Part 3

THE GREAT ENERGY DEBATE: THE NATIONAL SECURITY IMPLICATIONS OF GLOBAL CLIMATE CHANGE AND IMPACT POTENTIAL OF ALTERNATIVES

CHAPTER 6

Climate Change Risks in the Context of Scientific Uncertainty

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This chapter reviews potential future climate change impacts and identifies key uncertainties and "trap doors" that could result in unanticipated effects and attendant coping difficulties. Because of the potential global consequences, uncertainty surrounding abrupt global sea-level rise and its implications for decisions about the future receive particular attention. This report offers no predictions. Rather, it considers possible outcomes either supported by current scientific understanding or not ruled out because of remaining uncertainty. Assessments of this type require subjective judgments, as uncertainty inherently arises from a lack of solid objective information. The author attempts to clarify his own subjective judgments, as well as those of independent and more authoritative sources. Physically deterministic *predictions* of future climate are currently impossible; this is the unavoidable backdrop of uncertainty against which policymakers must make decisions regarding global climate change.

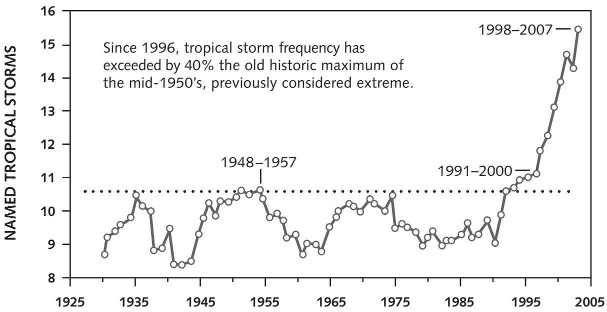
Two Myths about Climate Change

Some misconceptions have developed from the strained efforts of scientists to communicate knowledge about global climate change to decision makers. This section addresses two broad myths that seem to have propagated through the policy community. Specific areas of miscommunication are addressed in later topical sections.

Myth 1: Future climate change will be smooth and gradual. Climate change projections, such as those produced by the Intergovernmental Panel on Climate Change (IPCC), appear smooth and gradual because they are based on climatology forecasts averaged over space and time (e.g., Figure SPM.5 in ref. (21)). Climate history, however, reveals that climate actually changes in fits and starts, with abrupt and often dramatic shifts (9). Regardless of the causes, which may include global warming (19, 26, 49), the recent dramatic increase in the frequency of North Atlantic tropical cyclones (Figure 1) offers an example of abrupt modern climate change (12, 15). The tendency of climate to change abruptly ensures that surprising changes will occur in the future, even if average climate change is projected accurately (9). For example, a (hypothetical) projection of one meter of sea-level rise over one century might prove correct, but occur as several quick pulses with static periods between. Such a change is more difficult to adapt to than gradual change, as public works projects of the necessary scale would require several decades to complete. Surprises from abrupt climate change will likely impose a burden greater than expected based on current model projections.

Figure 1

TROPICAL CYCLONE FREQUENCY IN THE NORTH ATLANTIC



The running 10-year average of annual frequency shows a dramatic and abrupt increase above the previous maximum observed in the 1950s. DATA: Atlantic Hurricane Database Re-analysis Project; http://www.aoml.noaa.gov/hrd/data_sub/re_anal.html.

Myth 2: Impacts will be moderate in industrialized countries. To plan effectively for the future, policymakers must overcome the general impression that developed nations will not be seriously affected by climate change. In fact, the United States, southern Europe, and Australia are likely to be among the most physically impacted regions. By virtue of its size and varied geography, the United States already experiences a wide range of severe climate impacts, including droughts, heatwaves, wildfires, flash floods, and hurricanes, all of which are likely to be exacerbated by climate change (20, 21). For example, the United States ranked 7th in the world for the number of people killed by tropical cyclones during the period 1980 – 2000 (33). Japan and Mexico trailed the United States in deaths despite having similar numbers of people exposed to tropical cyclones. Australia also suffers from severe tropical cyclones. The IPCC projects that climate change will make tropical cyclones more destructive and the most intense storms more frequent (21). The United States is also one of the most susceptible countries to sea-level rise because it has the largest number of coastal cities, as well as two agricultural deltas, near or below sea level. The United States and coastal countries of the European Union are likely to experience some of the greatest losses of coastal wetlands, which support fisheries in the North Atlantic, the Gulf of Mexico, and the Mediterranean Sea (30, 31).

In 2003, central and southern Europe experienced a prolonged heatwave that was the hottest in at least 500 years and led to the premature deaths of 50,000 people (1). The probability of such a severe heatwave occurring again has more than doubled as a result of global warming, and this type of event is projected to be common in the region by 2040 (45). According to the IPCC, the southwestern United States, southern Europe, and southern Australia will experience progressively more severe and persistent droughts and heatwaves in future decades as a result of climate change (43).

The misconception that climate change will spare the industrialized world may stem from confusion between the concepts of *impact* and *vulnerability*. Vulnerability concerns the ability of a population to withstand impacts. Because of their more advanced infrastructures and stronger economies, industrialized countries may be more capable of devoting resources to preparing for and recovering from climate change impacts than developing countries with similar exposure. Even so, the United States and other industrialized countries will be impacted severely, and the potential to devote resources does not imply that the foresight and political will required to divert resources to managing impacts would prevail. Severe climate impacts in wealthy nations portend greater resource commitments — either proactively or reactively — at home and correspondingly less foreign aid. Reduced aid would likely increase the vulnerability of developing nations, generating greater potential for migration of environmental refugees.

Overview of Projected Climate Change

Although artificially smoothed projections of average climate change can be misleading when taken at face value, they allow us to gauge how much change we should expect overall, even if we cannot yet describe the course of change precisely through space and time.

Temperature. According to the 2007 IPCC Fourth Assessment Report (AR4), "best estimates" of the increase of global average surface air temperature during the 21st century range from 1.8 to 4.0°C (3.2 to 7.2° F), depending on future man-made greenhouse gas emissions (21). Temperature over land, particularly in continental interiors, warms about twice as much as the global average, as surface temperatures rise more slowly over the ocean. High northern latitudes also warm about twice as fast as the global average. Extremes change more than averages, leading to fewer freezes, higher incidence of hot days and nights, and more heatwaves and droughts. Larger warming at high northern latitudes leads to faster thawing of permafrost, with consequent infrastructure damage (e.g., collapsed roads and buildings, coastal erosion) and feedbacks that amplify climate change (e.g., methane and CO_2 release from thawed soils) (2). Winter temperatures rise more rapidly than summer temperatures, especially at higher latitudes. Wintertime warming in the Arctic over the 21st century is projected to be three to four times greater than the global wintertime average.

As discussed below, these projections omit a number of potential positive feedbacks in the physical climate system that might amplify the warming from man-made greenhouse gases alone (34). Consequently, actual warming could be larger than the AR4 projections indicate.

Precipitation. A consistent feature of model simulations is an increase in global average precipitation as a result of increasing greenhouse gas concentrations (29). However, the geographic distribution of this change is very uneven, and some regions experience decreased precipitation. In general, areas that are currently wet (i.e. the moist tropics and high northern latitudes) become wetter, while currently dry areas (i.e. the arid and semi-arid subtropics and mid-latitude continental interiors) become drier. Consequently, areas that currently suffer from seasonal flooding and areas that currently suffer from frequent drought will see these problems intensified by climate change (21, 23). South Asia is likely to be the most impacted by increased precipitation. The southwestern United States, Mexico, Central America, the Mediterranean basin, southern Africa, and southern South America will experience decreased precipitation and more frequent drought (29, 41). Decreases in precipitation and related water resources are projected to affect several important rain-fed agricultural regions, particularly in eastern Asia, Australia, and Europe. A decrease in summer precipitation is projected for Amazonia, where the world's largest complex of wet tropical forest depends on high year-round precipitation (14).

Regional Sensitivity. A given change in regional climate, such as a degree of warming or a 10 percent change in precipitation, does not affect all regions the same way. It is useful, therefore, to examine how sensitive different regions might be to changes in temperature or precipitation. Some regions experience a stable climate, and natural and human systems have developed around this stability; in such regions, even a small change may generate significant impacts. In regions with historically large climate variability, however, larger changes are required to exceed the bounds of climate variability to which natural and human systems have adapted. Sensitivity, therefore, can be examined as a function of the degree of future climate change in a region relative to the historical climate variability in that region (4).

A climate change index describing the climate sensitivity of different regions to changes in temperature and precipitation indicates that many of the same regions that support rain-fed agriculture are among the most sensitive areas to climate change (cf. References 4 and 14). The areas most sensitive to a combination of temperature and precipitation change relative to natural variability are in tropical Central and South America, tropical and southern Africa, Southeast Asia, and the polar regions (4). The Mediterranean region, China, and the western United States show intermediate levels of sensitivity. There is a general correspondence between physical climate sensitivity and marginal agricultural lands, such as in the southwestern United States, Central America, sub-Saharan Africa, southern Europe, central Asia—including the Middle East, and eastern China. The most affected region of South America completely covers the Amazonian rainforest. Reduced productivity of this forest would have strong feedbacks on global climate by releasing carbon to the atmosphere and modifying precipitation, and would result in massive loss of biodiversity, including many economically important species (14).

Sea-level rise. Based on model estimates of thermal expansion of ocean water and ice melt from glaciers and continental ice sheets, the 2001 Third Assessment Report of the IPCC (TAR) projected that sea level would rise by 0.09–0.88 meters (0.3–2.9 feet) by the end of the 21st century (22). In 2007, the AR4 projected a narrower range of 0.18–0.59 meters (0.6–1.9 feet) (21). At the upper end of this projection, the potential contribution from future changes in ice flow from the Greenland and West Antarctic ice sheets was not included. The AR4 states that linear acceleration of ice loss (a simple extension of recently observed acceleration) could add up to 0.2 meters (0.7 feet) of sea-level rise in the 21st century, which still leaves the upper end of the AR4 projection range lower than that of the TAR, yet there is no reason to believe that sea-level rise will actually be lower than estimated by the TAR (13), which may have been conservative in the first place (36).[1] Using an alternative method, Rahmstorf (35) projected sea level to rise by 0.5 – 1.4 meters (1.6 – 4.5 feet) by the end of the 21st century. This projection was published too late to be considered in the AR4.

The current eightfold range of uncertainty for 21st century sea-level rise is significant. The lower end represents a minor nuisance overall — low-lying island nations notwithstanding — whereas the upper end portends severe global impacts.

Underestimating Climate Change

Climate scientists have long recognized the potential for climate change to be underestimated because of a lack of understanding of positive feedbacks in the climate system. A positive feedback amplifies the rate and amount of change. For instance, if warming causes frozen arctic soils (permafrost) to thaw, and the wet soil emits more greenhouse gases to the atmosphere, these extra greenhouse gases will increase the rate and degree of warming. Although there is evidence that this very feedback is already operating (50), its contribution to future warming has not been incorporated into projections. Another potential positive feedback that is inadequately incorporated into climate projections and may already be proceeding is a decrease in the absorption of atmospheric CO_2 by the oceans and land ecosystems (7). Although negative feedbacks (i.e. dampers of change) are also possible, the Earth's climate system appears to be endowed disproportionately with positive feedbacks (16).

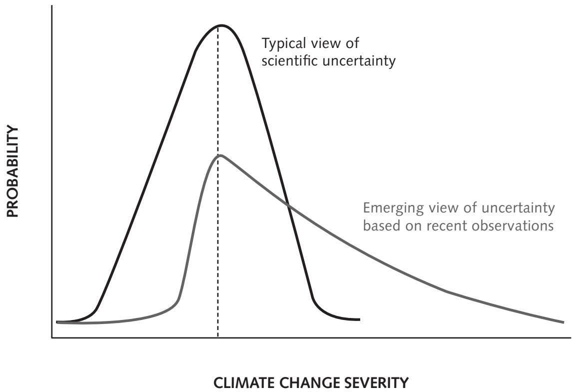
Recent observations indicate that climate models have been underestimating the rates of change of several key aspects of climate change, including ice loss from the Greenland and Antarctic ice sheets (42), arctic sea ice decline (46), global sea-level rise (36), and global precipitation increase (51). All of these changes were predicted before they were detected, but they are occurring sooner or more rapidly than expected (13). The observed rate of temperature change is closer to model projections, but is in the upper range of those projections (36). Although there may be multiple reasons for underestimating rates of change, inadequately treated positive feedbacks are probably involved (34).

Asymmetry of Uncertainty and Elevated Risk

The typical view of uncertainty assumes that the distribution of possible outcomes takes the shape of a bell curve, with equal chance that the actual outcome could be either smaller or greater than predicted (Figure 2). However, the fact that projections have consistently underestimated the rate and magnitude of climate change suggests that the uncertainty surrounding future climate conditions is systematically biased toward more severe climate change (Figure 3). In other words, the probability that climate change will be greater than projected is higher than the probability that climate change will be smaller than projected. Hence, the risk of severe outcomes is greater than the public and policymakers generally perceive.

Figure 2

MODIFIED VIEW OF **UNCERTAINTY SURROUNDING FUTURE CLIMATE CHANGE** BASED ON **RECENT OBSERVATIONS** COMPARED TO **PROJECTIONS**



The probability distribution appears to be biased systematically toward more severe climate change. Therefore, the risk to society is probably greater than generally perceived.

Ocean physicist Stefan Rahmstorf illustrates the point in a recent research article about sea-level rise (35):

> Although a full physical understanding of sea-level rise is lacking, the uncertainty in future sea-level rise is probably larger than previously estimated. A rise of over 1 m by 2100 for strong warming scenarios cannot be ruled out… On the other hand, very low sea-level rise values as reported in the IPCC [Third Assessment Report] now appear rather implausible in the light of the observational data.

In the past year, other leading climate scientists have expressed concurring opinions (25).

Potential "Trap Doors"

The greatest risks from future climate change may lie in thresholds of warming beyond which abrupt or irreversible changes in the climate system occur.

Components of the climate system can exhibit nonlinear change, especially under the influence of positive feedbacks. In nonlinear change, a small change in one part of the system stimulates a much larger response in another part of the system. This type of relationship can drive the responding component past a threshold, or tipping point, beyond which the behavior of the system changes abruptly or irreversibly. Such nonlinearities represent potential "trap doors" that could spring open, with surprising consequences for which society is unprepared. Some examples follow.

Trap Door 1: 'Noah's Flood'. Given that ten percent of the world's population currently lives in low-lying coastal zones and that this proportion is growing (28), sea-level rise is a key consideration for society on all time scales from decades to millennia. Unfortunately, what will happen with the largest potential source of future sea-level rise—the polar ice sheets—remains unresolved and it is impossible as yet to estimate realistic upper bounds to future sea-level rise from climate models (21). Until sound physical approaches are available for this purpose, ice sheet-dominated sea-level rise in the past may be our most realistic guide to the future (32).

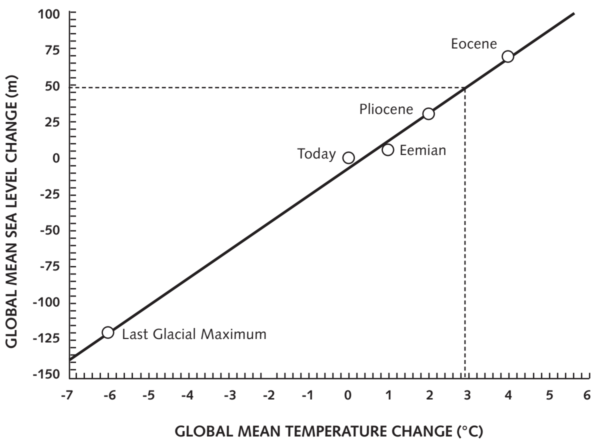
At the end of the last ice age, sea level rose at rates of 1–2 meters per century for several thousand years (16). Earlier, during the warmest part of the previous interglacial period, the globe was 1–2° C warmer than at present for only a few centuries, yet sea level reached 4–6 meters higher than it is now (32). We know therefore that ice sheet-dominated sea-level rise can exceed one meter per century and that rapid sea-level rise probably occurred when the Earth was only slightly warmer than it is today.

Regardless of how high the seas rise by 2100, many centuries will pass before sea level equilibrates with the warming realized this century (29). Local warming of about 3° C around Greenland above preindustrial level (1–2° C for the global average) would eventually eliminate Greenland's ice sheet, raising sea level by six meters; contributions from Antarctica would add more (21, 32). Moreover, ancient climate records indicate that the equilibrium relationship between global temperature and global mean sea level has been stable for millions of years (Figure 3). This relationship implies that the amount of warming projected by the AR4 for the 21st century would lead eventually to a rise of 50 meters (162 feet) above current sea level (3, 52). The shapes of continents would be redrawn. Equilibration would progress over millennia, but the process would be ongoing and would likely be unstoppable through human intervention after an unknown tipping point, which could occur within the next few decades (17, 18).

Avoiding abrupt sea-level rise entails stabilizing the global temperature this century below a level that would destabilize the polar ice sheets. Warming of not more than 2° C above pre-industrial temperature (about 1.2° C above present), may provide some margin of safety in this regard, although significant uncertainty remains about such "guard rails," and some argue that even 2° C above preindustrial temperature is too risky (16, 52).

Figure 3

THE HISTORICAL EQUILIBRIUM RELATIONSHIP BETWEEN **GLOBAL SEA LEVEL CHANGE** AND **GLOBAL TEMPERATURE CHANGE** RELATIVE TO **PRESENT-DAY CLIMATE**



The dotted line represents the mid-point estimate of average global warming for the 21st century relative to 1990 from the AR4. Graphic adapted from (3) and (52).

Trap Door 2: 'Death by a Thousand Cuts'. Another possible trap door scenario is one in which extreme weather events familiar to a given region simply become so frequent that every year is a bad weather year. In the United States, imagine having permanent Dust Bowl-like conditions in the Southwest; widespread wildfires in both eastern and western forests; catastrophic flash floods in California, the Midwest, and the Southeast; intense nor'easters pounding New York, Philadelphia, and Boston; enormous blizzards or thunderstorm systems halting commerce every few weeks from the Rockies to New England; and major crop failures from persistent or repeated drought interlaced with frequent hailstorms and flash floods. Moreover, imagine that most of the countries of the world are experiencing similar "piling on" of extreme weather events in most years. Severe drought, floods, and heat have all plagued Europe in recent years. Asia, Africa, Australia, and Central and South America all face similar possibilities. Add to the direct physical damage of extreme weather events the consequences for health and social systems, the insurance industry, and the economy at large, and the impacts of a nonlinear increase in familiar extreme weather events around the world can mean "death by a thousand cuts."

Trap Door 3: 'The George Foreman Effect'. "Down goes Frazier! Down goes Frazier! Down goes Frazier!," was the stunned cry of Howard Cosell when George Foreman took the world heavyweight championship title from previously undefeated Joe Frazier, knocking him to the canvas six times to score the KO in less than two rounds. The devastation that "Big George" imposed on his unfortunate opponents offers a graphic analog to another potential trap door—repeated severe climatic blows of a particular type against major population centers.

What if New York, Miami, Houston, and Los Angeles were all struck by Katrina-like hurricanes within a decade? What if Europe were plagued every few years by intense, lingering heatwaves like the one that took 50,000 human lives prematurely in 2003 (1)? Urban centers of the Midwestern U.S. may face similar prospects as longer, hotter heatwaves become a regular feature of the regional climate (11). What would be the social, economic, and political consequences of repeated strikes from such enormous climatic events on major population centers around the world? Population centers have developed their infrastructures and emergency response systems under the assumption that such devastating events have very low probabilities of recurrence. Climate change could increase those probabilities dramatically. A one-meter rise in sea level could convert what is now considered a 100-year flood in New York City to a four-year flood for some parts of the city (39). Adapting to this type of change may not be possible, particularly for coastal cities where a combination of sea-level rise, intense storms, shoreline erosion, and saltwater intrusion into water supplies may combine to make many coastal cities unsustainable.

Trap Door 4: 'Breadbasket Bandits'. Most of the staple grains that feed the world are produced in a handful of grain-exporting countries, including Argentina, Canada, Russia, members of the European Union, the United States, Thailand, and Viet Nam. Between 2002 and 2004, at least five of the major grain exporters experienced decreased grain production, causing them to curtail exports in order to hold food prices down at home (6). All of these shortages were related to heat and drought. Luckily, the United States, which supplies more than a third of global grain exports, did not have serious shortfalls during this period. But with climate change, the odds of several of the largest exporters experiencing multi-year shortfalls simultaneously may increase, especially if atmospheric circulation patterns change.

Broadly, climate change is expected to intensify current precipitation patterns, offering some degree of predictability and maintaining current geographic patterns of large-scale food production. A systematic reorganization of the atmosphere that shifts rain belts away from some of the traditional breadbaskets would be a much greater threat to food supplies. Such climate regime shifts could become "breadbasket bandits."

Several rapid climate regime shifts have been observed in recent decades, including a shift in the tropical Pacific sea surface temperatures toward El Niño-like conditions, which carry important implications for the distribution of rainfall throughout much of the world (48). Global precipitation patterns could be altered dramatically by a collapse of the North Atlantic overturning circulation (also called the thermohaline circulation or the ocean conveyor), which could occur suddenly as a nonlinear response to warming, although great uncertainty prevails (40, 53). In Europe, regional cooling would shorten growing seasons, exacerbating the effect of decreased precipitation.

Although formerly less productive regions may become more suitable for crop production under such scenarios, the immense agricultural industrial complex behind world grain production would not reside in those regions initially.

Trap Door 5: 'Self Sabotage'. In 1991, the eruption of Mount Pinatubo—the largest volcanic event of the twentieth century—injected millions of tons of sulfate aerosols into the upper atmosphere (stratosphere). Those aerosols blocked the sun's rays, cooling the Earth by a few degrees. The effect lasted a couple of years, then dissipated (38). This was the first large volcanic eruption ever monitored fully by satellite, and it proved what scientists had theorized for decades—that the climate is very sensitive to the shading effect of short-lived fine particles in the atmosphere.

Intentional injection of sulfate aerosols into the stratosphere as a sunscreen to cool the Earth has been proposed as a form of climate engineering (often called geoengineering) to counter the enhanced greenhouse effect (10). It is technically feasible and would be very inexpensive in comparison to transforming the world's energy system to reduce greenhouse gas emissions (5). Therein lies the danger: if an engineered sunshade were implemented as an alternative to reducing greenhouse gases, the risk of abrupt climate change could be much higher than from unabated greenhouse gas emissions alone.

Because the atmospheric lifetime of CO_2 from fossil fuels is on the order of centuries, and one-quarter remains in the atmosphere for millennia, once sulfate injection has been used to permit continued CO_2 accumulation, the measure must be maintained indefinitely (3). If the sunscreen were allowed to dissipate, the full warming effect of the accumulated CO_2 would be realized instantly, causing abrupt warming twenty times faster than projected from greenhouse gases alone (27). The latest research also suggests that the sunshade approach could cause precipitation to decline worldwide, in lieu of the net global increase expected to accompany greenhouse warming (27, 47).

Irrespective of temperature, continued accumulation of atmospheric CO_2 would acidify the oceans, with possible catastrophic effects on marine ecosystems (37). Hence, quick-fix climate engineering approaches could cause self-inflicted abrupt climate change as well as fishery collapse. The cure could be worse than the disease.

Given that the climate is changing more quickly than anticipated and that irreversible changes may be near, many scientists agree that climate engineering options, including sunshades, should be investigated fully but cautiously. Yet many of the same scientists consider such solutions an absolute last resort because of their unpredictability and potential to harm nature and humanity (8). Economics Nobel Laureate, Thomas Schelling, put it most succinctly: "When I'm feeling pessimistic I think climate engineering may become irresistible. I'd prefer to get carbon dioxide under control."[2]

Avoiding the trap doors: Decisions

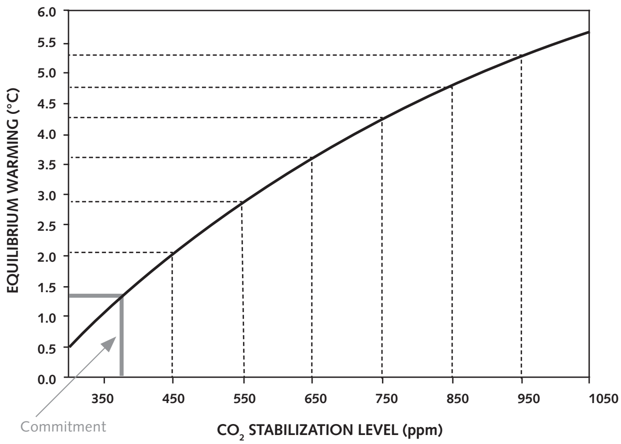
The difference between those who contested George Foreman's supremacy in the ring and those who stand to be impacted by climate change is that Foreman's opponents knew exactly what they were up against. But if scientists have consistently underestimated climate change, what is society to expect of the future? If the projections of the IPCC are conservative, perhaps they suggest the least change that society should expect, rather than the most probable.

Because the oceans warm first and equilibrate with the air later, we are already committed to some additional warming based on the current greenhouse gas concentration, as indicated by the gray line in Figure 4 (21). Generally speaking, how far beyond the gray line greenhouse gas concentrations rise, and therefore how much more the temperature rises, will be determined by decisions that society makes during the current decade. By deciding how high to allow greenhouse gas concentrations to rise, society chooses how hard to work to avoid undesirable climate change impacts, including ‘trap doors’ that carry especially severe consequences. One would hope that these critical decisions will be made with the best possible scientific information in mind, but science cannot identify the correct decisions. These decisions will be based on societal values, and an earnest and difficult social and philosophical debate is required to determine which impacts to avoid and the amount of effort to exert to that end.

Despite lingering uncertainties, science has begun to identify impacts that could be avoided by limiting global warming. Many types of impacts have begun already, such as damage to coral reefs and widespread rapid retreat of mountain glaciers, but the worst effects can still be avoided (Figure 5) (23, 24). There is a window of opportunity to avoid tipping points leading to catastrophic events, such as abrupt sea-level rise and large-scale shifts in the climate system. It is unlikely, however, that uncertainty surrounding the timing and effects of such events will be eliminated before this window closes. Hence, if society is to act to prevent the worst impacts of climate change, it will do so in the face of uncertainty.

Figure 4

RELATIONSHIP BETWEEN **STABILIZED ATMOSPHERIC CO_2 CONCENTRATIONS** AND **GLOBAL TEMPERATURE CHANGE** RELATIVE TO **PREINDUSTRIAL**

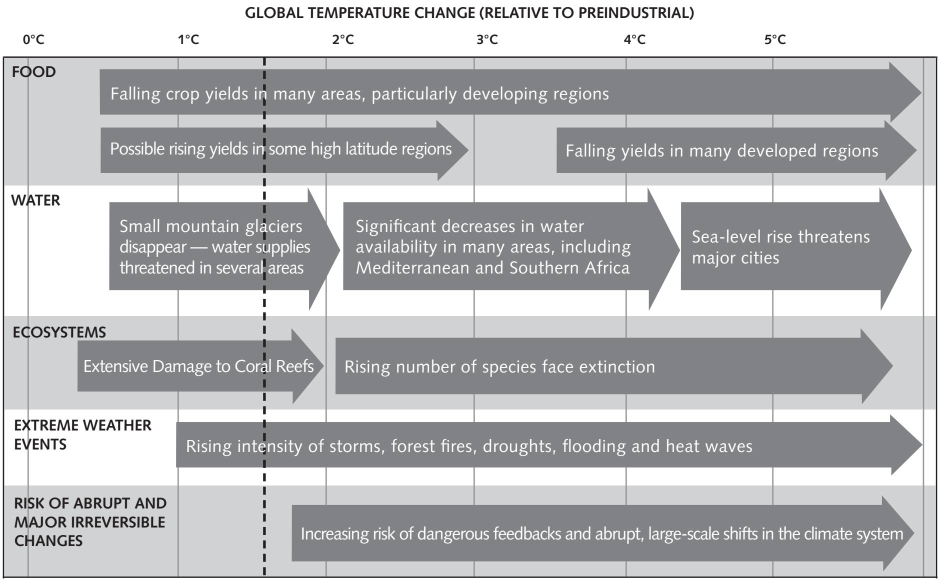


Gray lines show the temperature rise to which we are already committed based on current greenhouse gas concentrations.

Source: Plotted from data in Table SPM.5 in (24).

Figure 5

AVOIDABLE IMPACTS CHART



The left end of an arrow indicates at what temperature an impact begins. The dotted line represents temperature change to which we are already committed and examples of potentially avoidable impacts are shown to the right of this line.

Source: Fig. 2 in (44).

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[1] The AR4 authors never intended for their projections to be compared directly with the TAR projections, noting that "[t]he TAR would have had similar ranges to those in [the AR4] if it had treated the uncertainties in the same way." (29) Nor did they intend to communicate the notion that future sea-level rise would be lower than previously thought, stating that current understanding of polar ice sheet changes is insufficient to "…provide a best estimate or an upper bound for sea-level rise." (29) Unfortunately, these key nuances were lost in translation to the public.

[2] Personal communication with the author by email on July 15, 2007

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