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STATE OF THE WORLD

Into a Warming World

THE WORLDWATCH INSTITUTE

A Safe Landing for the Climate

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Our climate system is in trouble. It has warmed by over 0.7 degrees Celsius in the last 100 years. Most of the warming since at least the mid-twentieth century is very likely due to human activities. Warming's impacts on human and natural systems are now being observed nearly everywhere—perhaps most obviously in the recent loss of Arctic sea ice, which in 2007 and 2008 reached record low levels at the end of the northern summer. In spite of nearly 20 years of international attention, emissions of greenhouse gases (GHGs)—principally carbon dioxide (CO₂) from the burning of fossil fuels—continue to grow rapidly. As a consequence, the concentration of carbon dioxide in the atmosphere has increased faster during the last 10 years than at any time since continuous measurements began in 1960.¹

Unabated, current increasing trends in emissions can be expected to raise Earth's temperature by a further 4–6 degrees Celsius

(7.2–10.8 degrees Fahrenheit), if not more, by the end of this century. If even half that much warming occurs, it will bring huge damages and potentially catastrophic problems. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), which was released at the end of 2007, predicted serious risks and damages to species, ecosystems, human infrastructure, societies, and livelihoods in the future unless warming is reduced. The report's projected risks and damages are larger and more serious than previously estimated and threaten development in several regions of the world. The IPCC also found that reducing greenhouse gas emissions would lower the global temperature increase and consequently lessen the risks and damages. Yet it is also important to note at the outset that even reducing emissions 80 percent by 2050 will not eliminate all serious risks and damages.²

One of the great icons of the modern world,

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the jet aircraft, provides a telling metaphor for what the world faces in terms of climate change. Jet aircraft burn prodigious quantities of fossil fuels in order to move passengers and freight across vast distances in relative safety and luxury. Yet like the climate system, the rules of operating these machines are not widely understood by anyone except the few people whose job it is to know about such things. The climate system is like a jet aircraft that has become airborne safely but is now facing grave difficulty and must land as a matter of urgency before disaster becomes inevitable. If we do not reduce emissions fast enough and bring the warming of the climate system to a halt, we risk a major catastrophe.

This chapter is about how much and how fast the world needs to reduce greenhouse gas emissions in order to prevent or limit serious damage—in other words, to bring the climate system to a safe landing. But first it is important to review the current state of scientific knowledge on the risks, damages, and impacts estimated for different levels of warming in order to see what level might prevent dangerous changes and thus be “safe.”

Preventing dangerous climate change is the universally agreed ultimate goal of climate policy established in the 1992 U.N. Framework Convention on Climate Change (UNFCCC). (See Box 2–1.) Once a dangerous level of change has been defined, scientists can calculate with reasonable confidence an emission pathway that can limit warming and other changes to this level, taking into account continuing uncertainties in their understanding of the climate system.³

Projected Climate Change and Sea Level Rise

In the latest IPCC report the projected levels of global warming in the absence of efforts to reduce emissions are not dramat-

ically different from those made in earlier reports: warming by 2100 is projected to be in the range of 1.1–6.4 degrees Celsius above the average in the 1980–99 period. Given that emissions, warming, and sea level rise during the current decade have all been at the upper end of projected ranges, it would be prudent to assume that the likely warming in the absence of major emission reductions over the next century will be toward the mid or upper end of the range projected by the IPCC.⁴

The main reference point for greenhouse gas concentrations and temperature increases is typically preindustrial times. This is usually taken as 1750, so preindustrial CO₂ concentration levels are given as 278 parts per million (ppm) CO₂. Increases in greenhouse gases (taken together as CO₂-equivalent (CO_{2eq}) concentrations) are generally related to this number. A doubling of GHG concentrations means an increase that is equivalent to the effect of about 556 ppm CO₂ (often just rounded to 550 ppm CO₂).

As far as possible, global temperature increases here are referred to as increases above the preindustrial level. Given that a global instrumental temperature series only exists for the period after 1850, the preindustrial period is defined as the 30-year average from this year. (The average global mean temperatures between 1750 and the 1850s were quite similar, so this is considered satisfactory.) From the 1850s to the five-year period ending in 2007, global mean temperature increased by more than 0.7 degrees Celsius. In the IPCC report, projections are often stated with respect to the period 1980–99 (with 1990 used as the midpoint), which was a bit over 0.5 degrees Celsius warmer than the preindustrial period. So the IPCC’s projected increase for the twenty-first century of 1.1–6.4 degrees Celsius above 1980–99 levels would be about 1.6–6.9

Box 2-1. Preventing Dangerous Climate Change

The guiding principles of international efforts to deal with climate change were established in 1992 in the United Nations Framework Convention on Climate Change, which was adopted in Rio de Janeiro at the Earth Summit: “The ultimate objective of this Convention and any related legal instruments... is to achieve... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.”

This is a powerful statement, as it contains a legally binding requirement to prevent dangerous changes. In practice, however, exactly what this means remains undefined in international law. The article is ambiguous, as it leaves open core questions such as dangerous to whom and to what. What if food production increases in some regions due to global warming and increased CO₂ concentration, as is projected for the northern high latitudes, but decreases perhaps dangerously in other regions, as is projected for low-latitude tropical regions such as Africa? Is that dangerous within the meaning of the convention? Answering such questions is fundamental to the development of a fair and equitable global approach to climate change.

While most attention in debates about

climate change has focused on changes in climate, it needs also to be noted that under Article 2 “dangerous anthropogenic interference” relates to the climate system as whole: changes in ocean acidity due to human-induced CO₂ increases that result in adverse changes in the oceans and marine ecosystems could also be deemed dangerous. University of Toronto climatologist Danny Harvey has pointed that there are important differences between terms such as dangerous interference and dangerous climate change. (For simplicity’s sake, however, these are used synonymously in this chapter.)

Decisions as to what is “dangerous” fundamentally affect the rate, timing, and scale of emissions reductions required regionally and globally in the coming years and decades. If “dangerous interference” is considered to begin only once the global average temperature exceeds 4 degrees Celsius above the preindustrial level, then it will be hard to justify urgent and stringent mitigation action in the next 10–30 years, as greenhouse gas emissions would not need to peak until well after the 2050s before dropping. If, on the other hand, warming of more than 2 degrees above preindustrial is deemed dangerous, then there is acute and urgent emphasis on near-term emission actions leading to large global emissions reductions of 80 percent or more by 2050.

Source: See endnote 3.

degrees Celsius above preindustrial level. Since 1980–99, the climate system has already warmed about 0.25 degrees Celsius.⁵

For projected sea level rise the IPCC was unable to estimate fully all the contributions of global warming, as numerical computer models of the ice sheets of Greenland and Antarctica cannot yet adequately project the effects. So the range of sea level rise estimated by the IPCC—between 0.18 and 0.59 meters by 2100 above 1980–99 levels—was heavily qualified, given that the possible future

rapid loss of ice from Greenland and Antarctica could not be quantified. The already observed rapid loss of ice in response to recent warming of the atmosphere and ocean around Greenland and West Antarctica indicates that these ice sheets could be more vulnerable to warming than implied by ice sheet models and hence could add significantly to future sea level rise. As a consequence, the IPCC could not give a “best estimate” or upper bound for sea level rise.⁶

After the writing of the IPCC science

report was completed, Stefan Rahmstorf of the Potsdam Institute for Climate Impact Research projected future sea level rise based on the observed relationship between sea level and temperature over the last century. Using a similar range of emission and climate projections, he estimated a sea level rise in the range of 0.5–1.4 meters above 1990 levels by 2100. More recent work indicates that the increase during this century could be even higher. In short, the evidence points to a likelihood of meter-scale sea level rise by 2100, well above the top end of the range quantified by the IPCC. Thus, much larger risks to coastal zones and small islands seem likely during this century than had previously been estimated.⁷

There is much greater confidence now than in earlier IPCC assessments in the regional changes that can be expected in a warmer world. Warming will be greatest in the high north and in the interiors of the continents. Reduction in snow cover, a thawing of permafrost, and decreases in the extent of sea ice in both hemispheres can be expected.⁸

Weather extremes and water availability are two of the most important projections in terms of impacts on human and natural systems. More-frequent heat extremes and heat waves, more-intense tropical cyclones, and heavier precipitation and flooding can be expected in many regions. Recent projections confirm that extreme high surface temperatures will rise faster than global warming and indicate a 10 percent chance of “dangerously high” surface temperatures over 48 degrees Celsius every decade in much of the world by 2100 if the global temperature exceeds 4 degrees Celsius above the preindustrial level.⁹

Precipitation can be expected to decrease in most subtropical land regions but to increase in the high latitudes. The IPCC assessment found with “high confidence that

many semi-arid areas (e.g. Mediterranean basin, western United States, southern Africa and northeast Brazil) will suffer a decrease in water resources due to climate change.” By the 2050s it is projected that there will be less annual river runoff and water availability in dry regions in the mid-latitudes and tropics but an increase in high-latitude regions and in some tropical wet areas.

Especially Affected Systems, Sectors, and Regions

For the first time the systems, sectors, and regions most likely to suffer adverse effects were identified in the latest IPCC report, providing important details of risks, impacts, and vulnerabilities at different levels of future warming. The especially affected ecosystems identified were tundra, boreal forest and mountain regions, Mediterranean types, tropical rainforests where precipitation declines, coral reefs, mangroves and salt marshes, and systems dependent on sea ice. A sector identified as of special concern is the health of vulnerable populations who have a low capacity to adapt. As Hurricane Katrina and the European heat wave of 2003 showed, even in high-income countries the poor, the elderly, and young children can be particularly at risk from climatic extremes.¹⁰

For sea ice, the IPCC projected a decrease in both the Arctic and Antarctic under every unmitigated emissions scenario, with summer sea ice in the Arctic disappearing almost entirely toward the end of this century. This would have far-reaching adverse consequences for ice-dependent species and ecosystems as well as speeding up the warming far into the interior of the bordering continental regions of Russia, Canada, and Alaska.¹¹

Large losses of sea ice threaten the continued existence of polar bears. Based on the projections available for the latest assessment,

the IPCC predicted that this risk would occur for a global warming of 2.5–3.0 degrees Celsius above the preindustrial level. But it seems clear that this threshold could be much lower, as the observed rapid loss of summer ice (about 9.1 percent a year for the 1979–2006 period) exceeds the projections in nearly all the latest IPCC models.¹²

In already dry regions in the mid-latitudes, in drier parts of the tropics (predominantly developing countries), and in regions that depend on melting snow and ice for river and stream flows, water resources will be adversely affected. Glaciers in regions such as central Asia and the Himalaya and Tibetan plateau are melting faster than expected. Large adverse effects on water supply availability are predicted, threatening billions of people with water insecurity. Developing countries are not the only ones at risk. Serious water supply impacts have been seen in Australia from the 2001–07 drought—the most extreme and hottest drought recorded for this continent. Water inflows into Australia’s largest and most important river basin, the Murray-Darling, are expected to decline 15 percent for each 1 degree Celsius of warming, and dramatic and adverse impacts are forecast for the water supply for large cities in southeast Australia.¹³

Agriculture and food supply in low-latitude regions, which are predominantly poor developing countries, are projected to be adversely affected even at low levels of warming. Recent climate trends, some of which can be attributed to human activities, appear to have had a measurable negative impact on global production of several major crops. In India, for example, it is clear that agricultural production has suffered due to a combination of climate change and air pollution.¹⁴

Substantial to sometimes severe adverse effects on food production, water supply, and ecosystems are projected for sub-Saharan

Africa and small island developing states if the average temperature reaches 1.5 degrees Celsius above preindustrial level. Large river deltas, such as those of the Nile in Africa and of the Mekong and Ganges-Brahmaputra in Asia, are particularly at risk as they are home to large vulnerable populations and have a high exposure to sea level rise, storm surges, and river flooding.¹⁵

Tipping Points

Levels of warming that can trigger changes in large-scale components of the climate system, that can be irreversible for all practical purposes, and that have large-scale adverse consequences are often called tipping points. If a tipping point is passed, then a subsequent cooling of the climate system would likely not reverse the change. In some cases, such as disintegration of the West Antarctic ice sheet, the process would continue until a new equilibrium is reached.¹⁶

Elements of the climate system that are susceptible to “tipping” include Arctic summer sea ice (possible complete loss), the Greenland ice sheet (a meltdown would raise sea level 6–7 meters over many centuries to millennia), the West Antarctic ice sheet (disintegration would raise sea level 4–5 meters over several centuries), the circulation of the major Atlantic Ocean currents (risks of complete shutdown, with cooling of Europe and other adverse impacts), and the Amazon rainforest (risk of collapse due to warming and rainfall reductions).

A recent assessment indicates that a significant number of tipping points could be approached if the climate warms more than 3 degrees Celsius over the preindustrial level. Loss of the West Antarctic ice sheet is one such element. Other tipping points could be approached at warming levels over 1.5–2 degrees Celsius, such as the loss of the Green-

land ice sheet. Arctic summer sea ice could be lost at even lower levels of warming (0.8–2.6 degrees Celsius), and its rapid loss would amplify warming in the adjacent continents, accelerating permafrost decay.¹⁷

What Levels of Warming Might Be Safe?

Deciding what level of climate change is dangerous and what might be safe is not a purely scientific question. It involves normative and political judgments about acceptable risks. Science has, however, a fundamental role to play in providing information and analysis relevant to this question and has contributed to policy and political debates on acceptable levels of climate change since the 1980s.¹⁸

By the late 1980s the scientific community had begun to recognize that a warming of much more than 1–2 degrees Celsius over the preindustrial level could lead to rapid and adverse changes to many human and natural systems. In 1986 the U.N. Environment Programme set up an Advisory Group on Greenhouse Gases, which in 1990 reported that a 2-degree warming could be “an upper limit beyond which the risks of grave damage to ecosystems, and of non-linear responses, are expected to increase rapidly.” Also in the late 1980s the Enquete Kommission, a joint committee of German parliamentarians and scientists, sought to define acceptable limits. Warming more than 0.1 degree Celsius per decade was seen as especially risky to forest ecosystems, with an overall acceptable maximum warming estimated to be 1–2 degrees Celsius. In 1995 the German government’s Global Change Advisory Council found that 2 degrees Celsius should be the upper limit of “tolerable” warming.¹⁹

Efforts to define acceptable limits to warming at a political level started in the European Union and among its member states. Based

on the IPCC’s Second Assessment Report at the end of 1995, the European Union’s Council of Environment Ministers in 1996 called for warming to be limited to 2 degrees Celsius above the preindustrial level. Nearly a decade later this position was confirmed by European Union Heads of Government after consideration and debate over the findings of the IPCC’s 2001 Third Assessment Report, as well as more recent scientific developments. Since 2005 other countries have joined in calling for global mean warming to be limited to 2 degrees: Chile, Iceland, Norway, Switzerland, the Least Developed Countries, and Small Island Developing States. The latter two groups of countries have argued that 2 degrees may in fact be too much warming if their safety and survival are to be guaranteed.²⁰

From the nongovernmental sector, the Climate Action Network, which has worked on climate change since 1989, has called for warming to be limited to a peak increase as far below 2 degrees Celsius as possible. It also calls for warming to be reduced as fast as possible from this peak. In 1997, based on a review of risks identified in mid-1990s, Greenpeace International called for the long-term committed increase of temperature to be limited to less than 1 degree Celsius above preindustrial and for warming rates to be less than 0.1 degree Celsius per decade.²¹

Several groups of scientists who have attempted to define a safe limit have also endorsed the need to stop before warming by 2 degrees Celsius. In a 2007 paper, NASA’s James Hansen and colleagues argued for a limit of 1.7 degrees Celsius above preindustrial on the basis that potential changes above this level—including irreversible loss of the Greenland and Antarctic ice sheets and species extinction—would be “highly disruptive.” Following further analysis of ongoing climate changes and of Earth’s sensitivity to

climate changes in the past, Hansen and his colleagues called for an “initial” CO₂ stabilization level of 350 ppm, significantly below present levels of close to 390 ppm. This would produce a warming in the long term of around 1 degree Celsius if the climate sensitivity were close to the IPCC best estimate of 3 degrees Celsius. The present CO₂ level, they argued, “is already too high to maintain the climate to which humanity, wildlife, and the rest of the biosphere are adapted.” One implication of Hansen’s reasoning is that warming may need to be lowered even from this level in centuries to come in order to reduce the risks of large-scale loss of ice from the ice sheets.²²

Taking into account uncertainties in the sensitivity of the climate system to greenhouse gas increases, climatologist Danny Harvey of the University of Toronto has argued that even the present GHG concentration levels may constitute dangerous interference with the climate system. This would mean that a “safe” warming limit would be below 1.3–1.4 degrees Celsius above the preindustrial level, given that the present GHG concentration levels would likely warm the planet by about this amount once the world ocean and climate systems fully respond to these concentrations.²³

The findings of the latest IPCC assessment and more-recent studies strongly reinforce the conclusions reached by all these different groups that “safe” levels of warming lie at 2 degrees Celsius or below. Table 2–1 summarizes salient examples of highly significant projected risks both below and above that level of warming.²⁴

It is clear from this overview that substantial risks, dangers, and damages are likely across multiple sectors should global temperatures warm 1.5–2 degrees Celsius above the preindustrial level. Risks of extinction and major ecosystem disruption are evident

at the low end of this range and increase rapidly with the rising temperature. While scientists are uncertain of the probability that a warming in the range of 1.5–2 degrees Celsius would destabilize the Greenland or West Antarctic ice sheets, this would have very large consequences if it did happen and hence qualifies as a high risk that “is something that should rather be avoided.”²⁵

A warming of 2 degrees Celsius is clearly not “safe” and would not prevent, with high certainty, dangerous interference with the climate system.

It is hard to avoid the conclusion that even a warming of 2 degrees Celsius poses unacceptable risks to key natural and human systems. It is clearly not “safe” and would not prevent, with high certainty, dangerous interference with the climate system. From thermal expansion of sea water alone, a meter or more of sea level rise over centuries cannot be excluded if there is a 2 degrees Celsius warming.

Furthermore, there is no “magic number” lower than 2 degrees Celsius that would limit warming to safe levels with high confidence. Warming in the range of 1.5–2 degrees Celsius clearly contains a significant risk of dangerous changes. Thus the amount of time the climate system remains in this temperature region should be minimized if it cannot be prevented. Below 1.5 degrees Celsius, there still appears to be a risk of dangerous changes. And at even a 1 degree Celsius warming there remains a risk of significant loss of ice from the ice sheets as well as large damages to vulnerable ecosystems.

Thus it does not appear possible to define at present an ultimate warming limit that is unambiguously safe or that undoubtedly would prevent dangerous interference with

Table 2–1. Risks and Impacts at Different Warming Levels above Preindustrial Level

System	1.5–2.0 Degrees Celsius	2.0–2.5 Degrees Celsius	> 2.5 Degrees Celsius
Ecosystems and biodiversity	<ul style="list-style-type: none"> • 10–15 percent of species assessed committed to extinction, and significant risks for many biodiversity hotspots • Sharply accelerating risk of extinction for land birds, with loss of 100–500 species per degree of warming • Evidence from observed amphibian and reptile declines “portend a planetary-scale mass extinction” 	<ul style="list-style-type: none"> • Major losses of endemic plants and animals in Southern Africa, northeastern Australia 	<ul style="list-style-type: none"> • 20–30 percent of plant and animal species assessed at increased risk of extinction • Loss of 20–80 percent of Amazon rainforest and its biodiversity
	<ul style="list-style-type: none"> • Widespread damages to coral reef systems due to bleaching 	<ul style="list-style-type: none"> • Increasing damage to coral reefs 	<ul style="list-style-type: none"> • Widespread mortality of corals
	<ul style="list-style-type: none"> • Observed larger-than-expected losses of Arctic sea ice indicate increasing risk of extinction for the polar bear • High extinction risk projected for the King Penguin, with a reduction in adult survival of about 30 percent per degree of warming 		<ul style="list-style-type: none"> • High risk of extinction for the polar bear due to projected loss of Arctic sea ice
Food Production	<ul style="list-style-type: none"> • Decreases in cereal production for some crops in low-latitude poor regions • Risk of highly adverse and severe impacts on food production in some African countries • Substantial risks to rice production in Java and Bali 	<ul style="list-style-type: none"> • Significant decreases in crop production of around 5 percent for wheat and maize in India and rice in China • Agriculture losses of up to 20 percent of GDP in low-lying island states • Recent review indicates that increases in productivity projected in IPCC report for warming of up to 2 degrees Celsius may not occur 	<ul style="list-style-type: none"> • Risk of decline in crop yield globally
Coastal regions	<ul style="list-style-type: none"> • Increased damages from storms and floods, with up to 3 million additional people at risk of coastal flooding 	<ul style="list-style-type: none"> • Increasing damages 	<ul style="list-style-type: none"> • Increasing damages
Health	<ul style="list-style-type: none"> • Increasing burden from malnutrition and from diarrheal, infectious, and cardiovascular 	<ul style="list-style-type: none"> • Increasing damages 	<ul style="list-style-type: none"> • Increasing damages

Table 2-1. continued

System	1.5–2.0 Degrees Celsius	2.0–2.5 Degrees Celsius	> 2.5 Degrees Celsius
Health, continued	diseases, with increased mortality from heat waves, floods, and droughts		
Water	<ul style="list-style-type: none"> • Many hundreds of millions at risk of increased water stress in Africa, Asia, and Latin America • Glacial area in the Himalaya and Tibetan plateau regions could be reduced by 80 percent, adversely affecting billions of people • Transition to a more arid climate in southwestern North America 	<ul style="list-style-type: none"> • Increasing number at risk of water stress • Colorado River flow reduced to unprecedented levels that cannot be compensated by increased reservoir capacity or operating policies for water supplies 	<ul style="list-style-type: none"> • 2 billion at risk of increased water stress for warming over 2–2.5 degrees Celsius
Sea level rise	<ul style="list-style-type: none"> • Greenland ice sheet risk of irreversible meltdown for warming of 1.9–4.6 degrees Celsius • New data from the last interglacial period, 125,000 years ago, indicates that average rates of sea level rise in this period were rapid, around 1.6 meters per century 	<ul style="list-style-type: none"> • Increasing risk of Greenland meltdown raising sea level; rapid sea level rise from this “cannot be excluded” 	<ul style="list-style-type: none"> • Loss of ice sheet would raise sea level by some 2–7 meters over centuries to millennia
	<ul style="list-style-type: none"> • Accelerating ice loss from the West Antarctic ice sheet indicates risk of significant sea level rise at low levels of warming 	<ul style="list-style-type: none"> • Increasing risk 	<ul style="list-style-type: none"> • Increasing likelihood of partial or complete loss of the West Antarctic ice sheet, raising sea level 1.5–5 meters over several centuries to millennia
	<ul style="list-style-type: none"> • Commitment to minimum sea level rise of 0.3–1.2 meters over many centuries due to thermal expansion (0.2–0.6 meters per degree Celsius of global average warming) 	<ul style="list-style-type: none"> • New projections indicate likely well above 0.5 meters of sea level rise by 2100 • Commitment to minimum sea level rise over many centuries of 0.4–1.5 meters due to thermal expansion irrespective of loss of the ice sheets and glaciers, which would only add to this risk 	<ul style="list-style-type: none"> • New sea level rise projections of 0.5–1.4 meters above 1990 levels

Source: See endnote 25.

the climate system. It would seem safest and most prudent to reduce emissions fast enough in the coming decades so that global warming can be stopped soon and as far below 2 degrees Celsius as possible. The warming would then also need to be reduced as rapidly as possible, aiming to get it below 1 degree Celsius above preindustrial level—in other words, to at most about one fifth of a degree Celsius from where it is today.

Emission Pathways That Could Limit Warming to “Safe” Levels

Working out an emission path that would limit warming to any particular level involves accounting for a wide range of uncertainties in the causal chain from emissions to concentration to radiative forcing (the warming effect of changed concentrations in GHGs and aerosols, gaseous suspensions of fine solid or liquid particles that are associated with most CO₂ emissions, on the energy balance of the lower atmosphere) to climate change. Major uncertainties include the sensitivity of the climate system to changes in GHG concentration, the rate at which the ocean takes up heat from the atmosphere, the effects of aerosols on radiative forcing, and the response of the carbon cycle to changes in climate.²⁶

In addition to scientific and technical uncertainties, it is important to decide how much confidence there needs to be that a warming limit will be achieved—in other words, how certain to be that specific risks and damages will be avoided or prevented. The emission pathways that are consistent with limiting warming to, say, 2 degrees Celsius or below with a 50 percent confidence are very different, and higher, than those that would do so with 90 percent confidence. (See Box 2–2 for how GHG concentration levels

change for different probabilities of limiting warming to 2 degrees Celsius.) Before turning to the specific question of “safe” levels of emissions, this section reviews some of the important scientific aspects of generating an emission pathway.²⁷

The important greenhouse gases have long lifetimes in the atmosphere, with large fractions of emissions remaining there for decades to centuries—and in some case, such as CO₂, for a thousand years or longer. Cutting emissions of these long-lived gases therefore leads to only slow reductions in their warming effect. Aerosols from human activities (principally sulfate compounds, organic and black carbon, nitrates, and dust) have a net cooling effect on the lower atmosphere and offset some of the warming effect of the long-lived GHGs.²⁸

Aerosols have short lifetimes in the air, on the order of days or weeks. Reducing aerosol emissions thus has a rapid effect on temperatures since aerosol concentrations can drop quickly. The effect is so large that if all combustion and other activities that emit CO₂ and lead to the production of aerosols were cut to zero overnight, there would be a sharp warming spike before temperatures began to decline. The rapid drop in the concentration of aerosols would lead to a sudden loss of their cooling effect, which would occur faster than the slow reduction in the warming effect due to the much more slowly declining greenhouse gas concentrations. In realistic scenarios, when GHG emissions are reduced, air pollutants are also reduced. This leads to a more rapid reduction in aerosol concentrations, including those related to black carbon (suspended particles that absorb heat and contribute to warming), than in the greenhouse gas concentrations. As a consequence, the drop in aerosol cooling leads to a delay in the reduction of warming that would otherwise occur.²⁹

Box 2–2. Greenhouse Gas Concentrations and Global Warming

Converting greenhouse gas concentrations to temperature cannot be done with certainty, as scientific knowledge of the sensitivity of the climate system is uncertain. Climate sensitivity is defined as the global mean temperature increase that would result in the long term after a doubling of CO₂ concentration above the preindustrial level of about 278 ppm. This temperature would be reached after a few hundred years, when the climate system comes into balance with the increased greenhouse gas concentration. The IPCC Fourth Assessment Report found that this was higher than previously estimated. It increased the “best” estimate from 2.5 to 3 degrees Celsius and the lower bound estimate from 1.5 to 2 degrees Celsius, and it kept the upper bound of 4.5 degrees Celsius unchanged from earlier assessments. There is some possibility that the climate sensitivity could be higher than 4.5 degrees.

Climate sensitivity is a vital number: if it were low (1 degree Celsius), then CO₂ levels could perhaps be doubled to around a concentration of 550 ppm CO₂ without causing large risks to many systems. If it were high (4.5 degrees), a doubling of CO₂ concentration could lead to a potentially catastrophic level of warming.

For stabilization of greenhouse gas concentrations at 550 ppm CO₂, the best estimate of the warming at equilibrium would be 3 degrees Celsius. The uncertainty in scientists’ knowledge of climate sensitivity means that there is a chance the warming would be lower or higher than this.

Taking into account this uncertainty, there is about a 75 percent risk that stabilizing greenhouse gas concentrations at 550 ppm would lead to warming exceeding 2 degrees Celsius.

Stabilizing at a lower level, 475 ppm CO_{2eq}, would reduce the risk to about 50 percent: in other words, there would be about an even chance that warming would stabilize at 2 degrees. Risks of dangerous changes to the climate system at this level could not be avoided with any confidence. Finally, for a concentration pathway that peaks at 475 ppm CO_{2eq} and then drops to stabilize at 400 ppm CO_{2eq}, there would be about a 20 percent chance of exceeding 2 degrees Celsius. If concentrations were reduced further, the risk of exceeding 2 degrees would be lower still.

In 2005, atmospheric CO₂ concentrations were 379 ppm, and they are now over 382 ppm. The IPCC best estimate of the total CO₂-equivalent concentration in 2005 for all long-lived GHGs was about 455 ppm—and at the end of 2007 it was 460 ppm. For 2005, the most recent year for which comprehensive figures are available, the “net” forcing, after taking into account aerosols and other human-induced climate forcing agents, was around 375 ppm CO_{2eq}, or about the same as the CO₂ concentration. Aerosols are short-lived; hence reductions of these lead to rapid reductions in the net cooling effect, whereas reductions in long-lived GHGs produce only a slow reduction in the warming effect.

Source: See endnote 27.

A further important property of the climate system that has to be accounted for in devising a safe emission pathway is inertia. Although the atmosphere responds quickly to changes in greenhouse gas forcing, a substantial component of the overall response is linked to the very long time scales of hundreds to thousands of years that the ocean takes to respond fully to the same climate forcing changes. Once GHG concentrations are stabilized, global mean temperature

would very likely also begin to stabilize after several decades, though a further slight increase is likely to occur over several centuries. For sea level rise the inertia is even larger, as thermal expansion of the ocean continues for many centuries after GHG concentrations have stabilized due the ongoing heat uptake by oceans.³⁰

The response of the carbon cycle to additions of fossil CO₂ is also very long. Of 1,000 tons of fossil CO₂ emitted now, after one cen-

ture less than 500 tons would remain in the atmosphere. The rate of uptake of fossil CO₂ emissions by the world's oceans slows rapidly after a century or so; 1,000 years from now, 170–330 tons would remain in the atmosphere—and even after 10,000 years some 100–150 tons would remain. As David Archer, a geologist from the University of Chicago puts it, the lifetime of a fossil CO₂ emission in the atmosphere might best be described as “300 years, plus 25% that lasts forever.”³¹

Limiting the peak warming to less than 1 degree Celsius will require a multicentury commitment to action.

All these climate system processes and factors need to be brought within an integrated system model that accounts for the interactions between emissions of greenhouse gases and aerosol pollutants and the responses and interactions among the different components of the climate system. For the analysis here, a new version of the simple climate-carbon cycle model MAGICC has been used to comprehensively capture current scientific knowledge and uncertainties in the response of the climate system. MAGICC 6.0 has been calibrated against, and can emulate, the higher complexity Atmospheric Ocean General Circulation models and carbon cycle models reviewed in the latest IPCC assessment. And it includes enhanced representations of aerosol forcing, carbon cycle feedbacks, ocean heat uptake, and climate sensitivity behavior over time. Reduced complexity models such as MAGICC are used as it is not practical to run many different emissions scenarios through a full climate system model. And further, as no specific model is a perfect representation of the climate system, doing so would not describe the scientific

uncertainties in the response to a given emissions path.³²

The greenhouse gases covered in the UNFCCC and the Kyoto Protocol, as well as the ozone-depleting substances (also greenhouse gases) covered in the Montreal Protocol, need to be accounted for in devising emission pathways. The phaseout of these latter gases also has a positive benefit for the climate. Emissions of air pollutants affect aerosol concentrations, including black carbon, and also affect concentrations of tropospheric ozone, a short-lived GHG. All these key climate forcings are included in MAGICC 6.0.³³

Emission pathways are usually expressed in terms of CO₂-equivalent emissions, where the effects of non-CO₂ gases—methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride—are compared using global warming potentials calculated over a 100-year time frame, as in the UNFCCC and Kyoto Protocol. This convention is followed here.

Limiting the peak warming to less than 2 degrees Celsius will not be easy, and getting it back below 1 degree Celsius will be even harder, requiring a multicentury commitment to action. The inertia in the response of the climate system to rapid reductions in GHGs and aerosols means that even stringent short-term reductions in greenhouse gas emissions will not ensure that peak warming stays below about 1.6–1.8 degrees Celsius. Reducing emissions fast enough to actually lower the level of warming ultimately will be as difficult as it is essential.³⁴

The goal of the pathway in this chapter is to show what might be a safe emission scenario without requiring a full demonstration of technical feasibility. It could be argued that the “safest” pathway is one that immediately cuts emissions to very low levels. But since that lacks technical and economic fea-

sibility, such a pathway has little meaning. The jet plane metaphor is again helpful. Faced with a dire in-flight emergency, it would be safest to be on the ground immediately. In the real world, however, it takes time to prepare the aircraft, get into a safe configuration for descent and landing, and find a safe runway to land on. Otherwise the outcome would be an unmitigated disaster—the plane would crash.

The approach taken here is to construct a pathway whose achievement in practice is plausible technically. It goes beyond the technically and economically feasible pathways published elsewhere so far. No pathway published to date brings warming below 1 degree Celsius. A few pathways could get warming below 1.5 degrees Celsius by the twenty-third century if the negative CO₂ emissions at the end of the twenty-first century in these scenarios were sustained for at least 100 years.³⁵

Recent research has demonstrated that it is technically and economically feasible to reduce CO₂ emissions fast enough so that GHG concentrations can be limited to around 400 ppm CO_{2eq}, or to lower in the longer term. Under these scenarios it is likely that peak warming would occur close to, if not below, 2 degrees Celsius. And in some cases temperatures might slowly decline beyond the twenty-first century. All these scenarios require rapid fossil fuel CO₂ emission reductions, approaching zero emissions between 2050 and 2100, along with rapid reductions in deforestation.³⁶

One very important finding is that in order to reach low stabilization levels of GHG concentrations, nearly all these scenarios require negative CO₂ emissions by the last quarter of the twenty-first century at the latest. Without this it is impossible to draw down atmospheric CO₂ concentrations, owing to the long lifetime of this gas. With-

out this key component, CO₂ concentrations would drop only slowly, and warming would likely remain well above 1.5 degrees Celsius for many centuries.³⁷

The possible need to stabilize CO₂ at low concentration levels to avoid dangerous climate changes has been recognized for a long time, as has the need for negative CO₂ emissions if low CO₂ stabilization levels are to be reached. But evaluation of the implications of the technologies required to achieve this is only just beginning. In the low stabilization studies, models rely on the capture of CO₂ from biomass-fired power plants to essentially draw CO₂ out of the air so it can be stored underground in stable geological reservoirs (referred to often as biomass energy with carbon capture and storage, or BECS, technology). Biofuel plantations grow plants that take up CO₂ from the air as they grow, and if much of this is captured when the plants are burned, the process effectively pumps CO₂ out of the air. The environmental and sustainability consequences of such a strategy have yet to be fully evaluated. Air capture technology—taking CO₂ out of the air and storing it underground—has also been proposed as a feasible technology.³⁸

While reducing emissions from deforestation is important, the scale of potential uptake of carbon in forests and agricultural soils is unlikely to be sufficient to draw atmospheric CO₂ concentrations down significantly. Recent results using the LPJ (Lund-Potsdam-Jena) land biosphere model—with scenarios of population increase, deforestation, land use change, and agriculture from the Dutch IMAGE 2.2 integrated assessment model—indicate that under high environmental sustainability assumptions (taking into account the effects of increased CO₂ and climatic changes) the net uptake of carbon over the twenty-first century would not increase the additional carbon stored in terrestrial

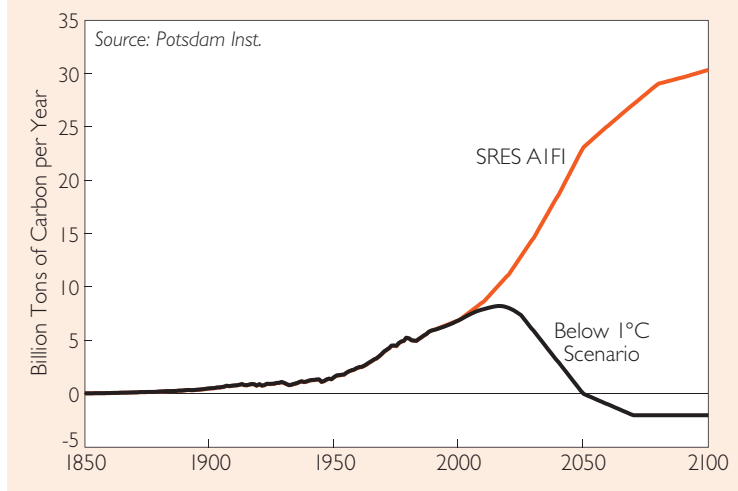
ecosystems due to human activities enough to outweigh the need for negative emissions from the energy sector.³⁹

Recent scenarios that keep warming below 2 degrees Celsius and get to concentrations of around 400 ppm CO_{2eq} or lower reduce CO₂ emissions 60–70 percent below 1990 levels and cut total GHGs around 40–60 percent by 2050. And they have negative CO₂ emissions in the range of 1 billion to 8 billion tons of carbon per year in 2100. All would require BECS.⁴⁰

The emission pathway required to limit warming to below 2 degrees Celsius with higher confidence and at the same time reduce warming rapidly to below 1 degree Celsius (see Figure 2–1) would require a more rapid reduction in emissions by 2050 than in the most recent scenarios, which have already been at the limits of what models indicate is feasible based on present technological assessments. Plausible additional measures to achieve this include a more rapid reduction in fossil fuel emissions.

Getting fossil CO₂ emissions down to close to zero in 2050—which would be 25 years earlier than in most low-stabilization scenarios—would require an earlier and more massive global deployment of renewable energy systems, accelerated energy efficiency measures, and a limit to the lifetime of coal power plants. (See Chapter 4.) Deploying as-yet-unproven carbon capture and storage (CCS)

Figure 2–1. CO₂ Emissions from Fossil Fuels through 2100, IPCC SRES (High) Scenario and the Below 1 Degree Celsius Scenario



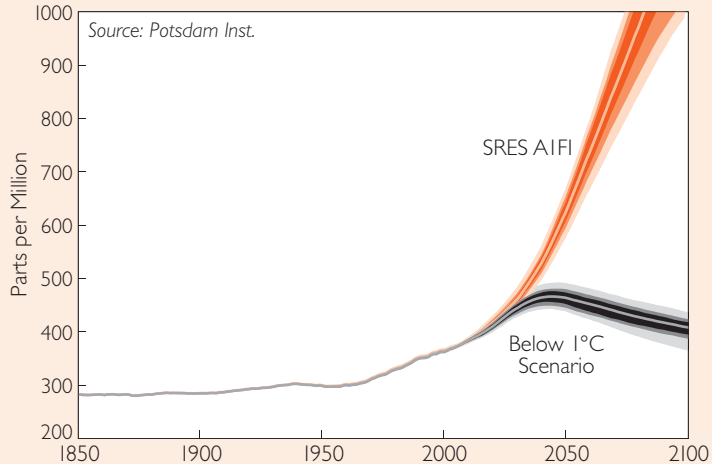
technology after the mid-2020s may also help. However, the expected large life-cycle energy and emissions costs of CCS technology indicate that it cannot be relied on to reduce fossil CO₂ emission to zero. The faster that renewable energy systems can be scaled up and deployed, the less will be needed of CCS coal and gas power plants.⁴¹

In addition to action on fossil fuels, deforestation would need to be halted well before 2030, and there would need to be large-scale efforts to store carbon in soils through progress toward sustainable agriculture and regrowing forests. (See Chapter 3.) The reductions assumed here for emissions of methane and nitrous oxide, two powerful greenhouse gases, from agriculture and industry are not taken significantly further than can be found in the literature for low scenarios. And the emission pathway is relatively insensitive to the phaseout schedules for emissions of ozone-depleting substances, hydrofluorocarbons, perfluorocarbons, and

sulfur hexafluoride.⁴²

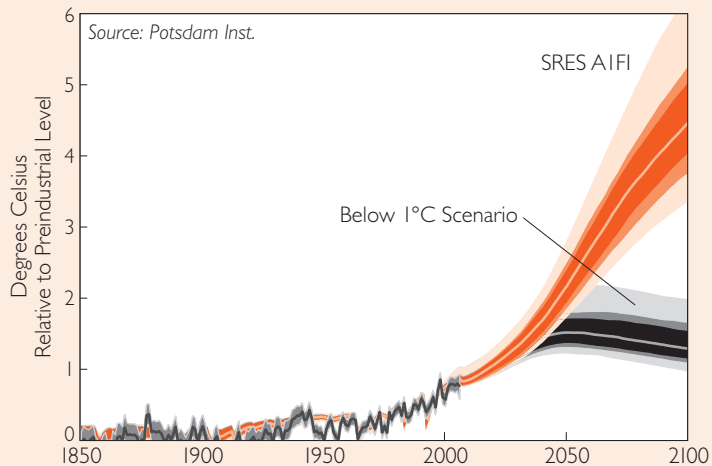
The resulting pathway has Kyoto GHG reductions of around 85 percent from 1990 levels by 2050 after peaking before 2020. (See Figure 2–2.) GHG atmospheric concentrations drop below today's levels by the mid twenty-second century and toward the preindustrial level by the twenty-fourth century. After the 2050s this pathway also would require the capture from the atmosphere and permanent storage of initially around 2.5 billion tons of carbon a year (about 9 billion tons of CO₂ per year) for more than 200 years in order to draw total GHG concentrations down to below 300 ppm CO_{2eq}. Global temperatures should peak below 2 degrees Celsius around mid-century and begin a slow decline, dropping to present levels by the last half of the twenty-third century and to 1990s levels by the end of the twenty-fourth century. (See Figure 2–3.) In Figures 2–2 and 2–3, there are bands of projected levels due to

Figure 2–2. Greenhouse Gas Atmospheric Concentration through 2100, IPCC SRES (High) Scenario and the Below 1 Degree Celsius Scenario



Note: The darker parts show the higher confidence range of changes for the emission pathway shown.

Figure 2–3. Global Mean Surface Temperature through 2100, with Uncertainty, IPCC SRES (High) Scenario and the Below 1 Degree Celsius Scenario



Note: The darker parts show the higher confidence range of changes for the emission pathway shown.

uncertainties in the science.

The amount of carbon that would need to be captured and stored to achieve all this would be on the same order as that emitted since the nineteenth century. As the amount of additional carbon that can be taken up and stored by the terrestrial biosphere due to human activities is limited—assumed here to be about 0.5 billion tons a year during much of the latter part of the twenty-first century and dropping to zero by 2200—the extraction of CO₂ from the atmosphere would have to be largely done using technologies similar to those just mentioned.

Just as the effects of climate change pose enormous long-term problems, a safe resolution of the problem will require a commitment to action that spans centuries. Returning to warming levels significantly below 2 degrees Celsius implies the need for large long-term extraction of CO₂ from the air and the storage of the captured carbon in secure underground reservoirs, which will need to be watched and managed over many centuries, perhaps millennia. Extracting CO₂ from the air appears to be a necessity that must be confronted within the next 50 years.

From any perspective the consequences of following an emissions pathway that keeps the temperature increase below 1 degree Celsius are quite radical and may be seen as technologically, economically, and politically close to impossible. But this needs to be placed against the also quite radical risks that global warming poses if emissions are not reduced to low levels.⁴³

As difficult as this emissions pathway seems, it is important to note that the low-emissions scenarios reviewed by the IPCC (all consistent with limiting warming to about 2 degrees Celsius) start out much like this one. In the lowest scenarios, global emissions need to peak before 2020. After that it may not be possible for technologies to be

introduced fast enough to lower emissions at the rate required to keep warming below 2 degrees Celsius. Delay in acting entails faster rates of emissions reduction and significantly increased costs to reach the goal. And it might totally foreclose the ability to reduce GHG concentrations to low levels once societies are locked into emission-intensive energy sources and other infrastructure as well as development pathways that are carbon-intensive. Delay obviously also increases the risk of more-severe climate change impacts.⁴⁴

Once a global emission pathway is defined, the next key question is, How much GHG can countries emit and still be consistent with global emissions limits? There are many possible ways to allocate emissions to countries to meet global limits, and review of these is beyond the scope of this chapter. Nevertheless it is useful here to point out the broad implications of the 2 degrees Celsius emissions pathway for different groups of countries in the next decade and beyond.⁴⁵

An indication of the required reductions can be seen from the IPCC Fourth Assessment Report, where the reductions for different regions from a range of models are reviewed for different GHG stabilization scenarios. The lowest scenario was for stabilization at 450 ppm CO_{2eq}, far higher than the CO_{2eq} stabilization levels that would provide a higher probability of keeping warming below 2 degrees Celsius. Industrial-country GHG reductions in 2020 were generally required to be 25–40 percent below 1990 levels. By 2050, reductions for these countries would need to be 80–95 percent below 1990 levels. (The reductions refer to emission allowances and hence do not necessarily indicate the physical emissions levels of the countries in 2020 or 2050.) The exact reduction for each industrial country depends on the emission allocation system, individual circumstances, and other assumptions in the

different models assessed.⁴⁶

For developing countries, by 2020 there would need to be a substantial reduction in the growth of emissions in Latin America, the Middle East, and East Asia (China and others), but not in South Asia (including India) or Africa. By then the wealthier developing countries would need to reduce significantly the growth in emissions from their business-as-usual emissions. By the 2050s, all these regions would have to substantially reduce the growth in emissions. For the few scenarios available that stabilize GHG concentrations at 400 ppm CO_{2eq}, which would provide around a 75 percent chance of limiting warming to below 2 degrees Celsius, the emissions reductions in 2020 and 2050 are quite similar to but a little lower than in the higher scenarios.

Critical Priorities for the Next 10 Years

Halting the increase in global warming at far below 2 degrees Celsius is possible, and lowering global warming as rapidly as possible to below an increase of 1 degree Celsius appears critical if there is to be a high probability of preventing dangerous climate change. The

emissions reduction actions required to achieve this are massive and appear to be at the outer edge of what is technically and economically feasible. Scenarios that can start to get within reach of these temperature goals require GHG emissions to peak before 2020 and then to drop toward 85 percent below 1990 levels by 2050, with further reductions beyond this time.

To return to the metaphor of the heavy jet aircraft facing an emergency, wherever the aircraft is going to land it needs to start preparing a long way out. Altitude needs to be lost without excessive speed buildup, fuel needs to be dumped and systems checked and prepared for a landing, and all this must be done quickly and expeditiously. As for climate policy, the vital preparation for a safe landing—whether the final safe landing place is a 2 degrees Celsius runway or a below 1 degree Celsius runway—is to halt the rise in global emissions by 2020 and to start to put in place the policies that can lower emissions. For policymakers, these are the decisions that must urgently be made at the end of 2009 when governments gather in Copenhagen for the next Conference of the Parties to the climate change convention.

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