choose between competing environmental, health, or socioeconomic problems is based on the flawed premises that (i) society can only solve one problem at any given time (this is plainly false), or that (ii) the problems facing society are independent of each other. The latter premise clearly does not hold for climate change. As I have already discussed in this essay, climate change is likely to aggravate other major societal and environmental threats, such as the loss of biodiversity, the scarcity of fresh water, and the spread of disease.

There are some promising new technologies in the pipeline that could assist efforts either to move away from a carbon-based energy economy, or to sequester carbon or otherwise prevent greenhouse gas emissions from entering the atmosphere. It is unlikely, however, that any foreseeable technological innovations will allow us to meet our growing energy demands in a carbon-free or carbon-neutral manner within the next few decades. The conundrum is that with each passing year of "business as usual" emissions, the likelihood of stabilizing the Earth's climate below the level of "dangerous anthropogenic interference" becomes increasingly small, evoking once again the notion of a "procrastination penalty" in dealing with climate-change mitigation. Indeed, some climate scientists have articulated the view that we are committed to dangerous climate-change impacts unless we both stabilize and begin to reduce greenhouse gas emissions in absolute terms within less than a decade.⁵⁸

In the absence of substantial action to mitigate future climate change, one can imagine various scenarios. In the most favorable of scenarios, a number of factors might conspire to set society on the path of one of the more moderate emissions scenarios even in the absence of directed mitigation efforts. Moreover, climate sensitivity might turn out to be at the lower end of the current range of estimates. In such a scenario, it is likely that human society and ecosystems will be able to adapt to some, but not all, changes. There will likely be a loss of species, many of which are currently already threatened by the changes taking place, and there will be some detrimental impacts on society. These impacts include moderate

⁵⁷ See Lomborg, Cool It.

⁵⁸ Hansen et al., "Global Temperature Change."

loss of coastal settlement and island nations associated with sea-level rise in the range of one meter, and moderately expanded patterns of drought threatening agriculture and freshwater supplies in many regions. Projected climate-change impacts, even in this best-case scenario, would likely lead to a world lacking some of its current natural beauty and wonder: for example, a world without a Great Barrier Reef, polar bears, or the "Snows of Kilimanjaro." Some of the great coastal cities of the modern world, such as Amsterdam, Venice, and New Orleans, could well be lost even with the most moderate projected future sea-level-rise estimates.

In the worst-case scenarios, the outlook is far more bleak. Adaptations of the sort explored in this essay would be difficult or impossible if climate sensitivity turns out to be at the upper end of the current estimated range, and if emissions continue along the "business as usual" course. In such a scenario, one can envision detrimental impacts on human civilization and our natural environment that are not entirely unlike the dystopian world depicted in the 1970s science fiction movie *Soylent Green*.

Unfortunately, no single approach to climate mitigation in isolation is sufficient to solve the problem of global climate change, that is, to avert breaching the level of "dangerous anthropogenic interference" with the Earth's climate. A viable solution will have to involve strategies for adaptation to changes that are inevitable, and mitigation of changes that can still be averted. It will require a concerted effort across nations, governments, and all strata of society, and hard work and perhaps difficult choices among individuals, governments, and industries. It will require the development and use of alternative energy sources, significant changes in lifestyle, and dramatically altered incentive structures that reward environmentally responsible behavior by people, industries, and governments.

Anthropogenic climate change has been argued by some to constitute the greatest threat human society has ever faced. At their worst, human civilizations under threat have succumbed to some of the worst of human instincts, such as greed and short-sightedness. The collapse of Easter Island—wherein systematic deforestation of the island by its human inhabitants undermined its sustainability for human occupation—provides a compelling example.⁵⁹ Yet at their best, civilizations have displayed a remarkable fortitude that has allowed them to triumph in the face of seemingly insurmountable adversity. We must hope that modern human civilization will follow the latter of these two very different possible paths as it confronts the daunting challenge of global climate change in the decades ahead.

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⁵⁹ This example is highlighted by Jared Diamond in *Collapse: How Societies Choose to Fail or Succeed* (New York: Viking, 2004).