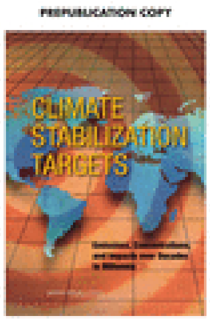
Stabilization Targets for Atmospheric Greenhouse Gas Concentrations



Committee on Stabilization Targets for Atmospheric Greenhouse Gas Concentrations; National Research Council

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Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia

Committee on Stabilization Targets for Atmospheric Greenhouse Gas Concentrations

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

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Summary

Society faces important choices in the coming century regarding future greenhouse gas emissions and the resulting effects on the Earth's climate, ecosystems, and people. Atmospheric concentrations of several important greenhouse gases have increased markedly since the start of the 20th century because of human activities, and the increased concentrations of these gases *very likely*[1] account for most of the globally averaged warming of the past fifty years. Carbon dioxide is responsible for more than half of the current impact of human emissions of greenhouse gases on Earth's climate, or radiative forcing[2], and its influence is projected to grow. Its atmospheric concentration has increased by more than 35 percent since 1750, and is now higher than at any time in at least 800,000 years. Looking to the future, the concentration of carbon dioxide could undergo a further doubling or tripling by the end of the century, greatly amplifying the human impact on climate.

Because of the long atmospheric lifetime of carbon dioxide and the time lags in the climate system (particularly slow processes in the ocean, see 3.2), human choices in the near-term have long-term ramifications on Earth's climate not only for the rest of the century but also for the next several millennia. Indeed, some effects of 21st century human choices would contribute to climate change for more than 100,000 years. {2.1, 3.2}[3]

One way of informing these choices is to consider the projected climate changes and impacts that would occur if greenhouse gases increase to particular concentration levels and then stabilize, as highlighted in the Statement of Task (see Appendix A). Alternative futures then can be represented by a broad range of atmospheric concentration "target" levels (hereafter referred to as stabilization targets). The committee was charged to evaluate different stabilization targets

[1] In this report, uncertainty ranges indicated as *likely* correspond to >66% probability (2 out of 3 chance), while *very likely* is used for >90% (9 out of 10 chance). Assessed uncertainty intervals are not always symmetric about the corresponding best estimate, and include statistical information and expert judgment.

[2] **Radiative forcing (RF)** refers to the radiative flux change evaluated at the tropopause (which has been adjusted for stratospheric changes, see Ramaswamy et al., 2007). Greenhouse gases such as carbon dioxide, methane, and nitrous oxide exert a warming influence on climate, and differ in their radiative forcing of the global climate system due mainly to their different radiative properties and abundances in the atmosphere. Some greenhouse gas changes (e.g., stratospheric ozone depletion) and aerosols produce negative radiative forcing. The net RF is the sum of positive and negative terms, and each term is defined as the change relative to 1750. These warming influences may be expressed as **CO_2-equivalent concentrations**, corresponding to the concentration of CO_2 that would cause the same amount of radiative forcing as a given mixture of CO_2 and other forcing components.

[3] Throughout this summary and the technical overview presented in the next section, numbers in curly brackets refer to sections of the main report where details and references are to be found.

with particular emphasis on the avoidance of serious or irreversible impacts on the Earth's climate system. This report does not evaluate the plausibility of any stabilization target, nor does it make any recommendations regarding desirable or "safe" targets.

It should be emphasized that choosing among different targets is a policy issue rather than strictly a scientific one, because such choices involve questions of values, e.g., regarding how much risk to people or to nature might be considered too much. Some climate changes could be beneficial for some people or regions, while being damaging to others.

The primary challenge for this study is to quantify, insofar as possible, the outcomes of different stabilization targets using analyses and information drawn from the scientific literature. Expected changes based on broad scientific understanding are discussed, as well as projected values based upon models. Where there is sufficient understanding to be quantitative, numerical values for projected climate change and impacts are provided as a function of stabilization target. A number of important aspects of climate change that are currently understood in a qualitative manner, or for which the time horizon of the response is poorly constrained, are also reviewed. The report represents a brief summary of a vast scientific literature and seeks to be illustrative and representative rather than comprehensive. Special emphasis is placed on climate changes and impacts in North America and the United States.

The report focuses on human forcing of the climate system from carbon dioxide emissions and rising atmospheric concentrations because of the dominant role and unique influences of carbon dioxide on long-term climate change. The role of other anthropogenic greenhouse gases, such as methane, nitrous oxide and halocarbon, and aerosols are also briefly discussed. For many purposes, the total radiative forcing of the suite of anthropogenic greenhouse gases and aerosols can be cast in terms of an equivalent level of atmospheric carbon dioxide, also known as the CO_2-equivalent concentration.

APPROACH

The goal and implications of stabilizing climate change are most often discussed in terms of stabilizing atmospheric concentrations of CO_2. This report takes a different approach by 1) using global temperature change as the frame of reference, and 2) focusing in part on the relationship between accumulated carbon emissions and global mean temperature change.

The motivation for this approach is both practical and conceptual. Available data and modeling suggest that the magnitudes of many key impacts can be quantified for given amounts of global warming through scaling of local to global warming and through coupled linkages to warming (such as alterations in the water cycle that scale with warming). But while published analyses of future climate impacts can be tied to specific warming levels in particular studies, this information often cannot readily be linked to CO_2-equivalent concentrations (because, for example, of lack of information on aerosol forcing used in many future climate impact studies based on emission scenarios).

Moreover, using warming as the frame of reference provides a picture of impacts and their associated uncertainties in a warming world – uncertainties that are distinct from the uncertainties in the relationship of CO_2-equivalent concentrations to warming. Use of warming as a metric of change also permits coverage of the transient climate changes and impacts while concentrations increase, as well as the lock-in to further changes after stabilization. Further, the approach taken here facilitates cataloguing ranges of impacts that should be expected for 1°C, 2°C, 3°C, or other levels of warming. The reader can thus consider how much warming s/he considers to be an appropriate target. Information is also provided to translate warming into best estimates of associated CO_2-equivalent target concentrations with these best estimates accompanied by estimated likely uncertainty ranges derived from uncertainty in climate sensitivity.

Furthermore, this report also describes the cumulative carbon framework, a perspective that has recently received considerable attention. Rather than CO_2-equivalent concentration levels, this approach considers the amount of carbon emissions accumulated over time and the implications of different accumulated emissions targets. Models consistently suggest a persistent temperature response to a given level of cumulative carbon emissions. Accumulated carbon emission targets link to impacts through temperature (or warming) and are clearly relevant to policy aimed at controlling emissions and reducing the risk of dangerous impacts. The approaches used here thereby provide additional policy-relevant information that would be lost in an analysis that only related impacts to CO_2-equivalent concentration levels.

KEY FINDINGS

There are three key findings of this report, which correspond to the structure of this summary:

1. Climate change in the very long term: Future stabilization targets correspond to altered states of the Earth's climate that would be nearly irreversible for many thousands of years, even long after anthropogenic greenhouse gas emissions ceased. The capacity to adapt to slow changes is generally greater than for near-term rapid climate change, but different stabilization levels can lock the Earth and many future generations of humans into large impacts that can occur very slowly over time, such as the melting of the polar ice sheets; similarly, some stabilization levels could prevent such changes.

2. Climate change in the next few decades and centuries: Understanding the implications of future stabilization targets requires paying attention to the expected climate change and to the emissions required to achieve stabilization. Because of time-lags inherent in the Earth's climate, the observed climate changes as greenhouse gas emissions increase reflect only about half of the eventual total warming that would occur for stabilization at the same concentrations. Moreover, emission reductions larger than about 80% (relative to whatever peak global emission rate may be reached) are required to approximately stabilize carbon dioxide concentrations for a century or so at any chosen target level (e.g., 450 ppmv, 550 ppmv, 650 ppmv, 750 ppmv, etc.), Even greater reductions in emissions would be required to maintain stabilized concentrations in the longer term. It should be emphasized that this finding is not linked to any particular policy choice about time of stabilization or stabilization concentration, but applies broadly, and is due to the fundamental physics of the carbon cycle presented in Chapter 2.

3. Climate changes, impacts and choices among stabilization targets: A number of key climate changes and impacts for the next few decades and centuries can now be identified and estimated at different levels of warming. Many impacts can be shown to scale with warming (see Figure S.5). Scientific progress has resulted in increased confidence in the understanding how global warming levels of 2, 3, 4, 5°C, etc. (see Figure S.1) affect precipitation patterns, extreme hot seasons, streamflow, sea ice retreat, reduced crop yields, coral bleaching, and sea level rise. This increased confidence provides direct scientific support for evaluating the implications of different stabilization targets. However, other climate changes and impacts are currently understood only in a qualitative manner. Many potential effects on human societies and the natural environment cannot presently be quantified as a function of stabilization target (see Figure S.6). This shortcoming does not imply that these changes and impacts are negligible. Some of these impacts, such as species changing their ranges or behavior, could be very important; indeed, some may dominate future risks due to anthropogenic climate change. Uncertainty in the carbon dioxide emissions and concentrations corresponding to a given temperature target is large, and choices about stabilization targets depend upon judgments regarding the degree of acceptable risk associated with both quantifiable and non-quantifiable impacts and changes.

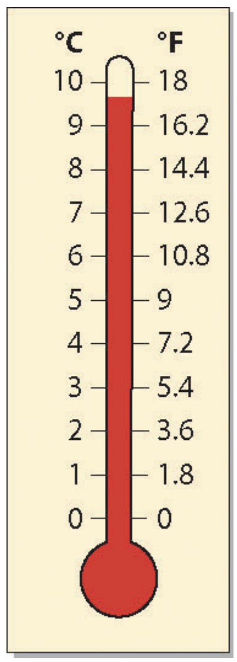

FIGURE S.1 Illustration of how temperature change in degrees Celsius (left side of thermometer) relates to temperature change in degrees Fahrenheit (right side of thermometer). For example, a warming of 5 degrees Celsius is equal to a warming of 9 degrees Fahrenheit. In this report estimates of temperature change are made in degreees Celsius in accordance with international scientific practice.

SUPPORTING EVIDENCE

1. Cumulative Carbon Dioxide Emissions and Climate Change Over Millennia

Climate changes that occur because of carbon dioxide increases are expected to persist for thousands of years[4] even if emissions were to be halted at any point in time. Recent scientific

[4] Approaches to 'geoengineer' future climate, e.g., to actively remove carbon from the atmosphere or reflect sunlight to space using particulate matter or mirrors are topics of active research. If effective, these may be able to reduce or reverse global warming that would otherwise be effectively irreversible. This

literature has shown that the contribution to global warming caused by anthropogenic CO_2 can be directly related to the cumulative emissions of carbon dioxide.

For example, our best estimate (see Figure S.2) is that one thousand gigatonnes of anthropogenic carbon (GtC) emissions leads to about 1.75°C increase in global average temperature[5], implying that approximately 1150 gigatonnes of carbon (or 4200 Gt CO_2) would lead to a global-mean warming of 2°C (the stated aspirational goal of the 'group of eight' nations). Based on current understanding, this warming is expected to be nearly irreversible for more than 1,000 years (Figure S.3). Figure S.2 shows best estimates and likely uncertainty ranges for cumulative carbon emissions leading to a range of warming levels, along with cumulative emissions to date (about 500 GtC). Carbon dioxide alone accounted for about 55 percent of the total CO_2 equivalent concentration of the sum of all greenhouse gases in 2005. The contribution of carbon dioxide increases to between 75 and 85 percent of total CO_2-equivalent by the end of this century based on a range of current emission scenarios. Some anthropogenic carbon dioxide is removed by the oceans and biosphere in decades to centuries, but the slow time-scales of the long-term uptake of carbon in the ocean means that some is expected to persist in the atmosphere for many thousands of years. This behavior is unique to carbon dioxide among major radiative forcing agents. Choices regarding continued emissions or mitigation of other warming agents such as methane, black carbon on ice/snow, and aerosols can affect the global warming of coming decades but have little effect on the lock-in to longer-term warming of the Earth over centuries and millennia; that commitment is primarily controlled by carbon dioxide. {2.1, 2.2, 2.3, 3.4}

BOX S.1
GtC (Gigaton of carbon)

One gigaton of carbon is one billion tons of carbon, where "carbon" refers literally to the mass of carbon, *not* the mass of a molecule as a whole (i.e., all the atoms), but just the mass of carbon atoms.
<u>Example</u>: Burning 1 gallon of gasoline emits approximately 19.6 lbs of CO_2 (http://cdiac.ornl.gov/pns/faq.html), so if you assume a typical American vehicle gets 20 miles per gallon and it travels 15,000 miles per year, then the typical American vehicle emits about 1.8 tons of carbon per year. Stated differently, about 550,000,000 average American vehicles would emit 1 GtC per year.

The Earth is now entering a new geological epoch, sometimes called the Anthropocene, during which the evolution of the planet's environment will be largely controlled by the effects of human activities, notably emissions of carbon dioxide. Actions taken during this century will determine whether the Anthropocene climate anomaly will be a relatively short term and minor deviation from the Holocene climate, or an extreme deviation extending over many thousands of years.

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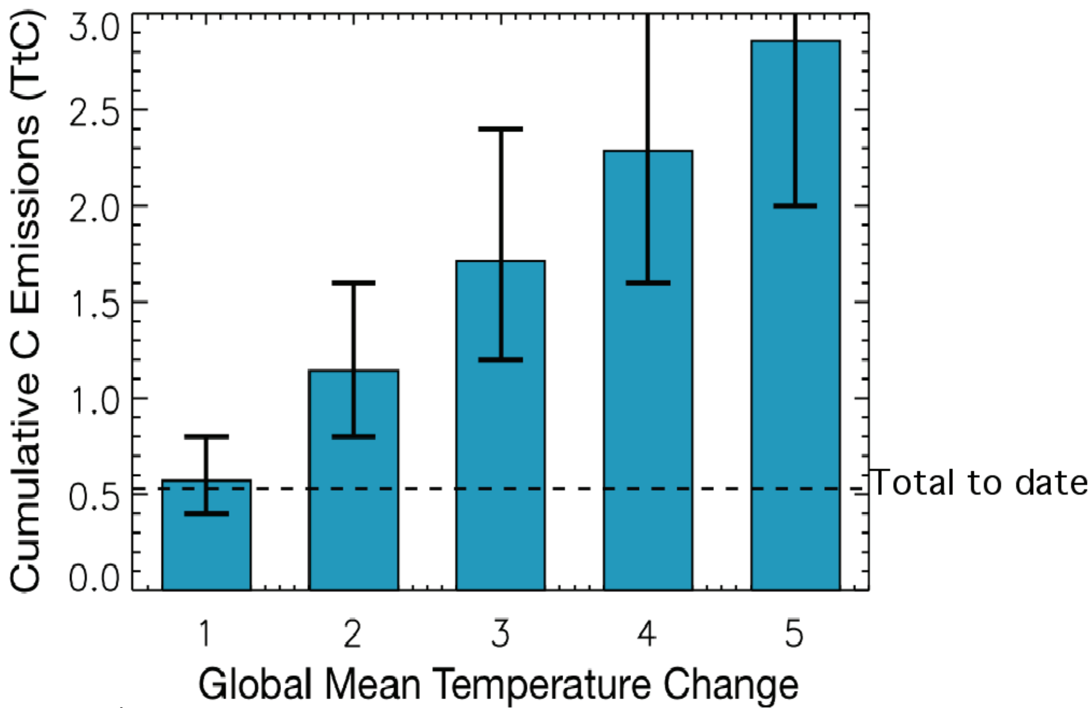
study does not evaluate geoengineering options, and statements throughout this report regarding the commitment to climate change over centuries and millennia from near term emissions should be read as assuming no geoengineering. Reforestation or other methods of sequestration of carbon are also not considered.

[5] The quasi-linear response of temperature to cumulative carbon is discussed in detail in Section 2.7.



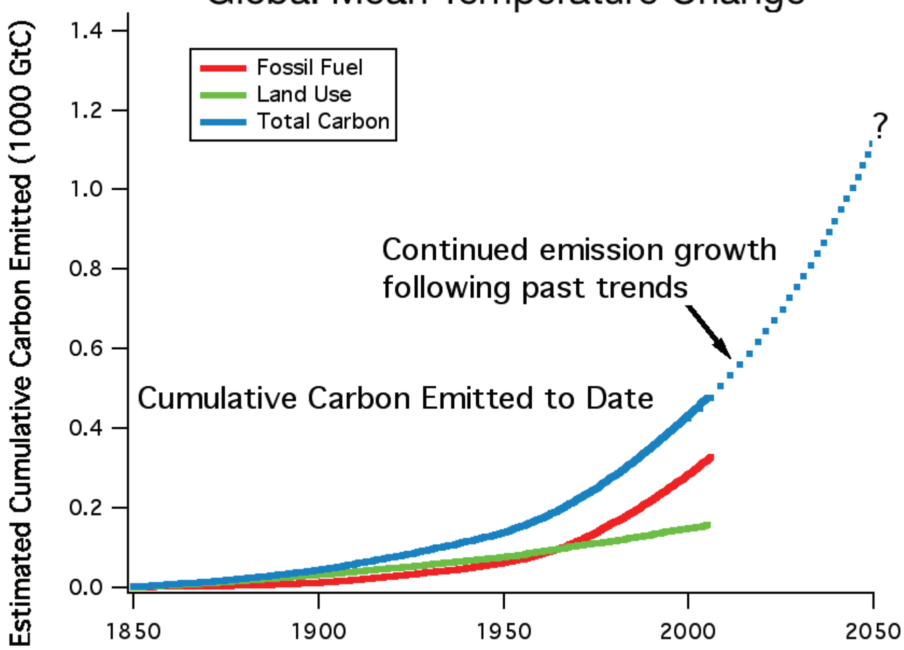


FIGURE S.2 (top) Best estimates and likely range of cumulative carbon emissions that would result in global warming of 1, 2, 3, 4, or 5°C (see Figure S.1), based on recent studies which have demonstrated a near-linearity in the temperature response to cumulative emissions (see Section 3.4) Error bars reflect uncertainty in carbon cycle and climate responses to CO_2 emissions, based on both observational constrainsts and the range of climate-carbon cycle model results (see Section 3.4). (bottom) Estimated global cumulative carbon emissions to date from fossil fuel burning and cement production, land use, and total. The figure also shows how much cumulative carbon would be emitted by 2050 if past trends in emission growth rates were to continue in the future, based upon a best fit to the past emission growth curve. {3.4}

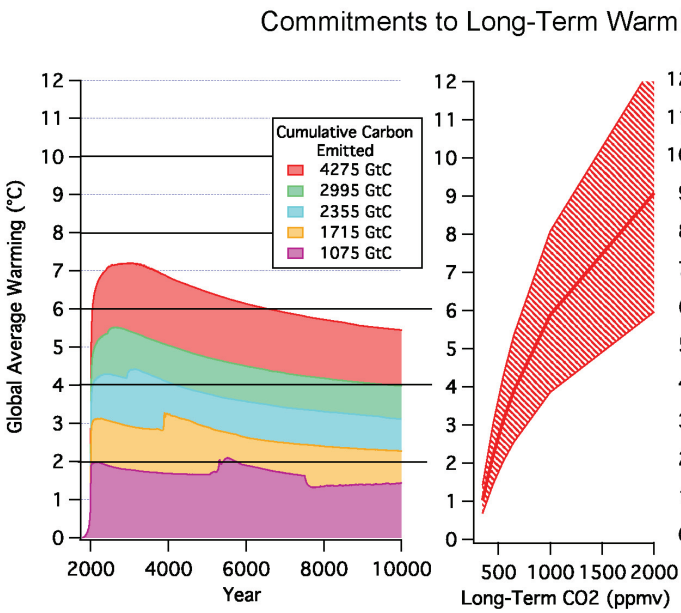


FIGURE S.3 Commitments to global warming over thousands of years, expressed as best estimates depending upon the cumulative anthropogenic carbon emitted (direct human emission plus possible induced feedbacks such as release of carbon from clathrates, see below) by the end of the next few centuries from a model study (left, from the calculations presented in Eby et al., 2009), the corresponding long-term carbon dioxide concentrations, shown as best estimates and likely ranges (middle, from Table 3.1 of this report), and estimated range of corresponding global average sea level rise (right, see Section 6.1; the adopted equilibrium long-term thermal sea level rise is 0.2-0.6 m per degree as noted in Meehl et al., 2007). The 'low' and 'high' onset values in the right panel reflect differences between available climate models in the global mean temperature at which the Greenland ice sheet will disappear after thousands of years since the accumulation cannot sustain the ice loss by melt in the ablation area and rapid ice flow-related loss along the margins. This depends not only on increased ice loss from warming but also on increased accumulation from greater snowfall in a warmer world, and the balance between these terms differs from model to model. The range across models is taken from Meehl et al., 2007, based on a detailed analysis of the models evaluated in the IPCC report. Additional contributions from rapid ice discharge are possible (see Chapters 4 and 6). The climate sensitivity used to construct the likely ranges shown in the middle panel is discussed in chapter 3 where it is noted that larger or smaller warmings than the estimated likely value for a given carbon dioxide concentration cannot be ruled out. Bumps in the warming curves in the left panel are because of adjustments in ocean circulation in response to warming in this particular climate model and should be thought of as illustrative only. {3.2, 6.1}

Higher cumulative carbon emissions result in both a higher peak warming and a longer duration of the warming (see Figure S.4). The duration of the warming is critical, because an extended period of warming provides more time for the components of the Earth system that may respond very slowly (such as the deep oceans and the great ice sheets) to assert themselves, even very long after anthropogenic emissions have ceased. {6.1}

The sea level rise implications of the Anthropocene could lead to major changes in the geography of the Earth over the coming millennia. Model studies suggest that a cumulative carbon emission of about 1000 to 3000 GtC would lead to eventual sea level rise due to thermal expansion and glacier and small ice cap loss alone of the order of 1 to 4 meters. Additional contributions from Greenland could contribute as much as a further 4 to 7.5 m on multi-millennial timescales, for a possible total of order 5 to 11.5 meters from thermal expansion, glaciers and small ice caps, and Greenland.

Widespread coastal inundation would be expected if anthropogenic warming of several degrees is sustained for millennia; while these slow changes allow time for adaptation, they are essentially irreversible. The projected fragility of the Greenland ice sheet is in accord with studies suggesting that Greenland was essentially free of ice during the Pliocene era (which was probably about 3°C warmer than pre-industrial times in the mid-Pliocene, about 3-3.3 million years ago). Changes in Antarctica are less clear, in part because both the West and East Antarctic ice sheets must be considered: one study suggests that cumulative carbon emission of about 2000-5000 GtC could also contribute up to five meters of additional sea level rise from West Antarctic ice sheet loss. Future changes in East Antarctica could offset at least part of West Antarctic changes. While carbon emissions in the 21st century are expected to determine the commitments to these eventual future changes, the sea level rise expected to occur in the 21st century is considerably smaller, in the range of 0.5 to 1.0 meters. Some semi-empirical models predict sea level rise up to 1.6 m by 2100 for a warming scenario of 3.1°C, a possible upper limit which cannot be excluded. {6.1, 4.8}

Some slow climate components could act as amplifiers that would greatly increase the size and duration of the Anthropocene.

If elevated global temperatures were to persist for a thousand years or more, some studies suggest that the resulting warming of the deep ocean could release deep-sea carbon stored in the form of methane clathrates[6] in marine sediments. Other contributions could come from the substantial reservoir of near-surface organic carbon in soils and permafrost, whose stability is poorly understood. For example, a release rate of a half GtC per year from such sources would add 2500 Gt of carbon over 5000 years to the carbon emitted directly by humans. For reference, paleoclimate studies suggest that during the Paleocene-Eocene Thermal Maximum (about 55 million years ago), similar amounts of carbon were released in less than 10,000 years. A number of recent studies show that large methane releases from particular local sites have been observed, but these are too limited to imply that globally significant changes are already occurring or will occur for warming levels in the near term. {6.1}

[6] Methane clathrates, also called methane hydrates, are material in which methane is trapped inside a larger crystalline water chemical structure.

2. Stabilization and Climate Change of the Next Few Decades and Next Several Centuries

Because the global anthropogenic source of carbon dioxide greatly exceeds the net global sink (through removal mechanisms in the ocean, land, and biosphere), stabilization of carbon dioxide concentrations at any selected target level would require reductions in total emissions of at least 80 percent (relative to any peak emission level).

Unless the source matches the sink, concentrations of carbon dioxide (and resulting warming influences) will continue to rise, much like the water in a bathtub when water is coming in faster than it is going out. Because current carbon dioxide emissions exceed removal rates, stabilization of carbon dioxide *emissions* at current rates will not lead to stabilization of carbon dioxide concentrations (see Figure S.4). A robust consequence of the stock and flow nature of atmospheric carbon and the physics of the carbon cycle is that emission reductions larger than about 80% (relative to whatever peak emission level occurs) are required to approximately stabilize carbon dioxide concentrations for a century or so and even greater reductions in emissions would be required in the longer term; this applies for any chosen stabilization target.

Observed climate responses in coming decades will be smaller than the longer-term temperature response to any given stabilization level. If carbon dioxide equivalent concentrations were to be stabilized at some point in the future, there would be a lock-in to further warming of comparable magnitude to that already occurring at the time of stabilization.

The instantaneous response of the Earth's atmosphere and oceans to increases in greenhouse gases and net radiative forcing represents a transient climate change, which can be linked to 'transient climate response'.[7] The transient climate response is smaller than the longer-term 'climate sensitivity' that includes adjustments by the oceans to the added heat. For example, if carbon dioxide equivalent concentrations (including aerosols and other gases) were to increase from today's best estimate levels of about 390 parts per million by volume (ppm) to 550 ppm at rates of growth similar to those occurring today, averaged warming would be expected to increase in a manner that scales with the change in radiative forcing relative to the transient climate response; for 550 ppm the best estimate total warming since pre-industrial times is about 1.6°C (within a likely uncertainty range of 1.3-2.2C). In the hypothetical case where concentrations are then immediately stabilized at 550 ppm, further warming would subsequently occur over the next several centuries, reaching a best estimate 'climate sensitivity' of about 3°C (likely in the range of 2.1-4.3°C). The horizontal arrow in Figure S.4 depicts such a transition from transient to equilibrium warming. {2.2, 2.4, 3.2, 3.3}

Climate sensitivity remains subject to considerable uncertainty. The estimated "likely" range presented in this report corresponds to the range of model results in the CMIP3 global climate model archive, and is roughly consistent with paleoclimate evidence. However, the possibility of climate sensitivities substantially higher than this range cannot at present be ruled out. This

[7] The transient climate response is defined as the warming at the time of doubling of CO_2 concentration (compared to a pre-industrial value of 278 ppm this is about 550 ppm). Scaled by radiative forcing, the same relationship characterizes warming that has occurred during the 20th century as well as further warming that is projected to continue with growing CO_2 concentrations in the 21st century for a broad range of plausible scenarios.

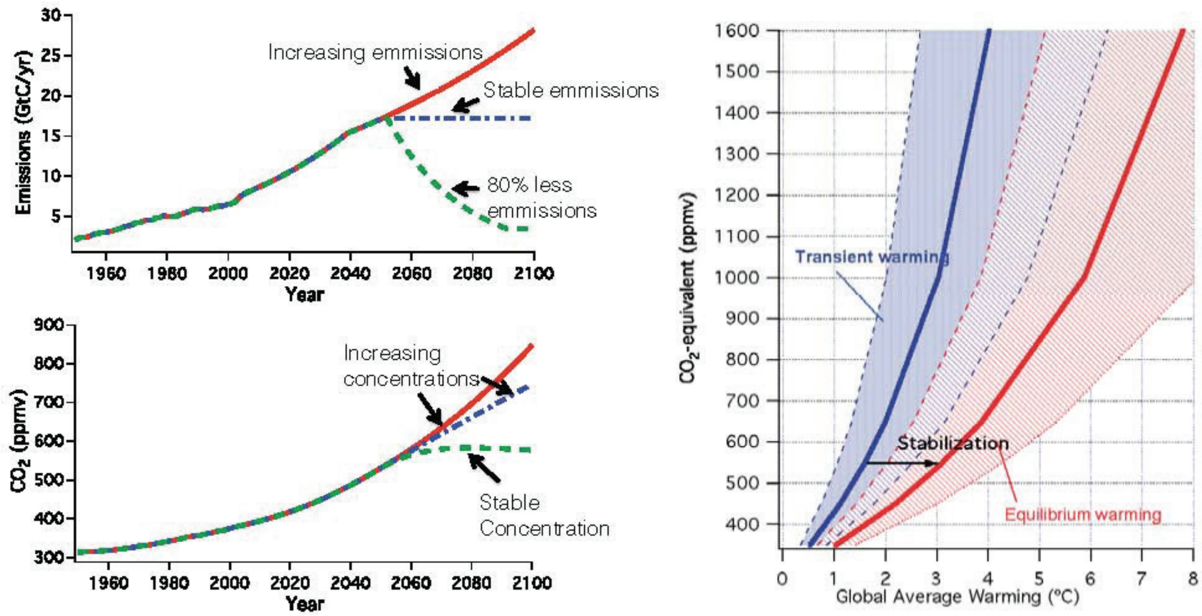


FIGURE S.4 The left panel shows illustrative examples (from calculations using the Bern Earth Model of Intermediate Complexity, see Chapter 2 and Methods) of how carbon dioxide concentrations would be expected to evolve depending upon emissions. Stable emissions (blue lines) do not result in stable concentrations because the source of carbon is much larger than the sink. Emission reductions larger than about 80% are required if concentrations are to be stabilized (green lines). The right panel shows the best estimates and likely ranges of global warming projected for various levels of carbon dioxide concentration in the transient (blue) and equilibrium states, or climate sensitivity (red); see Table 3.1. As carbon dioxide emissions increase, average global warming is projected to follow the blue curve. If concentrations of carbon dioxide were to be stabilized, the global warming is expected to increase from the blue to the red curve, as depicted by the arrow. Note that the equilibrium warming indicated in the figure incorporates only feedbacks from water vapor, clouds sea ice or snow changes; the slower acting feedbacks incoroporated in Earth System Sensitivity may increase the warming (by about 50% over the values shown according to one study by Lunt *et al.* 2009) {2.1, 3.2, 3.3}

TABLE S.1 Estimated likely ranges and best estimate values for transient and equilibrium global averaged warming verus carbon dioxide equivalent concentrations.

CO_2-equlvalent concentration (ppmv)	Best estimate transient warming (°C)	Estimated likely range of transient warming (°C)	Best estimate equilibrium warming (°C)	Estimated likely range of equilibrium warming (°C)
350	0.5	0.4-0.7	1	0.7-1.4
450	1.1	0.9 -1.5	2.2	1.4-3.0
550	1.6	1.3-2.1	3.1	2.1-4.3
650	2	1.6-2.7	3.9	2.6-5.4
1000	3	2.4-4.0	5.9	3.9-8.1
2000	4.7	3.7-6.2	9.1	6.0-12.5

report should be read with this proviso in mind, as these high sensitivities, if realized, would amplify many of the impacts discussed and associated risk. (3.2, 3.3, 6.1)

3. Climate Changes, Future Impacts, and Choices among Stabilization Targets

Increases in global mean temperature caused by higher anthropogenic greenhouse gas concentrations would be expected to lead to a diverse range of changes in potentially damaging climate-related parameters and impacts, affecting many aspects of human society and the natural environment.

The magnitude of some near-term (next few decades and centuries) climate changes and impacts can be estimated for specific levels of global mean temperature change experienced, illustrating how stabilization at different levels of greenhouse gas forcing would be expected to alter our world (see Figure S.5). Approximate estimates of these effects, per degree C of global warming, include:

- 5-10% changes in precipitation in a number of regions
- 3-10% increases in heavy rainfall[8]
- 5-15% yield reductions of a number of crops[9]
- 5-10% changes in streamflow in many river basins worldwide, including several in the U.S.
- about 15% and 25% decreases, in the extent of annually averaged and September Arctic sea ice, respectively

In addition, effects at particular levels of warming include:

- Increases in the number of exceptionally warm summers (i.e., 9 out of 10 boreal summers that are "exceptionally warm" in nearly all land areas for about 3°C of global warming, and every summer "exceptionally warm" in nearly all land areas for about 4°C, where an "exceptionally warm" summer is defined as one that is warmer than all but about 1 of the 20 summers in the last decades of the 20th century).
- 200-400% increases per degree in wildfire area burned in several western North American regions for 1-2°C
- Increased coral bleaching, and net erosion of coral reefs, due to warming and changes in ocean acidity (pH) for carbon dioxide levels corresponding to about 1.5-3°C of global warming.
- Sea level rise in the range of 0.5 to 1.0 m in 2100 (reached in a scenario corresponding to about 3±1°C of global warming) and an associated increase in the number of people at risk from coastal flooding by 5-200 million[10] as well as global wetland and dryland losses of more than 250,000 square kilometers.

{4.1, 4.2, 4.5, 4.6, 4.7, 4.8, 4.9, 5.1, 5.2, 5.3, 5.4}

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[8] heaviest 15% of daily falls
[9] unless adaptation measures not presently in hand become available

[10] with the range depending mainly on uncertainty in adaptation measures undertaken

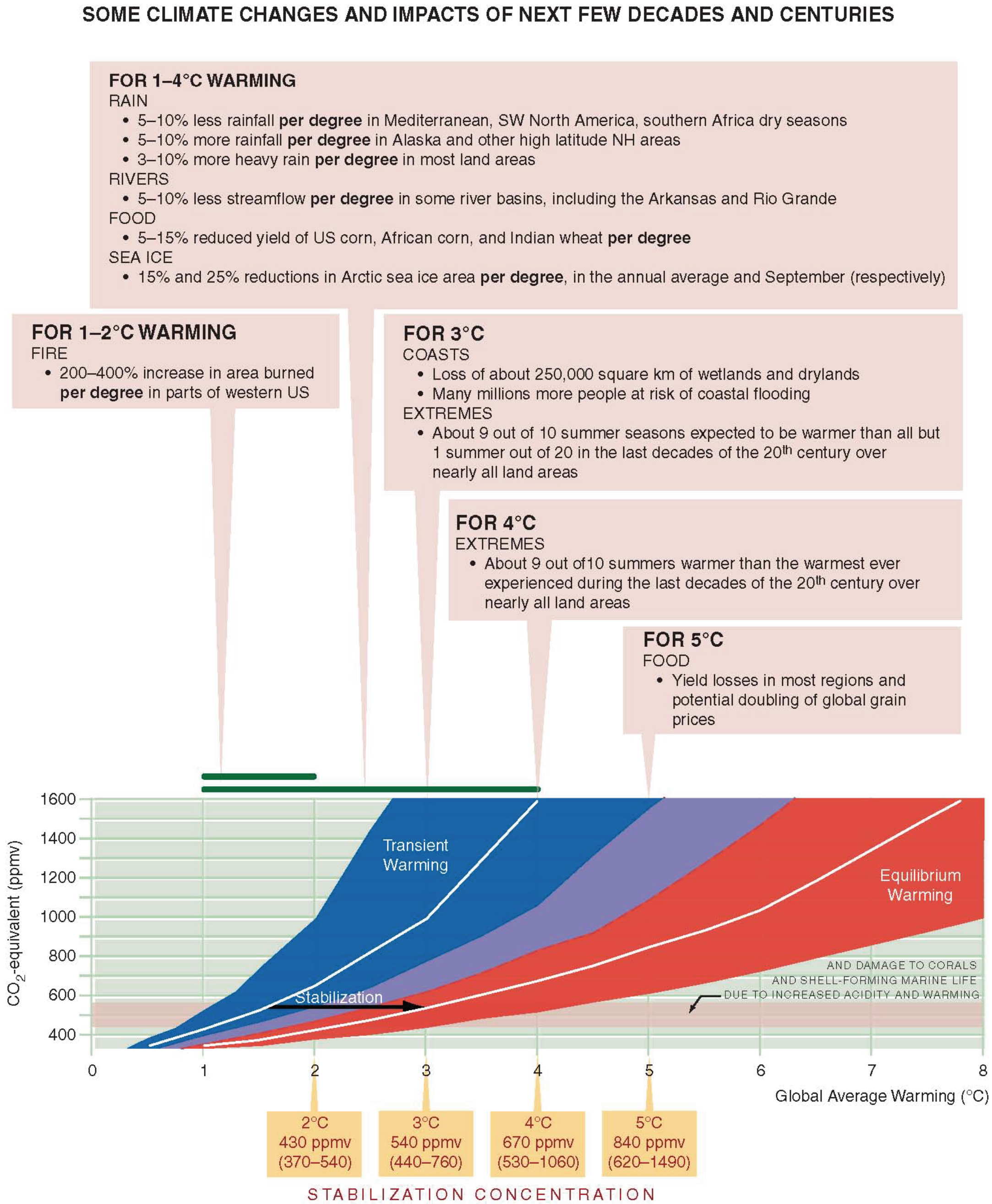


FIGURE S.5 Climate changes and climate impacts as a function of global warming (not in priority order or implied importance). These anticipated effects are projected to occur in the 21st century following the transient warming for a given CO_2 equivalent concentration, followed by further warming to the equilibrium value for stabilization at a given target concentration. As in previous figures, for discussion of transient and equilibrium warming see chapter 3, where it is noted that the probability distribution of climate sensitivity is uncertain; larger or smaller warmings than the estimated likely value for a given carbon dioxide equivalent concentration cannot be ruled out. Ranges are shown for climate impacts over the globe or over large regions; specific regions, crops, river basins, etc. and their uncertainties are discussed in detail in the full report. {3.2, 3.3, 4.2, 4.5, 4.6, 4.7, 4.8, 4.9, 5.1, 5.2, 5.3, 5.4, 5.7, 5.8}

Many important impacts of climate change are difficult to quantify for a given change in global mean temperature, but the risk of adverse impacts is likely to increase with global mean temperature change.

For some impacts, this difficulty arises because temperature is a primary, but not necessarily the only, driver of change. Quantification can also be difficult due to uncertainty in observing and modeling the response of a given system to temperature changes or other climate and non-climate factors, and additional complexity due to the influence of multiple environmental and other anthropogenic factors. It is clear from many scientific studies documenting projected impacts across numerous sectors and regions, however, that a number of impacts do scale approximately with global temperature. Hence, these are expected to intensify in response to a greater temperature change. An illustrative set of temperature-dependent impacts are summarized in Figure S.6. These include shifts in terrestrial and marine species ranges and abundances (including die-off in some cases), increased risk of heat-related human health impacts, loss of infrastructure in coastal regions (due to sea level rise) and the Arctic (due to sea level rise, retreat of sea ice and associated coastal erosion, and permafrost loss). This summary of temperature-related impacts is intended to be indicative rather than comprehensive. Figure S.6 does not include all possible temperature-sensitive impacts, such as projected extinctions due to climate change and increased risks to national security. {4.7, 4.9, 5.5, 5.6, 5.7, 5.8}

Uncertainty in the cumulative carbon or stabilized carbon dioxide concentration that corresponds to a given temperature target is large. It follows that choices about stabilization targets depend upon judgments regarding the degree of acceptable risk.

The likely range of cumulative carbon emissions corresponding to a given warming level is estimated to lie between -30% to +40% of the best estimate. This range is due mainly to uncertainties in the carbon cycle response to emissions and the climate response to increased radiative forcing. For a cumulative anthropogenic emission of 1000 GtC, our best estimate of the warming remains below 2°C, but there is about an estimated 17% probability that the warming could exceed 2°C for more than 1500 years. When cumulative emissions are increased to 1500 GtC, the best estimate of the anthropogenic warming remains above 2°C for over 3500 years, and the very likely upper end warming is still over 2.5°C for more than 10,000 years. Higher values cannot be excluded, implying additional risk which cannot presently be quantified. On the other hand, at the lower end of carbon-climate likely uncertainty range, there may be about an 17% chance that warming could remain below 2°C even if as much as 1700 GtC are emitted. Figure S.3 and S.5 provide some scientific reasons why global warming of a few degrees could be considered dangerous to some aspects of nature and society, but the corresponding uncertainty ranges should be emphasized here. For example, while the best estimate of a stabilization target corresponding to a long-term warming of 2°C is 430 ppm, the likely uncertainty range for this value spans from 380 (below current observed levels) to 540 ppm (almost a doubling of carbon dioxide relative to pre-industrial times). {3.4, 6.1}

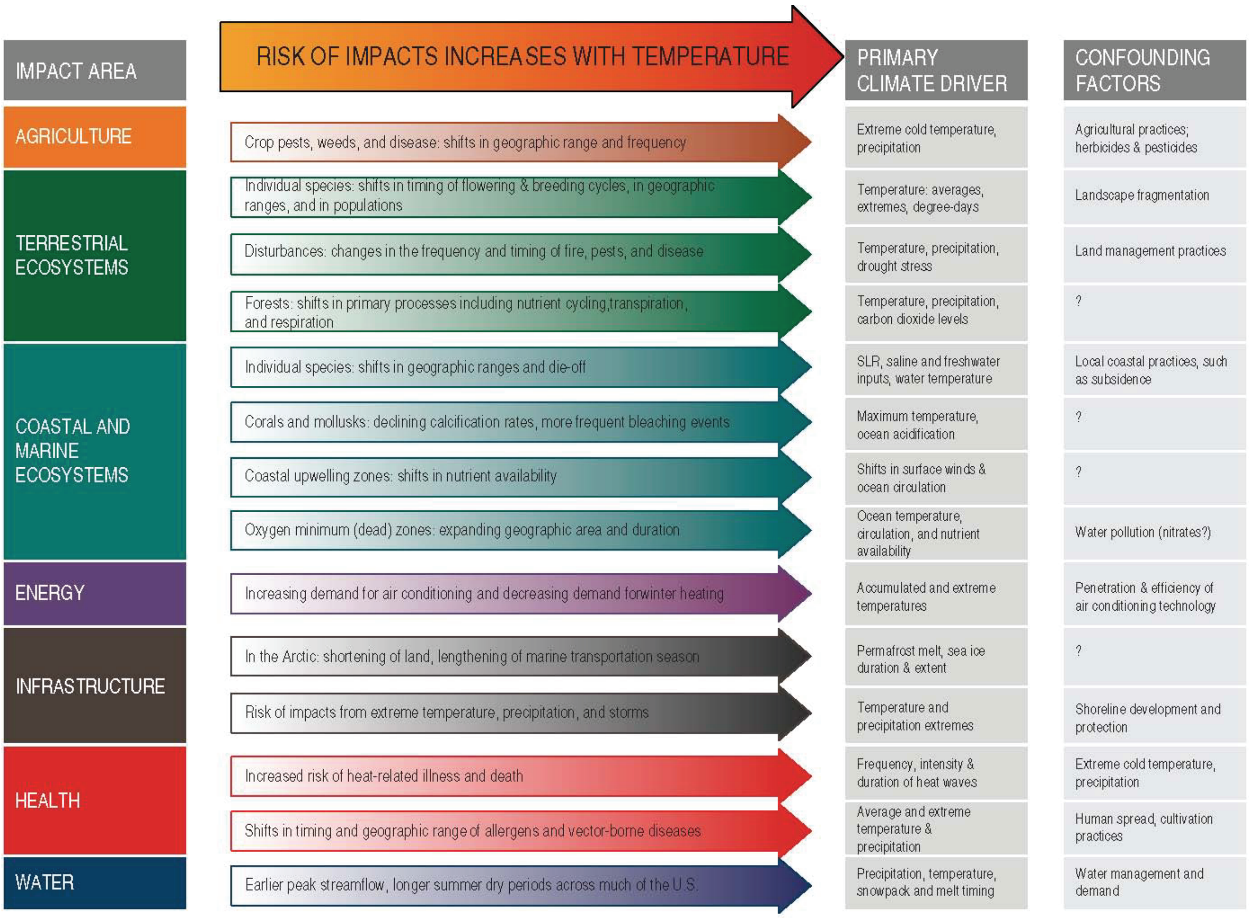


FIGURE S.6 Our understanding of the impacts of climate change is still evolving and quantitative information is currently too limited to provide numerical estimates of the scale, scope, and timing of some impacts. This figure illustrates a number of such possible impacts along with their primary drivers as well as available information on confounding factors. {5.1-5.8, 2.4}

Many important aspects of climate change and its impacts are expected to be approximately linear and gradual, slowly becoming larger and more significant relative to climate variability as global warming increases.

This report highlights the importance of 21st century choices regarding stabilization targets and how they can be expected to affect many aspects of Earth's future. Progressively warmer temperatures are expected to slowly lead to larger and more significant changes for impacts including wildfire extent, decreases in yields of some (but not all) crops, streamflow changes, decreased Arctic sea ice extent, increases in heavy rainfall occurrence, and other factors presented. However, it should be noted that many climate changes and impacts remain poorly understood at present. For example, the record of past climates suggests that major changes such as dieback of the Amazon forests or substantial changes in El Nino behavior can occur. This report identifies some areas where recent science suggests reduced effects compared to earlier studies (including e.g., projected future changes in hurricane activity). This report does not identify any specific projections of abrupt climate changes that the committee considers to be robustly established, e.g. based on clear physical understanding of processes and multiple models. However, it is clear that the risk of surprises can be expected to increase with the duration and magnitude of the warming. Finally, this report shows throughout that present emissions represent commitments to growing current and future impacts, including the very long-term future over many thousands of years. {2.4, 3.4, 4.3, 4.4, 5.8, 6.1, 6.2}

2
Emissions, Concentrations, and Related Factors

2.1 CONTRIBUTION OF DIFFERENT CHEMICALS TO CO_2 EQUIVALENT LEVELS AND CLIMATE CHANGES

A range of anthropogenic chemical compounds contribute to changing the Earth's energy budget, thereby causing the planet's global climate to change. For example, increases in greenhouse gases absorb infrared energy that would otherwise escape to space, acting to warm the planet, while some types of aerosol particles can contribute to cooling the planet by reflecting incoming visible light from the Sun. These components of our atmosphere are emitted from a variety of human activities, including for example fossil fuel burning, land use change, industrial processes such as cement production, and agriculture. The gases and particles involved are frequently referred to as drivers of climate change, or radiative forcing agents. A detailed review of radiative forcing is presented in Forster et al. (2007) and Denman et al. (2007). Radiative forcing due to various climate change agents can be converted to equivalency with the concentration of CO_2 (CO_2 equivalent), one frame of reference for this report (see Figure 2.1). Here we briefly summarize how major forcing agents contribute to current and future CO_2 equivalent target levels and explore implications for global mean temperature increases.

Some greenhouse gases and aerosols are retained for days to years in the atmosphere after emission. The concentrations of such compounds in the atmosphere are tightly coupled to the rate of emission. Their concentrations would drop rapidly if emissions were to cease. Increasing emissions lead to increases in concentrations of such gases, while constant emissions are required for their concentrations to be stabilized. Methane is a key greenhouse gas with an atmospheric lifetime of about 10 years whose concentration has approximately doubled since the pre-industrial era (1750), and it is the second most important greenhouse gas, currently contributing about 25 ppmv of CO_2 equivalent (see Figure 2.1). Over the period from about 1998 to 2007, methane concentrations remained nearly constant (Forster et al., 2007). Methane has, however, begun increasing after about 2007. In the absence of mitigation, methane is expected to continue to make significant contributions to climate change over the 21st century (see Section 2.2).

In sharp contrast, some greenhouse gases have biogeochemical properties that lead to atmospheric retention times (lifetimes) of centuries or even millennia. These gases can accumulate in the atmosphere whenever emissions exceed the slow rate of their loss, and concentrations would remain elevated (and influence climate) for timescales of many years even in the complete absence of further emission. Like the water in a bathtub, concentrations of carbon dioxide are building up because the anthropogenic source substantially exceeds the natural net sink. Even if human emissions were to be kept constant at current levels, concentrations would still increase, just as the water in a bathtub does when the water comes in faster than it can flow out the drain. The removal of anthropogenic carbon dioxide from the atmosphere involves multiple loss mechanisms, spanning the biosphere and ocean (see Section

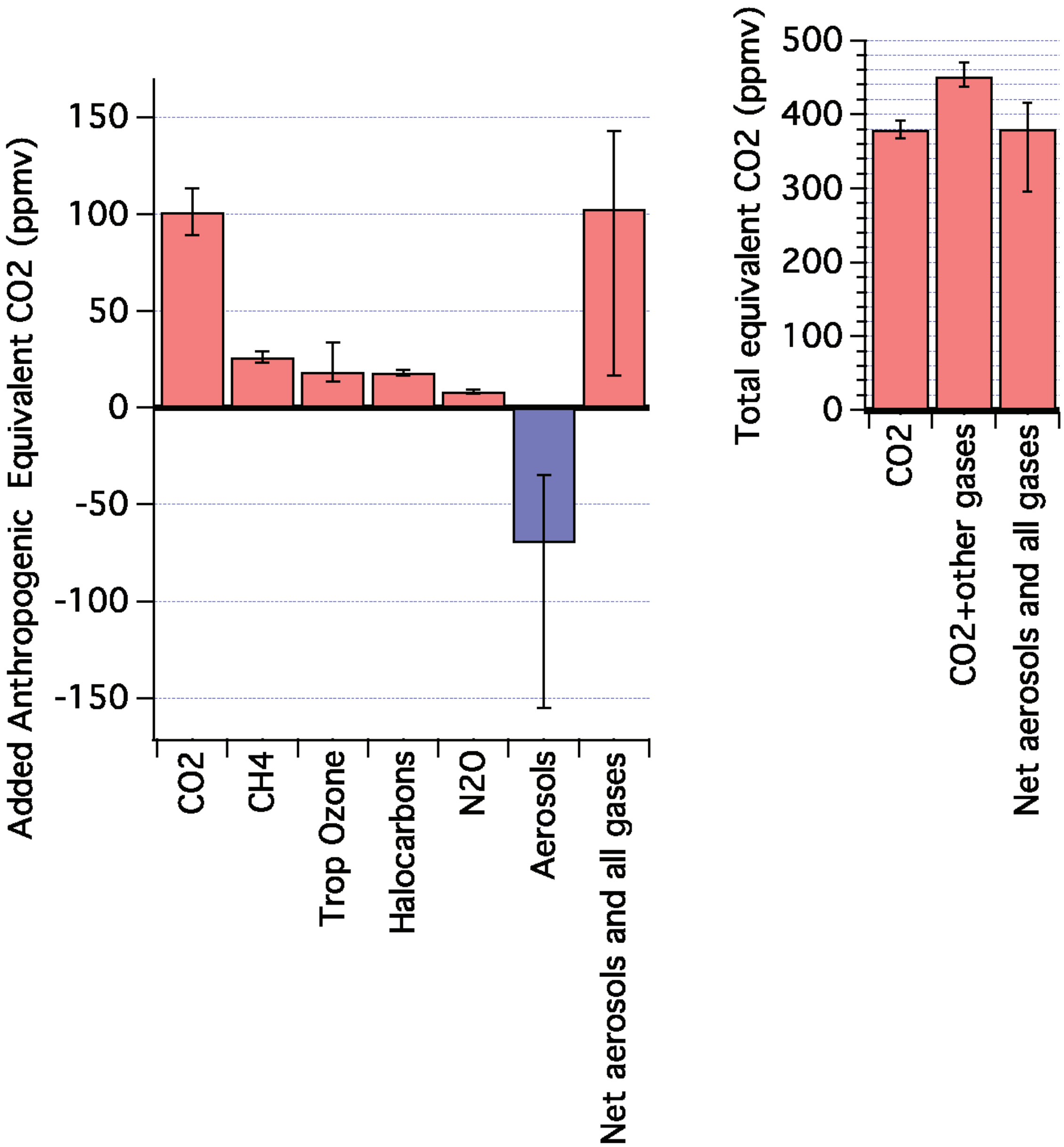


FIGURE 2.1 (left) Best estimates and very likely uncertainty ranges for aerosols and gas contributions to CO_2-equivalent concentrations for 2005, based upon the radiative forcing given in Forster et al. (2007). All major gases contributing more than 0.15 W m^{-2} are shown. Halocarbons including chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, and perfluorocarbons have been grouped. Direct effects of all aerosols have been grouped together with their indirect effects on clouds. (right) Total CO_2 equivalent concentrations in 2005 for CO_2 only, for CO_2 plus all gases, and for CO_2, plus gases plus aerosols.

2.4), and carbon dioxide removal cannot be characterized by any single lifetime. While some carbon dioxide would be lost rapidly to the terrestrial biosphere and to the shallow ocean if human emissions cease, some of the enhanced anthropogenic carbon will remain in the atmosphere for more than a thousand years, influencing global climate (Archer and Brovkin, 2008). The warming induced by added carbon dioxide is expected to be nearly irreversible for at least 1000 years (Matthews and Caldeira, 2008; Solomon et al., 2009), see Section 3.4.

Figure 2.1 shows that carbon dioxide is the largest driver of current anthropogenic climate change. Other gases such as methane, nitrous oxide, and halocarbons also make significant contributions to the current total CO_2 equivalent concentration, while aerosols (see Section 2.3) exert an important cooling effect that offsets some of the warming. The best estimate of net total CO_2 equivalent concentration of the sum across these forcing agents in the year 2005 is about 390 ppmv (with a very likely range from 305 to 430 ppmv). Global carbon dioxide emissions have been increasing at a rate of several percent per year (Raupach et al., 2007). If there were to be no efforts to mitigate its emission growth rate, scenario studies suggest that carbon dioxide could top 1000 ppmv by the end of the 21st century. Carbon dioxide alone accounts for about 55% of the current total CO_2 equivalent concentration of the sum of all greenhouse gases, and increases to between 75 and 85% by the end of this century based on a range of future emission scenarios (see Section 2.2). Thus carbon dioxide is the main forcing agent in all of the stabilization targets discussed here, but the contributions of other gases and aerosols to the total CO_2-equivalent remain significant, motivating their consideration in analysis of stabilization issues.

How large a reduction of emissions is required to stabilize carbon dioxide concentrations, and does it depend upon when this is done, or on the chosen target stabilization concentration? Studies over the past five years of so using many different carbon cycle models have improved our understanding of requirements for carbon dioxide stabilization. This is because of more detailed treatments of carbon-climate feedbacks, including the ways in which warming decreases the efficiency of carbon sinks as compared to earlier work (e.g., Jones et al., 2006; Matthews, 2006). Figure 2.2 shows an example of stabilization for two different Earth Models of Intermediate Complexity (EMICs), the University of Victoria model and the Bern model (see Methods section for descriptions of these two models; see also Plattner et al., 2008 and references therein for a model intercomparison study). In this example test case, carbon dioxide emissions increase at current growth rates of about 2% per year to a maximum of about 12 GtC per year, followed by a decrease of 3%/year down to a selected total reduction of 50, 80, or 100%. The rate of decrease of 3%/year used here is derived from scenario analysis described in the next section. This section together with the next section aims to probe what plausible rates of emission reduction based upon scenario studies imply for the future evolution of carbon dioxide concentrations. The rate of possible emission reductions of carbon dioxide depends upon factors including e.g., commitments to existing infrastructure and development of alternatives, see Section 2.2. It is interesting to note that even in the case of the phaseout of ozone-depleting substances under the Montreal Protocol, emission reductions were about 10% per year initially but stalled at a total reduction of about 80% of the peak, with some continuing emissions of certain gases occurring due for example to the challenge of finding alternatives for fire-fighting applications (see IPCC, 2005).

Figure 2.2 shows that carbon emission reductions of 50% do not lead to long-term stabilization of carbon dioxide, nor of climate, in either of these models, as has also been shown in previous studies (e.g., Weaver et al., 2007). . . It is noteworthy that the Bern model has weaker carbon-climate feedbacks than the UVIC model; nevertheless both models show the need for emissions reductions of at least 80% for carbon dioxide stabilization even for a few decades, while longer-term stabilization requires nearly 100% reduction. Very similar results were obtained in other test cases run for this study considering peaking at higher values, or decreasing at rates from 1 to 4% per year (see also Weaver et al., 2007, Meehl et al., 2007). Figure 2.3 shows sample calculations evaluated in Meehl et al. (2007) using three different models, for various stabilization levels. Figure 2.3 shows that stabilization levels of 450, 550, 750, or 1000 ppmv require eventual emission reductions of 80% or more (relative to whatever peak emission occurs) in all of the models evaluated. Thus current representations of the carbon cycle and carbon-climate feedbacks show that anthropogenic emissions must approach zero eventually if carbon dioxide concentrations are to be stabilized in the long term (Matthews and Caldeira, 2008). This is a fundamental physical property of the carbon cycle and is independent of the emission pathway or selected carbon dioxide stabilization target. Box 2.1 discusses how emissions of non-CO_2 greenhouse gases could affect attainment of stabilization targets.

Figures 2.2 and 2.3 illustrate a fundamental change in understanding stabilization of climate change that has been prompted by the scientific literature of the past two years or so (see Jones et al., 2006; Matthews and Caldeira, 2008). Early work on stabilization using relatively simple models suggested that slow reductions in emissions could lead to eventual stabilization of climate (e.g., Wigley et al., 1996). But recent studies using more detailed models of key feedbacks in the ocean, biosphere, and cryosphere, have underscored that while a quasi-equilibrium may be reached for a limited time in some models for some scenarios, stabilizing radiative forcing at a given concentration does not lead to a stable climate in the long run. Cumulative emitted carbon can more readily be linked to climate stabilization, due to the irreversible character of the induced warming driven by carbon dioxide (see Section 3.4).

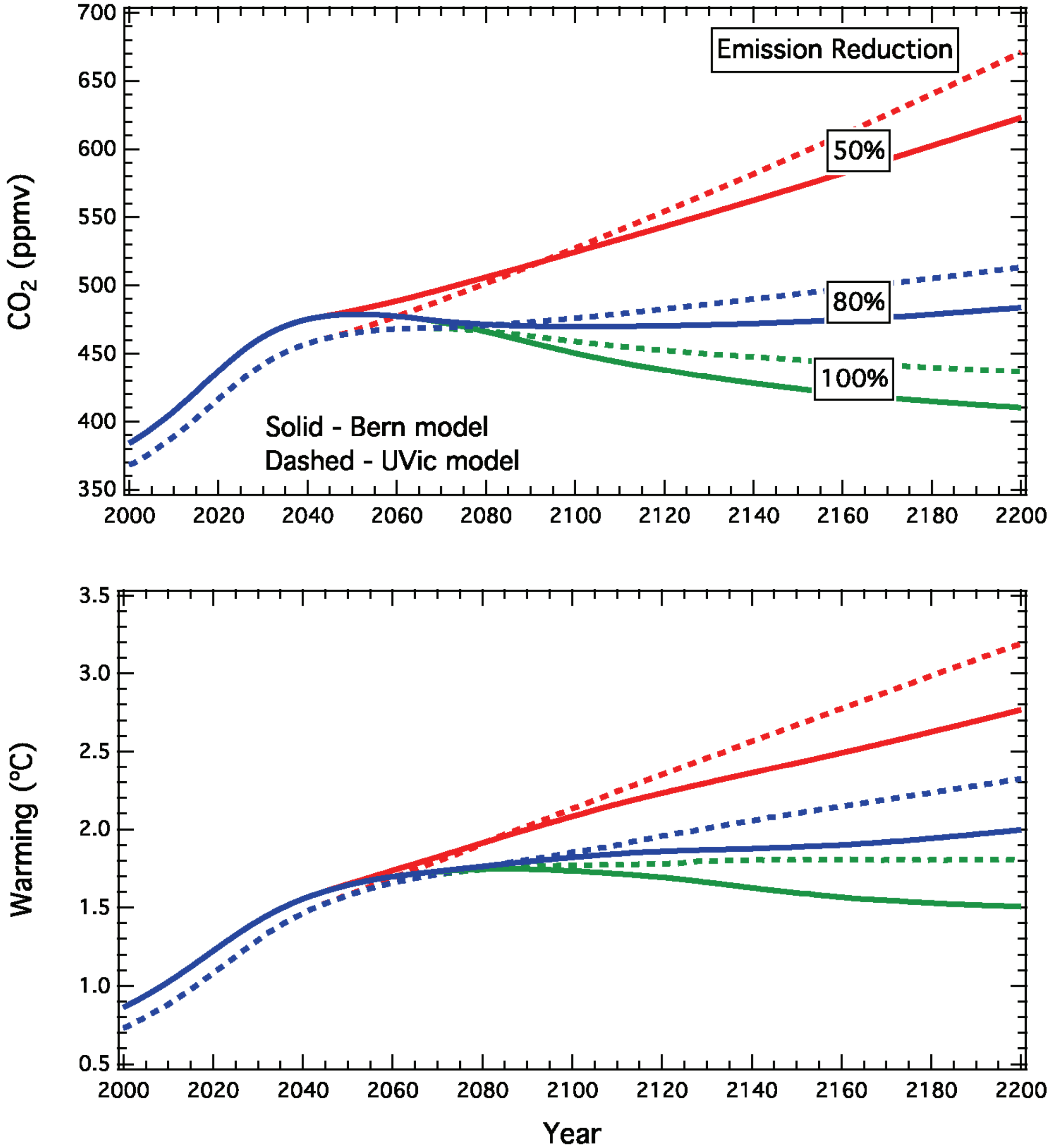


FIGURE 2.2. Illustrative calculations showing CO_2 concentrations and related warming in two EMICS (the Bern model and the University of Victoria model, see Methods) for a test case in which emissions first increase, followed by a decrease in emission rate of 3% per year to a value 50%, 80%, or 100% below the peak. The test case with 100% emission reduction has 1 trillion tonnes of total emission and is also discussed in Section 3.4.

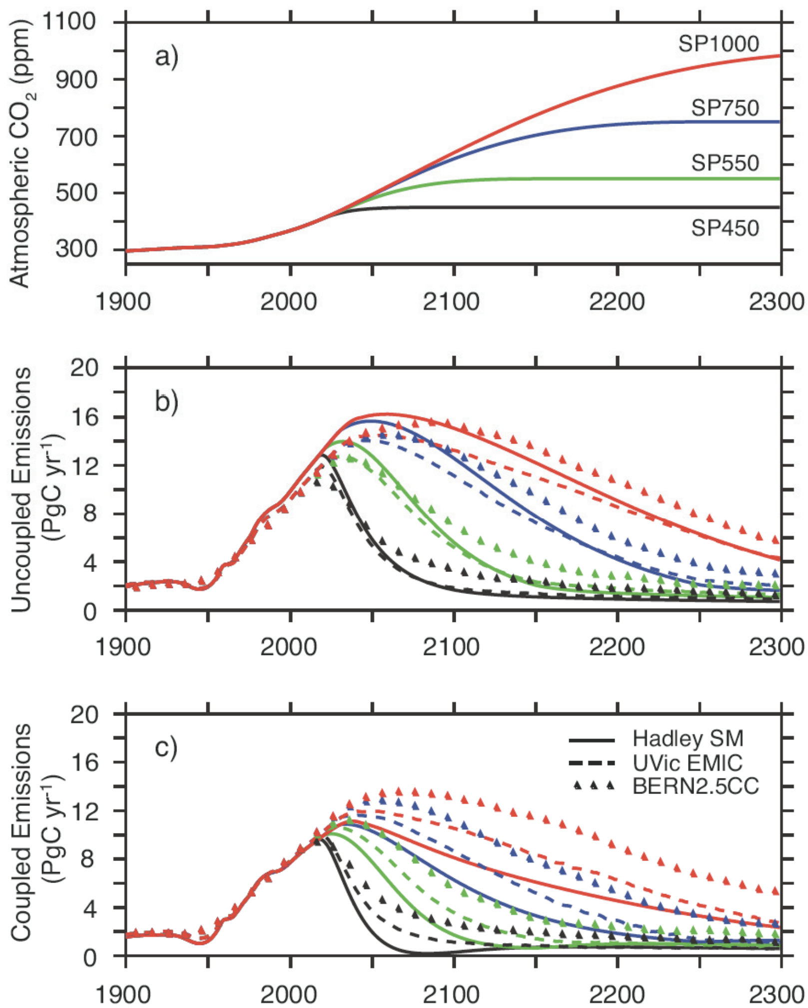


FIGURE 2.3 (a) Atmospheric Illustrative atmospheric CO_2 stabilisation scenarios for 1000, 750, 550, and 450 ppmv; SP1000 (red), SP750 (blue), SP550 (green) and SP450 (black), from Meehl et al. (2007). (b) Compatible annual emissions calculated by three models, the Hadley simple model (solid), the UVic EMIC (dashed) and the BERN2.5CC EMIC (triangles) for the three stabilisation scenarios. Panel (b) shows emissions required for stabilization without accounting for the impact of climate on the carbon cycle, while panel (c) included the climate impact on the carbon cycle, showing that emission reductions in excess of 80% (relative to peak values) are required for stabilization of carbon dioxide concentrations at any of these target concentrations.

BOX 2.1
STABILIZATION AND NON-CO_2 GREENHOUSE GASES.

Because carbon emissions reductions of more than 80% are required to stabilize carbon dioxide concentrations, small continuing emissions of carbon dioxide, or emissions of CO_2-equivalent through other gases, could have surprisingly important implications for stabilizing climate change. For example, emissions of the hydrofluorocarbons (HFCs) currently used as substitutes for chlorofluorocarbons make a small contribution to today's climate change. However, because emissions of these gases is expected to grow in future if they are not mitigated, and because of the stringency of the requirement of near zero emissions of CO_2-equivalent emissions, these gases could represent a significant future impediment to stabilization efforts. For example, the Figure below shows that in the absence of mitigation, the HFCs could represent as much as a third of the allowable CO_2-equivalent emissions in 2050 required for a stabilization target of 450 CO_2-equivalent. Thus, the analysis presented here underscores that stabilization of climate change requires consideration of the full range of greenhouse gases and aerosols, and of the full suite of emitting sectors, applications, and nations.

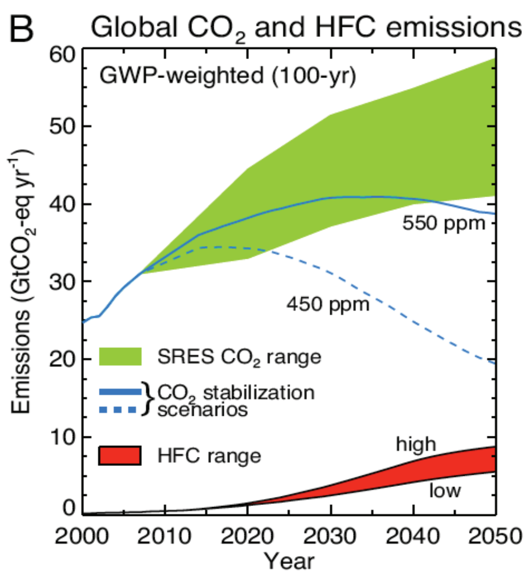


FIGURE 2.4 Global CO_2 and HFC emissions expressed as CO_2-equivalent emissions per year for the period 2000 –2050. The emissions of individual HFCs are multiplied by their respective GWPs (direct, 100-year time horizon) to obtain aggregate emissions across all HFCs expressed as equivalent $GtCO_2$ per year. A high and low estimated range based on analysis of likely demand for these gases and assuming no mitigation of HFCs is shown. HFC emissions are compared to emissions for the range of SRES CO_2 scenarios, and two 450-and 550-ppm CO_2 stabilization scenarios. The estimated CO_2-equivalent emissions due to HFCs in the absence of mitigation reach about 6 $GtCO_2$-equivalent in 2050, or about a third of the emissions due to CO_2 itself at that time in the 450 stabilization scenario. From Velders et al. (2009).

2.2 INFORMATION FROM SCENARIOS

Figure 2.5 shows the emissions of man-made greenhouse gases from various sectors of the U.S. economy (U.S. E.P.A., 2008). For highly industrialized countries such as the United States, the difficulty in reducing emissions will depend in large part on the lifetimes of the *existing* capital stock associated with the major emitting sectors. The electric sector is the largest source of man-made emissions in the United States, primarily due to the carbon dioxide emitted during the combustion of fossil fuels. The lifetime of coal-fired power plants is measured in decades. The next largest source of U. S. greenhouse gases is the transportation sector, again due to the combustion of fossil fuels. Here the lifetime of the capital stock is typically a decade or two.

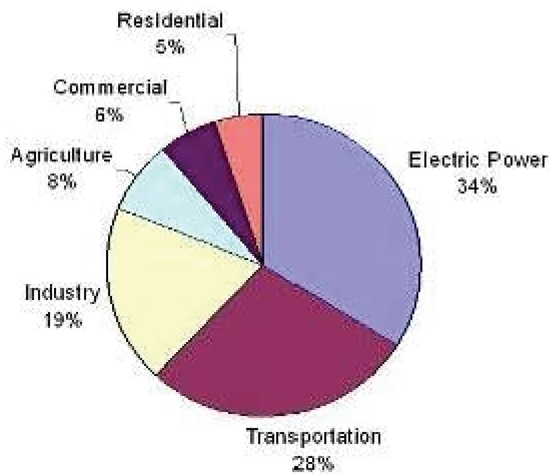


FIGURE 2.5 U.S. Greenhouse Gas Emissions by Sector in 2006 (Source, U.S. EPA (2008))

While historically, developed countries have been the major emitter of greenhouse gases, developing countries are on track to overtake them in the next few years. In their case, the issue becomes one of the capital stock put in place in the *future* to support their industrialization process. With the huge economic growth projected for developing countries and in the absence of incentives to act otherwise, these countries will likely turn to the cheapest energy sources to fuel their growth. These fuels currently are fossil based: coal, oil and gas. A recent study by the Energy Modeling Forum, based on eight Energy-Economy models, projected an annual growth rate of CO_2 emissions globally from the burning of fossil fuels and industrial uses, to be of the order of 1 to 2 percent per year over the remainder of the century, in the absence of intervention (EMF 22, 2009). The study attributes much of the growth to developing countries.

Even if wealthier countries like the United States were to reduce their emissions to zero immediately, it is unlikely that global CO_2 emissions would be stabilized, much less global atmospheric concentrations (Blanford et al., 2009). Being in their post industrial phase of development, the economic growth rates in developed countries are expected to be lower than those of developing countries and their mix of goods and services less carbon intensive. The cumulative reductions of developed countries, even with aggressive emission reduction programs, are expected to be low when compared to those of developing countries.

One important contribution that developed countries can make to global emission reductions is to develop the technological wherewithal that would not only be necessary for their own emission reductions, but is also essential for developing countries to meet their economic development goals with affordable climate friendly technologies.

As noted above, both the existing capital stock and that put in place in the future are critical to understanding the difficulty of transitioning away from the current path of growth in greenhouse gas emissions. Figure 2.6 shows representative carbon pathways (RCP) for limiting radiative forcing (watts per m^2) at two alternative levels. These are referred to as the RCP 2.6[14] and RCP 4.5 scenarios. These are among a suite of pathways being developed for use in the IPCC 5th Assessment. The pathways shown in the figure were developed by the IMAGE and MiniCAM models, respectively (Moss, 2010).

Figure 2.6 highlights the importance of the carbon budget. That is, the area under the allowable emissions curve associated with a particular radiative forcing target. Being much lower in RCP 2.6 scenario than the RCP 4.5 scenario, we see the rate of growth first slow and then rapidly decline beginning in 2020. In the case of the higher CO_2 budget, emissions rise for another two decades before peaking. Notice that the maximum rate of decline is comparable in the two scenarios (about 3.5% per year); however, in the later it is shifted out in time. The reason for this shift are both the higher carbon budget and a greater array of low-carbon, economically competitive alternatives which are assumed to become available in the future.

We stress that there is a great deal of flexibility regarding the rate at which new technologies are substituted for existing ones, both on the supply and demand sides of the energy sector. The rate of retirement of existing carbon-intensive plant and equipment and their replacement with more climate friendly alternatives will depend upon a number of factors. These include the stabilization target, reference case emissions in the absence of a price on CO_2 (either explicit or implicit), the availability and costs of alternatives, and the *willingness* to pay the costs of the transition to a low-carbon economy. The latter will depend on society's perception of the benefits (reduction in damages due to climate change). From a purely physical perspective, decline rates much higher than those shown here are feasible. It is a matter of the perceived urgency and the motivation to decarbonize.

Figure 2.7 shows the CO_2-equivalent concentrations for these two scenarios at three points in time. Notice that in the case of the tighter radiative forcing goal, there is some "overshoot". That is, the target is exceeded in the middle part of the century and then gradually approached. This is due to the assumption that there will be a "negative" emitting technology, Bioenergy with Carbon Capture and Sequestration (BECS). Otherwise a faster decline rate of the capital stock would be required.

[14] Although Moss (2010) refers to this as the RCP2.6 scenario, this is the one RCP scenario that peaks and then declines. For this reason it is also referred to as the RCP3-PD scenario. The RCP3-PD has a unique shape. The radiative forcing of RCP3-PD peaks and declines (PD), while the radiative forcing of the other RCPs stabilize or rise towards their higher 2100 levels. Specifically, the final RCP3-PD prepared for climate modeling peaks at 2.99 W/m^2 in 2050 and then declines to 2.71 W/m^2 in 2100 with the decline continuing beyond 2100. The decline is due to the availability later in the century of a negative emitting technology, biomass with carbon capture and storage (BECs).

Figure 2.6 CO2 Mitigation Paths for Meeting RCP2.6 and RCP4.5 Goals

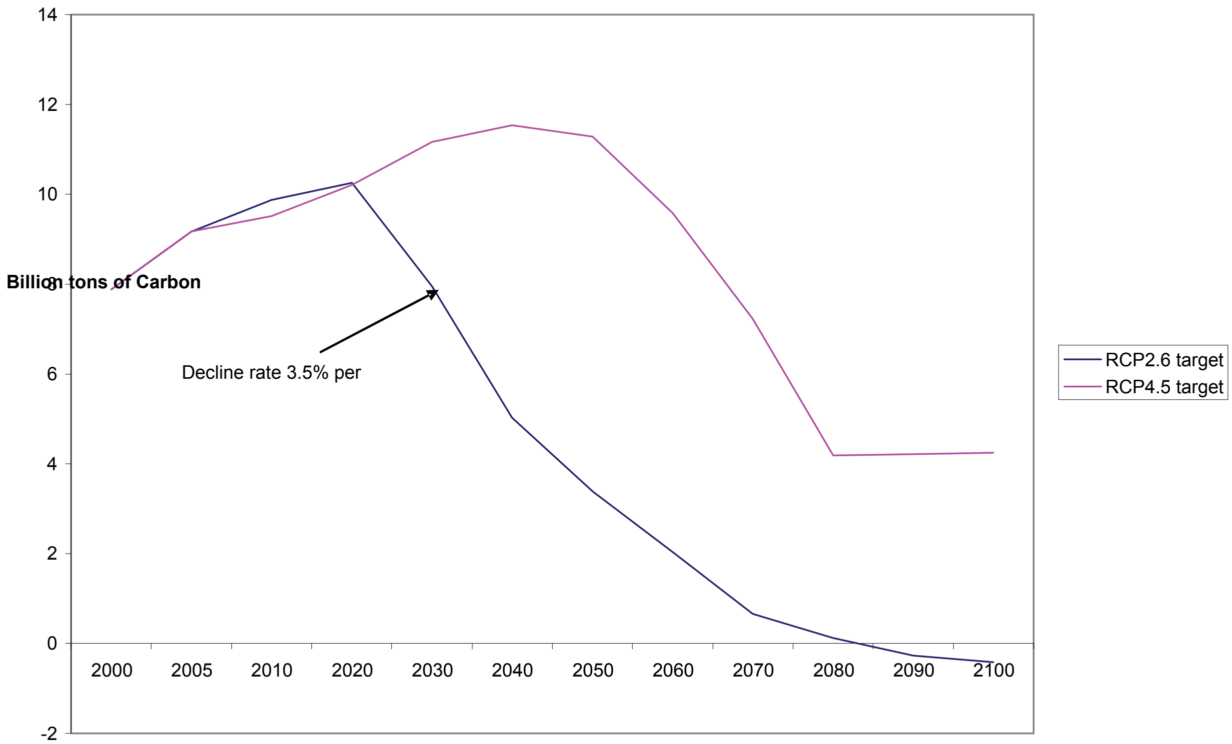
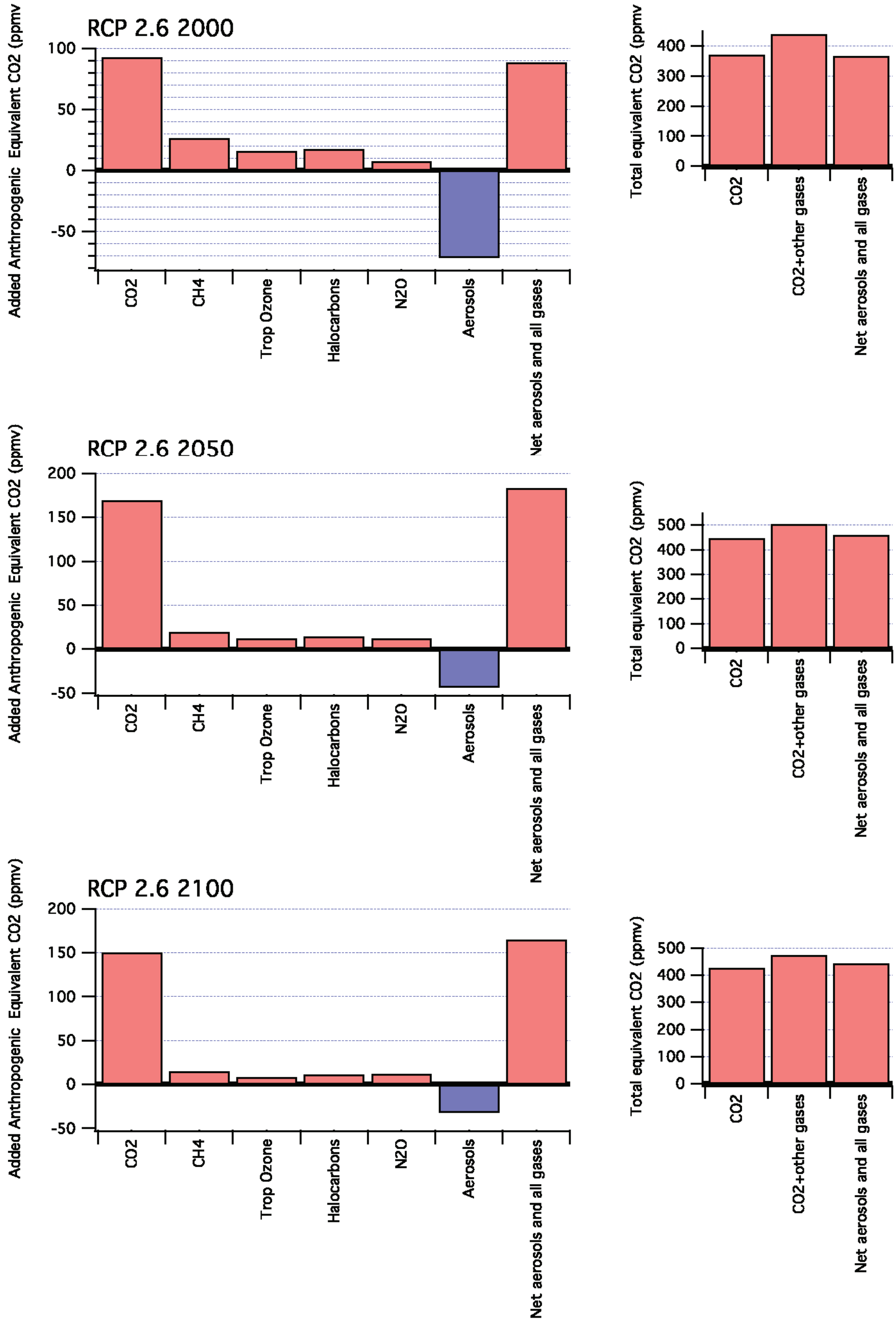


FIGURE 2.6 shows representative carbon pathways (RCP) for limiting radiative forcing (watts per m^2) at two alternative levels. The tighter the limit, the earlier the reductions must take effect. With the RCP 2.6 scenario, the rate of growth first slows and then rapidly declines beginning in 2020. In the case of the less stringent constraint, emissions rise for another two decades before peaking. Here the decline is shifted out in time


RCP 2.6 2000
Added Anthropogenic Equivalent CO2 (ppmv)
100
50
0
-50
CO2
CH4
Trop Ozone
Halocarbons
N2O
Aerosols
Net aerosols and all gases
Total equivalent CO2 (ppmv
400
300
200
100
0
CO2
CO2+other gases
Net aerosols and all gases
RCP 2.6 2050
Added Anthropogenic Equivalent CO2 (ppmv)
200
150
100
50
0
-50
CO2
CH4
Trop Ozone
Halocarbons
N2O
Aerosols
Net aerosols and all gases
Total equivalent CO2 (ppmv)
500
400
300
200
100
0
CO2
CO2+other gases
Net aerosols and all gases
RCP 2.6 2100
Added Anthropogenic Equivalent CO2 (ppmv)
200
150
100
50
0
-50
CO2
CH4
Trop Ozone
Halocarbons
N2O
Aerosols
Net aerosols and all gases
Total equivalent CO2 (ppmv)
500
400
300
200
100
0
CO2
CO2+other gases
Net aerosols and all gases

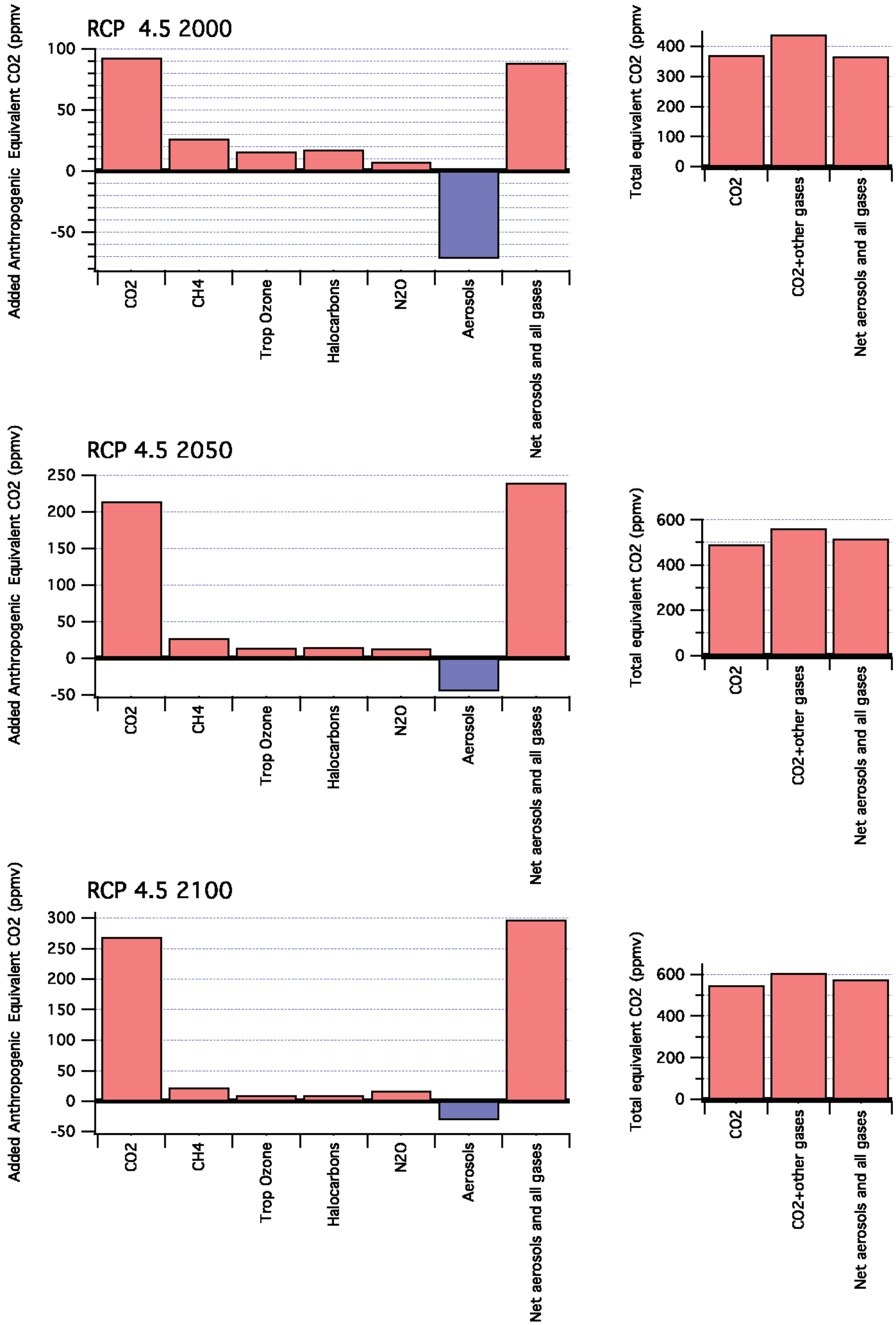


FIGURE 2.7 This figure illustrates components of radiative forcing (in CO_2-equivalent concentration units) for the RCP 2.6 (a) and RCP 4.5 (b) scenarios (see Moss et al., 2010). RCP 2.6 peaks at 3 W/m^{-2} before 2100 and then declines. There is some "overshoot" where the target is exceeded and is then gradually approached (see footnote 1). RCP 4.5 stabilizes at 4.5 W/m^{-2} after 2100.