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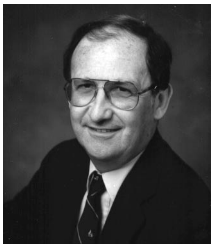

Prospects for Future Climate Change and the Reasons for Early Action

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ABSTRACT

Combustion of coal, oil, and natural gas, and to a lesser extent deforestation, land-cover change, and emissions of halocarbons and other greenhouse gases, are rapidly increasing the atmospheric concentrations of climate-warming gases. The warming of approximately 0.1–0.2 °C per decade that has resulted is very likely the primary cause of the increasing loss of snow cover and Arctic sea ice, of more frequent occurrence of very heavy precipitation, of rising sea level, and of shifts in the natural ranges of plants and animals. The global average temperature is already approximately 0.8 °C above its preindustrial level, and present atmospheric levels of greenhouse gases will contribute to further warming of 0.5–1 °C as equilibrium is re-established. Warming has been and will be greater in mid and high latitudes compared with low latitudes, over land compared with oceans, and at night compared with day. As emissions continue to increase, both warming and the commitment to future warming are presently increasing at a rate of approximately 0.2 °C per decade, with projections that the rate of warming will further increase if emission controls are not put in place. Such warming and the associated changes are likely to result in severe impacts on key societal and environmental support systems. Present estimates are that limiting the increase in global average surface temperature to no more than 2–2.5 °C above its 1750 value of approximately 15 °C will be required to avoid the most catastrophic, but certainly not all, consequences of climate change. Accomplishing this will require reducing emissions sharply by 2050 and to near zero by 2100. This can only be achieved if: (1) developed nations move rapidly to demonstrate that a modern society can function without reliance on technologies that release carbon dioxide (CO_2) and other non-CO_2 greenhouse gases to the atmosphere; and (2) if developing nations act in the near-term to sharply limit their non-CO_2 emissions while minimizing growth in CO_2 emissions, and then in the long-term join with the developed nations to reduce all emissions as cost-effective technologies are developed.

INTRODUCTION

It was only 40 yr ago that the Apollo 8 mission orbited the Moon and the astronauts observed the first Earthrise, prompting poet laureate Archibald MacLeish[1] to characterize the Earth as a blue orb in space with "ourselves as riders on the Earth together." Majestic as the imagery, the reality is that humans are no longer *riders* on the planet, we are now the *drivers*, directly determining atmospheric composition and surface cover and indirectly controlling the climate and sea level. As Nobelist Paul Crutzen has suggested, we have shifted the geological era from the relative constancy of the *Holocene* (i.e., the last 10,000 yr) to the changing conditions of the new *Anthropocene*, the era of human dominance of the Earth system.[2,3]

That human activities are having a global-scale influence is most evident in satellite views of the nighttime Earth. Excess light now illuminates virtually all of the developed areas of the planet, locating the cities, industrial areas, tourist centers, and transportation corridors. With roughly 2 billion people having to rely on fires and lanterns instead of electricity, what is visible only hints at the full extent of the human influence on the planet. Roughly 80% of the world's energy (and a higher fraction if rural biomass sources are excluded) comes from the combustion of coal, petroleum, and natural gas.[4] Combustion of these fuels, derived from the fossilized remains of plants and animals accumulated over hundreds of millions of years, are providing tremendous benefits to the approximately 6.5 billion people on Earth, ensuring food, medicine, shelter, and a longer and easier life. Fossil fuels have become the dominant source of energy because they are relatively abundant, accessible, transportable, storable, and concentrated. In addition, a global infrastructure is in place that provides their energy for use day or night, rain or shine. Fossil fuels are currently indispensable to the support of today's standard-of-living for people around the world.

However, the global use of fossil fuels and several other societal activities introduce a range of health and environmental problems. Some problems, such as inefficient combustion and failure to treat sewage, create air and water pollution, are inherently wasteful, and can readily be controlled by improved technologies. The emission of other substances, such as mercury and sulfur dioxide (SO_2) from coal combustion, result from trace contaminants and can generally be controlled at relatively low cost—once a commitment is made to improve environmental quality rather than just foster economic growth. Carbon dioxide (CO_2), however, is different in two important ways: (1) it is a primary constituent of fossil-fuel exhaust streams; and (2) a significant fraction of the increment to the global atmospheric CO_2 concentration persists for many centuries, acidifying the ocean for millennia and leading to societal and environmental consequences that last far longer than the lifetimes of days to weeks of traditional air contaminants.

The understanding that the CO_2 concentration is an important determinant of the global climate and that increases in its concentration would cause climate change goes back over 100 yr (for a brief review on early history, see supplemental data published at http://secure.awma.org/onlinelibrary/samples/10.3155-1047-3289.58.6.735_supplmaterial.pdf). Definitive observations that the CO_2 concentration has been rising were first made 50 yr ago, and since then not only has the record been extended back in time, but it has also been recognized that the concentrations of methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and many halocarbons (particularly chlorofluorocarbons [CFC]-11 and CFC-12, but also many others) are also contributing to changes in the global climate.

With the evidence mounting that human activities were modifying atmospheric composition, the nations of the world established the Intergovernmental Panel on Climate Change (IPCC) in 1988 to summarize and assess the state of scientific understanding about the science of climate change, resultant impacts, and the potential for limiting further change (see supplemental data for a brief history of assessments on climate change and an explanation of the IPCC and its structure and process). Since its establishment, the IPCC has completed four comprehensive assessments (see IPCC 1990,[5–7] 1995,[8–10] 2001,[11–14] and 2007[15–18]), prepared many additional reports, and prompted a significant expansion of research on climate change.

The IPCC assessments, particularly their supporting chapters, are the most authoritative and complete reviews of the scientific literature. These assessments represent the international scientific consensus on climate change, its impacts, and the possibilities for responding. Taken as a whole, the IPCC's work provides a comprehensive baseline of information for consideration by governments and the public. However, the reports of each of the IPCC Working Groups approach 1000 pages in length, and the series of four IPCC assessment reports and numerous special reports since 1990 build upon each other, creating a tremendous amount of information. An unfortunate outcome is that it has become very difficult for those with a technical interest who have recently become interested in the subject to gain a basic understanding of the issue from the latest materials; there is just too much understanding and knowledge that is assumed.

This review seeks to provide a bridge from basic understandings about physics and the climate system to the latest results that are presented in support of acting to limit further change. The review does not attempt to be comprehensive, and is instead organized around six overarching findings related to the nature and impacts of climate change. These findings are each strongly supported by the understanding gained through the IPCC assessments, presenting the underlying reasoning and seeking to build intuitive understanding. The options for limiting climate change, which were the focus of IPCC Working Group III, are covered only briefly. Except where noted and where the science and findings are changing rapidly, the results presented are based on the content of the IPCC assessments (especially those published in 2007), generally without statement-by-statement reference. For more complete information and for primary references to the literature, references are provided to the most relevant chapters in the various IPCC assessment volumes (these references appear in the form of ref no., chapter no.).

Although the IPCC assessments are the primary source, the results of other assessments are also drawn upon, especially for additional information relevant to North America. In particular, the Arctic Climate Impact Assessment (ACIA),[19] the U.S. National Assessment,[20,21] and the Canada Country Study[22] provide much more information about impacts for the United States and Canada. Given the broad scope of this review, the focus will be primarily on the continental to global scales, with pointers provided, as available, to information at finer scales.

Recognizing that the problem is very complex, this review will indicate the areas in which uncertainty and disagreement remain substantial and in which the outcome is likely to have a significant impact on the major findings. Although many articles in the media have given the impression that the scientific community is nearly evenly divided on the science of climate change, this is not really the case. In reality, the IPCC position represents the carefully prepared and documented central view, although because of its review and consensus-seeking processes, this view is assured to lag the cutting edge of scientific findings.

On one side of the IPCC's central position, there are those who suggest that the IPCC is overstating scientific understanding, arguing, for example, that the changes identified result from a biased observation system, or are due to natural factors, or that some single aspect of the IPCC's argument is contradicted by the results of a single paper.[23–25] Although there are real uncertainties,[26] most of the often highly publicized objections have been carefully addressed by the IPCC[15–17] and found to be overstated. Some of the criticisms are still being evaluated, indeed, understanding is not (and cannot ever be) perfect, and the IPCC process causes it to be quite slow to come to conclusions.

In any case, the scientific understanding that the IPCC documents is not a "house of cards" that falls if one point is not fully understood; it is a pyramid built on extensively tested findings that interlock with understanding of observations and analyses drawn from such disparate situations as Earth's climatic history and the evolution of planetary atmospheres. Alternative explanations attributing the observed changes to natural variability, forcing by the Sun or cosmic rays, or other exotic factors may show good correlations in particular situations but generally fail quickly when evaluated against the broader set of supporting information. Thus, although it is interesting to discuss the uncertainties of specific critics,[27] organizing this review around specific criticisms by well-known dissenters would divert attention from the overwhelming evidence supporting the key findings. Instead, responses to the most important of the criticisms will be covered as the topics arise.

On the other side, there are also many who criticize the IPCC for understating the intensity and seriousness of climate change and its impacts, arguing that the IPCC process keeps it from being current on the most recent and dramatic changes. Indeed, because its process limits conclusions to those well established in the scientific literature, lags are introduced into its findings as a result of the time it takes scientists to develop detailed, quantitative understanding about particular issues and the time between assessment teams completing their evaluations. In addition, because the IPCC works to develop a consensus among all nations for its findings, its statements tend to be somewhat behind the cutting edge. As an example of the implications of these delays, Pittock[28] identifies 10 reasons why climate change may be more severe than reported in IPCC's most recent assessment. In this review, because each of the successive IPCC assessments has presented evidence for a grimmer outcome than the preceding one, discussions of uncertainties focus more intensely on the softness of the estimates of upper bounds, processes, and factors that have yet to be adequately explored or resolved than on the firmness of the estimates of the lower bounds that many of the dissenters raise.

Although there is significant attention in the media and in public discussion to the various views on the science itself, there are also several reasons that the issue is very challenging, creating even more discussion. These reasons arise from such factors as the issue's complexity, arguments about the adequacy of evidence for findings at the cutting edge of science, the time lag between emissions and the full climatic response to them, the increasing intensity of the impacts over time, the chaotic nature of the climate and changes in climate over Earth's history, and the gradual changeover from a climate dominated by natural variability to being dominated by human influences. As groups with different interests and viewpoints evaluate the scientific findings and the potential impacts of the climate change itself, the potential responses to it, and the possible impacts of the responses, each weighting a wide set of factors in their own way, it should not be surprising that a range of different contending perspectives emerge, each offering a different and legitimate take on the issue.[29] Add to this the heat generated in the political decision-making process[30–32] and it should not be surprising that polls and surveys find the public perceiving greater controversy than is actually found in the scientific literature.[33]

In this review, I will seek to maintain focus on what the scientific results indicate, identify where cutting edge science suggests that the findings may change in coming years, and, given all the controversy, conclude with my view of what the message must be from the scientific community to international negotiators about what must be done to limit future change and its impacts.

SIX KEY FINDINGS

For the scientific community, the challenge of understanding and projecting climate change and its impacts out a century or more into the future is, at the same time, complex, difficult, audacious, and extremely relevant for society. Understanding the origins of the Universe is difficult, but this finding does not directly affect everyday life. Deciphering the human genome and applying the findings for humanity is both difficult and relevant, but there are 6.5 billion people and innumerable plants and animals from which to learn.

There is, however, only one Earth, its time history is poorly known and hard to reconstruct, and the evolution to its current state represents only one of many possible pathways that could have resulted from the complexly coupled and chaotically behaving combination of the atmosphere, oceans, land surface, biosphere, and cryosphere (the domain encompassing water in its solid form on or beneath the Earth's land surface and ocean, including snow, sea ice, lake and river ice, glaciers, ice caps and ice sheets, and frozen ground [including permafrost]). The challenge includes looking back to decipher and understand the past and then looking forward for a century and more across a very diverse world with changing social and political structures and interactions. Not only is an understanding of natural processes needed, but also capabilities for predicting how humans will behave, how technology will develop, and how cooperatively the world system of nations is likely to function. Australian scientist A. Barrie Pittock, reflecting on both the complexity of the Earth system (including Man as part of it) and the strong evidence that the world is and will change, expressed the dilemma being faced: "Uncertainty is inevitable, but risk is certain."[34]

Beginning with its first assessment report in 1990,[5–7] and continuing with full assessment reports in 1995,[8–10] 2001,[11–14] 2007[15–18] and a wide series of special reports,[35–40] IPCC has been able to galvanize the international scientific community and promote development of reports describing the consensus views of the international scientific community. The assessment reports that have been prepared are detailed and exceedingly well referenced; they have undergone extensive review, and through the iterative process of successive reports, they have updated, modified, strengthened, clarified, and sometimes corrected their analyses. However, the most fundamental scientific findings about climate change science have held steady over many years.

Although uncertainties do exist, the following six findings, which have long been recognized, make clear that climate change poses a very real problem for society:

1. Emissions from human activities, particularly combustion of fossil fuels, are changing atmospheric composition.
2. Enhancing the natural greenhouse effect will lead to long-term global warming.
3. Changes in the climate as a result of past activities are already evident, and these changes are consistent with a human influence.
4. Future warming is projected to be substantial.
5. The environment and society will both be impacted in significant ways.
6. Slowing the ongoing change will require substantial reductions in greenhouse gas (GHG) emissions over coming decades to limit anthropogenic interference with the climate system.

Overall, the first two findings are very well established, the second two findings are becoming increasingly well established, and the last two findings address the challenge society faces in dealing with the issue. These findings are considered in the subsequent sections of this review.

FINDING 1: HUMAN ACTIVITIES HAVE BEEN AFFECTING ATMOSPHERIC COMPOSITION

That life on Earth could affect the composition of the atmosphere is fundamental to our understanding of the

Earth's history.[41] The Earth's earliest atmosphere was reducing, and it was not until early plant life formed that oxygen was generated and the atmosphere became oxidizing. Through photosynthesis, plants continue to convert CO_2 in the atmosphere into complex organic molecules and in the process release oxygen into the atmosphere. Then, animals, using atmospheric oxygen, consume the plant material directly or indirectly and oxidize it back into CO_2. Earth system history shows that there have been some large variations in the concentrations of CO_2 and oxygen in the atmosphere, partly driven by geological processes[42] and partly by biological processes. Lovelock and Margulis have even argued that the set of chemical and biological processes controlling these changes is self-balancing over very long time scales, making it clear that life can affect atmospheric composition and climate. And, indeed, the main way proposed to identify life on other celestial bodies is to look for evidence that life is changing the composition of the atmospheres of these bodies. So, there should be no question about whether life can alter atmospheric composition—the question is instead to what extent humans are doing this now.

Although early clearing and planting of lands and burning of biomass has been going on since civilization began, there was no substantial effect on atmospheric composition until the Industrial Revolution (although Ruddiman[43] takes exception, suggesting changes began 8000 yr ago), when the drawing of resources from the environment began to significantly exceed the rate of replacement by regrowth of vegetation. With respect to changes in land cover, net deforestation occurred mainly as a result of the spread of agriculture, the net effect of which was modest until the Industrial Revolution created the tractor and demanded wood as fuel for industry. Indeed, atmospheric composition was not significantly affected until the use of coal and other carbonaceous fuels began the transfer of carbon into the atmosphere that had been stored underground for many tens to hundreds of millions of years. This finding depends on understanding both the global-scale changes in atmospheric composition and the emissions that are causing these changes.

Observed Changes in Atmospheric Composition

In 2005, the CO_2 concentration measured at the Mauna Loa Observatory in Hawaii averaged 379 parts per million by volume (ppmv); it is likely approximately 385 ppmv at present on the basis of the recent history of annual increments.[44] This concentration is approximately 22% higher than the value of approximately 315 ppmv observed when the station was established in 1957.[45] Measurements at other locations indicate that the measurements from Mauna Loa, which are carefully screened to eliminate occasional contamination from nearby volcanic emissions and growing vegetation, represent a reasonable average of what is happening around the Northern Hemisphere. Although there is a slightly shorter record, measurements across the global network of stations extending from the Arctic to the South Pole confirm that the annual average CO_2 concentration has been rising at essentially the same rate at all stations. The records do show, however, a time lag of 1–2 yr from the Northern Hemisphere mid-latitudes, where emissions are highest, to the South Pole. This delay is in accord with expectations, on the basis of modeling and measurements of other tracers, for the time it takes the hemispheres to exchange masses of air.

The most obvious feature in the early record, which is shown in Figure 1, was the annual cycle, with the Northern Hemisphere CO_2 concentration being highest in March and lowest in September–October. The amount of the annual variation is approximately 7–8 ppmv at Mauna Loa and the timing coincides well with the cycle of vegetation growth, the concentration being highest at the start of the growing season and lowest at its end. In the Southern Hemisphere, the annual timing is reversed and the seasonal cycling is smaller, which is expected given the inversion of the seasons and the reduced variation in seasonal vegetation. Assuming the CO_2 concentration at Mauna Loa represents the average Northern Hemisphere concentration and recognizing that the exchange time of air between hemispheres is a few times longer than the seasonal variation, multiplying the range of its seasonal variation by the volume of the Northern Hemisphere can be used to provide a rough estimate of the net seasonal uptake and release of carbon by the Northern Hemisphere biosphere. The result is 7–8 petagrams of carbon (C) per year (PgC/yr or 10^{15} gC/yr, sometimes expressed as gigatons of C/yr or GtC/yr), which provides a quantitative estimate for the seasonal greening seen in the National Aeronautics and Space Administration (NASA) satellite time-lapse movies.

Soon after the first measurements from Mauna Loa, the search began for "old air" that might give an indication of the concentrations of CO_2 and other gases at earlier times and help to determine whether the observed values reflected a trend or were a natural fluctuation. Tests were made of air inside old brass buttons and trapped inside old wine bottles, each having obvious potential

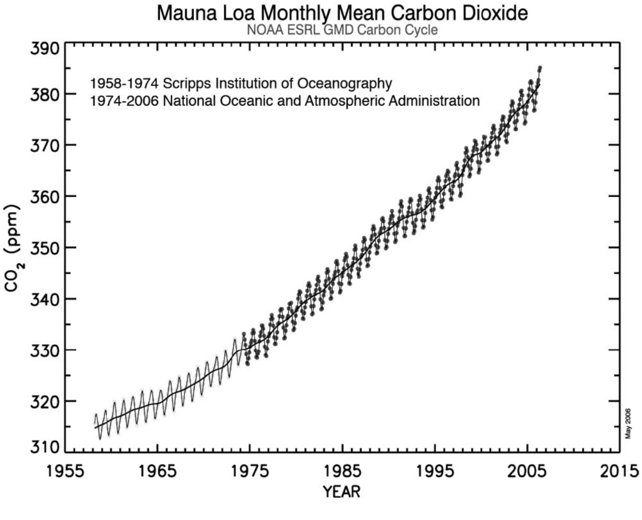


Figure 1. Monthly mean and running annual mean concentration of CO_2 (in ppmv) taken at the Mauna Loa Observatory in Hawaii. The record from 1958 to 1974 is from data gathered by C. David Keeling of the Scripps Institution of Oceanography[46] and the record since 1974 is from the Global Monitoring Division of NOAA's Earth System Research Laboratory[47] (source: figure courtesy of NOAA, available at http://celebrating200years.noaa.gov).

biases. The best record found has been derived from the air trapped in bubbles in glaciers and ice sheets. It took some time to work out the details of the observation techniques, in particular making measurements with very small amounts of air and accounting for the time it takes bubbles to seal off as the deepening snow is converted to ice.

The next challenge was to find the most informative locations for extracting ice cores. For high temporal resolution, cores from glaciers that have high snowfall rates have provided the best information. Deep cores drilled in Greenland go back approximately 200,000 yr[48] with very good, near-annual resolution for most of the record. For longer times, but with less temporal resolution (typically centennial or longer), cores in Antarctica now provide data back as far as 800,000 yr.[49–52] The ice core results make clear that over the 800,000 yr before the Industrial Revolution, the CO_2 concentration varied from approximately 190 ppmv during glacial periods up to approximately 300 ppmv during the relatively brief interglacial periods (discussion on the connection of these variations to climate change can be found under the second finding).

Increases in concentration have occurred not only for CO_2, but also for CH_4, N_2O, and other gases. Figure 2 shows the combined ice core and instrument records of the concentrations of CO_2, CH_4, and N_2O over the past 10,000 yr (i.e., since the end of the last glacial cycle).[15] These records indicate that the concentrations were, somewhat surprisingly, quite steady throughout the Holocene. Over this time, the CO_2 concentration climbed from approximately 260 ppmv 8000 yr ago to approximately 280 ppmv in 1750. The CH_4 concentration increased from a low of approximately 580 parts per billion by volume (ppbv) 5000 yr ago to approximately 730 ppbv in the mid-18th century. These levels are somewhat higher than during previous interglacials. Ruddiman[43] suggests, somewhat controversially, that the increase in CO_2 may be due to the deforestation that occurred approximately 8000 yr ago when nomadic peoples settled and cleared fields for agriculture, and that the CH_4 increase, which started approximately 4000 yr ago, coincided with the introduction of rice agriculture in China and southeastern Asia. Although these early agricultural and land-clearing activities may well have had some influence on atmospheric concentrations, the sharp rise beginning around 1750 is clearly attributable to the start of the Industrial Revolution, thereby implicating human activities and the combustion of fossil fuels.

Table 1 lists changes in the atmospheric concentrations (or, for aerosols, changes in loading) that are attributed to human activities over the Industrial period. The National Oceanic and Atmospheric Administration (NOAA)'s Climate Monitoring and Diagnostics Laboratory and World Meteorological Organization (WMO)'s Global Atmospheric Watch have cooperatively operated a network of observation stations around the world for several decades to develop a time history of the atmospheric concentrations of these and other species. Relatively uniform concentrations around the world indicate a small loss or destruction rate and a relatively long atmospheric half-life (i.e., decades to centuries or more), whereas highly varying concentrations in space and time suggest strong removal processes and a relatively short atmospheric half-life (days to weeks or months). Species with large and rapidly increasing concentrations indicate larger sources or closeness to a major source as compared with species with small and slowly increasing concentrations. Table 1 also provides an estimate of the persistence time of the anomaly that is created, which is the relevant factor in determining past and future influences of the changes on the climate.

Documenting that changes have occurred is the first step in understanding; the second is to figure out why the changes have been occurring. Tracking changes in the ratios of carbon isotopes has been used to confirm that human activities are the primary cause of the increases in the CO_2 and CH_4 concentrations since the start of the Industrial Revolution. The time history of the stable (and natural) isotope carbon-13 (^{13}C) has proven useful for tracking the role of vegetation, and the time history of the radioactive isotope carbon-14 (^{14}C) has proven useful for tracking contributions from fossil-fuel combustion. Because ^{14}C and ^{13}C are a bit heavier than the more ubiquitous isotope, carbon-12 (^{12}C), each undergoes various distillation processes that affect their uptake by plants, rate of evaporation from the upper ocean, and concentration in precipitation. Differentiating the effects of the distillation processes and keeping track of the radioactive decay of ^{14}C, time histories of the roles of land-cover change and fossil-fuel combustion can be distinguished.

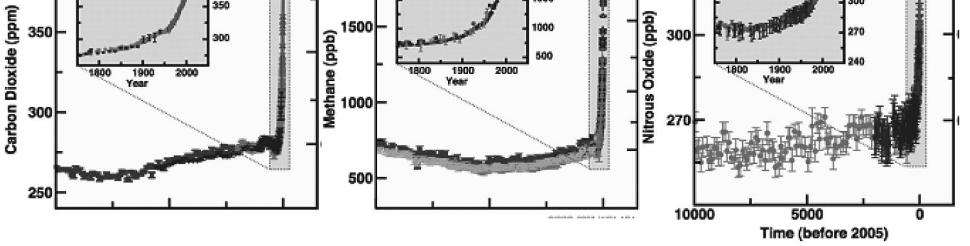


Figure 2. Atmospheric concentrations of CO_2, CH_4, and N_2O over the last 10,000 yr (large panels) and since 1750 (inset panels). Measurements are derived from ice cores (different symbols indicate different studies), except for the past few decades when direct observations were taken. Reprinted with permission from the IPCC[15] (chapter 2). Copyright 2007 Cambridge University Press.

Table 1. Changes in the composition of the atmosphere resulting from human activities over the period 1750–2005 and their estimated influence on the global energy balance,[11,15] and the likely source and duration of the perturbation to the change in composition (adapted from Scientific Expert Group[53]).

Atmospheric Component	Concentration or Burden in 1750	Concentration or Burden in 2005	Human-Induced Warming Influence (W/m^2) in 2005	Primary Sources	Persistence of Increased Amount after Sources Are Reduced
CO_2	~280 ppmv	379 ± 0.65 ppmv	1.66 ± 0.17	Emissions from fossil fuel combustion, deforestation, etc.	Centuries and longer
CH_4 (and resulting contribution to stratospheric water vapor)	~730 ppbv	1774 ± 1.8 ppbv	0.48 ± 0.05 (0.07 ± 0.05)	Emissions from rice agriculture, ruminants, energy production, biomass burning, and landfills	Decades
N_2O	~270 ppbv	319 ± 0.12 ppbv	0.16 ± 0.02	Emissions from agriculture, cattle and feedlots, industry, and biomass burning	Centuries
Halocarbons such as CFCs (and resulting reductions in stratospheric O_3)	Not present	A few to ~500 pptv	0.34 ± 0.03 (−0.05 ± 0.10)	Emissions from refrigeration, foam, industry, fire protection, and agriculture	Centuries and longer, even out to millennia
Tropospheric O_3	Global average of 25 Dobson units[a]	Global average of 34 Dobson units[b]	0.35 [−0.1, +0.3]	Formed in the atmosphere as a result of emissions from pollutants resulting from fuel combustion	Days to weeks
Black soot and absorbing aerosols (and associated decrease in snow albedo)	Very small global effect due to near-surface emission	Increased, but modest, global effect due to longer lifetime for emissions from tall stacks and increased emissions from inefficient engines in poor countries	+ 0.20 ± 0.15 (0.1 ± 0.1)	Emissions from fossil-fuel combustion and biomass burning	Days to weeks
Sulfate aerosols (plus nitrate and organic aerosols)	Very small due to near-surface emission	Modest global effect due to elevated emissions that greatly increase the conversion of SO_2 to sulfate aerosols and extend the lifetime	−0.40 ± 0.20 (and −0.15 ± 0.15)	Mainly a result of combustion of coal and other fossil fuels	Days to weeks
Biomass burning aerosols	Limited due to low population	Extensive in Southern Hemisphere	+0.03 ± 0.12	Mainly from burning of biomass	Days
Indirect effects of aerosols on clouds	Very small	Noticeable	−0.7 ± [−1.1, +0.4]	Brightening due to increase in small particle concentration; changes in cloud duration	Days
Change in land surface albedo	Not applicable	Not applicable	−0.20 ± 0.20	Deforestation, agriculture, fire, urbanization	Months to decades or longer
Contrails and cirrus clouds	Not present	Visible on some days along major air corridors	0.01 ± [−0.007, +0.02]	Mainly a result of water vapor emissions from high-flying jet aircraft	Days
Mineral dust aerosols	Mainly over and downwind of nonvegetated areas	Increased as result of reductions in global vegetation	−0.10 ± 0.20	Mainly from wind lofting from cleared areas of land and from unpaved roads, construction, etc.	Days to weeks
Total	–	–	1.6[c] ± [−1.0 to + 0.8]	Mainly emissions from energy generation, transportation, agriculture, and buildings	Centuries and beyond

Notes: [a]Dobson unit[15] is a “measure of the total amount of O_3 in a vertical column above the Earth’s surface. The number of Dobson units is the thickness in units of 10^{-5} m that the O_3 column would occupy if compressed into a layer of uniform density at a pressure of 1013 hPa and a temperature of 0°C.” [b]This value is for 1998;[11] [c]Addition to 1.6 instead of 1.7 is based on ref 15, chapter 2.

The ^{14}C isotope is created in the stratosphere when a cosmic-ray-generated thermal neutron replaces a proton in the nucleus of a nitrogen atom and has a half-life of 5730 ± 40 yr. For this reason, ^{14}C is particularly useful for looking at processes that involve millennial time scales and longer. Once formed in the stratosphere, ^{14}C reacts with oxygen and then mixes over a few years through the atmosphere so that the ratio of ^{14}C to ^{12}C in CO_2 becomes relatively homogeneous. Although having a slightly heavier molecular weight, plants readily take up $^{14}CO_2$ and the ^{14}C is chemically bound and structurally fixed in place. Comparing the ratio of ^{14}C, which decays over time, to ^{12}C in the plant material to the ratio of ^{14}C to ^{12}C in the atmosphere allows determination of the time since the plant material was formed. Although corrections are needed to account for such factors as small variations in solar output (which modulates the cosmic-ray flux), this term can be estimated using tree-ring records that independently date the material. Because the CO_2 formed from the combustion of fossil fuels contains carbon that is generally hundreds of millions of years old, all of the ^{14}C has decayed to ^{12}C. As a result, the addition of fossil-fuel-derived CO_2 to the atmosphere reduces the ^{14}C-to-^{12}C ratio. Changes in this ratio have been recorded in tree rings as well as in air samples.

Although ^{14}C dilution due to fossil-fuel combustion explains much of the increase in the observed CO_2 concentration since 1750, it does not explain it all. The difference suggests that shifts are occurring between the land, air, and ocean reservoirs of carbon over time scales of a few centuries (therefore too short to involve significant decay of ^{14}C). To investigate such changes, the isotope ratio of ^{13}C to ^{12}C can be used. Because of various distillation processes relating to their different molecular weights, the ratio is less in plants than in the atmosphere, but by a different amount than for ^{14}C. Because vegetation tends to be relatively young, so little of the ^{14}C has decayed, the relative contributions of fossil-fuel combustion and changes in the amount of standing biomass (i.e., trees and other plants) and root matter to the increase in atmospheric CO_2 can be differentiated.

Although the concentrations of many other gases are also changing, the primary focus in this review will be on the effects of changes in the CO_2 concentration. This choice was made because the increasing CO_2 concentration is having the largest effect on the climate and because the concentration has been rising for a considerable time, suggesting that the concentration increase above preindustrial levels will be relatively long lasting. Those interested in detailed information on the other gases are referred to the IPCC assessments (ref 15, chapter 2).

Past and Future Emissions to the Atmosphere

As briefly indicated in Table 1, many human activities are contributing to the observed changes in atmospheric composition. Production, transport, and combustion of coal, oil, and natural gas to provide energy for society are the most important, with land use and land-cover change also playing a role. Annual fossil-fuel emissions totaled approximately 1 PgC/yr in 1900, approximately 7 PgC/yr in 2000, and have risen sharply to approximately 8.4 PgC/yr in 2006.[54] This recent acceleration in emissions is occurring primarily as a result of the rapid growth in the global economy, especially because of the increase in the number of coal-fired electric plants being constructed in China and elsewhere in eastern Asia. Recent net emissions of CO_2 from land use, decay, and deforestation are estimated to have been approximately 1.5 ± 0.5 PgC/yr for the last 50 yr (ref 17, chapter 1; reinforced by Canadell et al.[54]).

For a world population of approximately 6.5 billion, each year each person is currently responsible, on average, for emission of approximately 1.2 t of carbon (tC) from fossil-fuel combustion and approximately 0.35 tC from deforestation and unsustainable agriculture. However, the contributions of those in different nations vary significantly depending on standard of living, the level of industrial activity, and the intensity of change in land cover. In the poorer countries where there are few cars, air-conditioned buildings, or industry, per capita emissions are generally less than 0.5 tC/yr from fossil fuels, and per capita emissions from biomass-derived carbon are somewhat larger than average because unsustainable sources of wood are serving as an important fuel.

By contrast, in industrialized countries with widespread road, air, and rail transport systems; home and business ownership; and industry, per capita emissions are typically several times higher than the global average. In North America, per capita emissions are approximately 6 tC/yr, whereas in Europe, with its higher fuel costs, higher population densities, and extensive rail and mass transit systems, per capita emissions average about half of the amount in North America. Variations among countries and regions arise because of several factors, including the standard of living, prevailing modes of transportation, prevailing climate, the availability of hydroelectric and other renewable sources of energy, the amount of industrial and mining activities, the export and import of energy and products that require energy to produce, and the history of efforts to improve the energy efficiency of buildings, appliances, and transportation. Although the regrowth of forests and enhanced uptake of CO_2 by plants as the CO_2 concentration rises does lead to the sequestering of carbon in some developed nations, this uptake mainly makes up for past deforestation and only marginally offsets long-term fossil-fuel emissions.

Although national per capita emissions provide some insight, they do not fully represent the policies and lifestyle of the people living in the nation. Because we globally share the products that generate the long-lived GHGs, the world is locked together into this problem. As world population and standard of living continue to rise, continuing reliance on fossil fuels to power global economic development is on a path leading to much higher emissions in the future. Assuming the world population grows 50% by the end of the century, and each of the 10 billion people relies on fossil fuels for about two-thirds of the per capita amount of energy currently derived from fossil fuels by Europeans (or about one-third of that derived from fossil fuels by North Americans), annual per capita emissions would be approximately 2 tC/yr. Multiplying population by per capita use, total emissions would be approximately 20 PgC/yr, or more than 3 times the level in 2000.

THE CARBON CYCLE

Carbon is present throughout the Earth system, being present primarily as the gases CO_2 and CH_4 in the atmosphere; stored as complex hydrocarbons in animals (including humans), plants, and soils; sequestered well below the Earth's surface as coal, petroleum, and natural gas; tied up in calcium carbonate and other minerals formed by sedimentary processes; and dissolved in various forms in ocean waters, from which it is taken up by marine organisms. Although much of the carbon is chemically bound up such that little of it will move over many millions of years, carbon in other forms can move relatively quickly from one form and location to another. The set of reservoirs and processes determining the amounts and fluxes of carbon in and moving between reservoirs defines carbon's biogeochemical cycle, or simply, the "carbon cycle" (see Figure 3 and descriptions in ref 11, chapter 3 and ref 15, chapter 2).

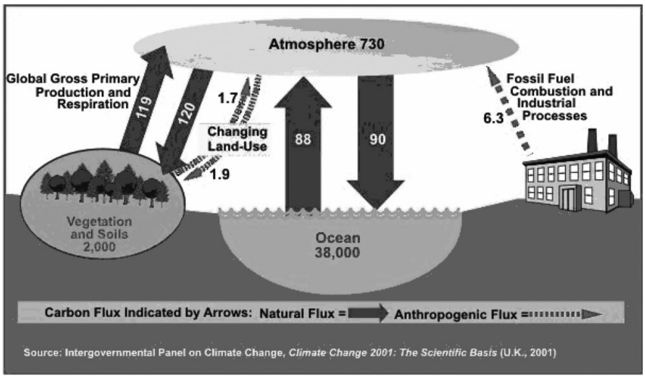
Of particular interest are the amounts of carbon in the:

- Biosphere, from which we draw food and other resources;
- Atmosphere, because the CO_2 concentration is important in determining the climate;
- Oceans, because the amount of dissolved CO_2 plays a critical role in determining ocean chemistry and the viability of marine life; and
- Fossil fuels, because extraction and combustion of these fuels provide more than 80% of the world's energy.

In units of PgC (equivalent to billions of metric tons of C, or GtC), the terrestrial biosphere holds approximately 2000 PgC, of which almost one-third makes up the aboveground biomass in plants and animals. The atmosphere contains approximately 750 PgC, which is comparable in magnitude to the amount of aboveground biomass. The ocean as a whole contains around 38,000 PgC, but, with the ocean averaging roughly 4 km in depth, only a few percent (i.e., ~1500 PgC) is present in its upper 100–150 m, which is well mixed by the winds; the rest is in the deep ocean. The slow exchange in mass between the upper and deep ocean leads to an average replacement time for deep waters of approximately 1000 yr, far longer than the exchange time of water in the mixed layer of nearly 3 decades.

The uptake and release of atmospheric CO_2 by the biosphere as part of photosynthesis, respiration, and decay, leads to annual transfer of approximately 120 PgC in each direction, of which release of carbon in CH_4 accounts for less than 1%. The near constancy of the CO_2 concentration from the end of the last glacial until the start of the Industrial Revolution, except see Ruddiman,[43] suggests that the net annual uptake and release of carbon by the terrestrial biosphere must have been small, even though the 7- to 8-PgC/yr seasonal variations evident in the Mauna Loa CO_2 record provided an opportunity for net growth.

The gross fluxes between the atmosphere and ocean amount to approximately 90 PgC/yr as a result of the solution and release of CO_2 molecules across the air-sea interface. Were the upper mixed layer of the ocean unconnected to the deep ocean, the net flux would be just enough to rebalance the partial pressure between the increasing atmospheric concentration and the amount dissolved in the upper ocean. There are, however, two important processes that lead to the net transport of carbon to the deep ocean: (1) very cold, and therefore very dense, water formed at high latitudes (especially during the formation of sea ice) sinks into the deep ocean, carrying an amount



Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (U.K., 2001)

Figure 3. Schematic diagram of the carbon cycle showing the stored carbon (in PgC) in each of the active reservoirs of carbon (atmosphere, oceans, vegetation and soils) and the natural fluxes (in PgC/yr) into and out of these reservoirs. The fluxes are also shown that result from human influences on terrestrial vegetation and in adding geologically sequestered fossil-fuel carbon to the atmosphere. Since 2001, the emissions due to fossil-fuel combustion have climbed to 8.4 PgC/yr (source: DOE Energy Information Administration using estimates from ref 11, chapter 3).

THE CARBON CYCLE (Cont.)

of CO_2 in equilibrium with the present atmospheric concentration; the downward transport is balanced by upwelling waters in low latitudes carrying a CO_2 concentration characteristic of earlier times; and (2) uptake of CO_2 by marine zooplankton and shell-forming organisms transfers carbon to the deep ocean by the sinking of skeletons and fecal matter. Much of this carbon dissolves while passing through deeper waters before reaching the ocean floor to be taken up in sediments. The net transport to deeper waters by both processes is estimated to be 2 PgC/yr. Incorporation of carbon in sediments is a small fraction of even this small amount, and this term may become even smaller as oceanic pH is reduced by the increasing amount of dissolved CO_2—a process popularly referred to as "ocean acidification."

Adding together the gross fluxes of carbon into the terrestrial biosphere and the oceans (i.e., 120 + 90 PgC/yr = 210 PgC/yr) means that the average residence time of a particular carbon molecule in the atmosphere is between 3 and 4 yr (750/210 = 3.5 yr). This short lifetime was confirmed following the atmospheric nuclear tests in the 1950s and 1960s as the ^{14}C that was created (overall, in a trace amount) mixed from the atmosphere into the upper ocean and terrestrial biosphere. This short time is not, however, the time to use in calculating how long the human-induced increment to the atmospheric CO_2 concentration will persist in the atmosphere because upper ocean uptake is matched by simultaneous release to the atmosphere to maintain chemical equilibrium.

To estimate the persistence time of the elevated CO_2 concentration, the rates of long-term net uptake by vegetation and the deep ocean must be considered. With respect to the terrestrial biosphere, net biomass would adjust over several decades to a higher CO_2 concentration. Over centuries to millennia, the excess CO_2 in the upper ocean would be mixed through the deep ocean, reducing the initial CO_2 increment in the upper ocean and atmosphere, to which it is coupled. Finally, over many millennia and longer, a further adjustment would take place as the excess carbon was transferred to the sediments.

Although all of the various interactions do need to be considered, the carbon cycle model most often cited by the IPCC suggests that the fraction of CO_2 remaining in the atmosphere (known as the "airborne fraction") drops quickly to around 50–60% of the initial increment that would result from mixing emissions throughout the global atmosphere, but does not decrease to less than 25% for a century, and remains above zero for many millennia.[58] Ominously, analysis of geological evidence[59,60] suggests that the response to emissions over the last century may well overestimate how rapidly carbon will be taken up in the future and that, for example, 25% of the human-created increment to the CO_2 concentration will remain for 5000 yr, making clear the long-range import of continuing emissions.

Both net land-cover change and addition of fossil carbon to the atmosphere, most of which is from fossil-fuel combustion with a much smaller amount from cement production, create increments to the atmospheric CO_2 concentration that the carbon cycle redistributes to all reservoirs. Although the net flux of carbon from the terrestrial biosphere to the atmosphere as a result of land-cover change (i.e., including from deforestation, loss of soil carbon, etc.) is now quite small, the net deforestation due to human activities over the past few centuries is estimated to total almost 160 PgC.[54] Accounting for the timing of the releases, these emissions are estimated to have contributed approximately 24 ppmv to the CO_2 increase since preindustrial times.

In contrast, emissions from fossil-fuel combustion, which have risen to an estimated 8.4 PgC/yr in 2006 and total approximately 330 PgC since 1750,[54] have had a significantly larger effect, being responsible for over 80 ppmv of the increase above the preindustrial CO_2 level.

To provide a basis for estimating the consequences of human activities, the IPCC has coordinated development of a series of scenarios of future emissions that are based on projections of population; economic development and productivity; development, improvement, and selection of technologies for providing energy; and the degree of international cooperation and coordination of energy policies. The primary scenario used in IPCC's second assessment[55,56] was focused around a "business-as-usual" (BAU) scenario that assumed ongoing global economic growth and population growth to approximately 10 billion. Allowing for ongoing improvement in energy efficiencies at the current rate and for switching to less carbon-intensive energy technologies as they are developed decreases the projected emissions in 2100 from over 60 PgC/yr to approximately 20 PgC/yr. That the ongoing rate of efficiency improvement of 1–1.5%/yr is already included in the development of the emissions projections is often overlooked,[57] even though not doing so would lead to very unrealistic projections. Therefore its inclusion in the scenarios means that further reductions in emissions will require significant additional measures.

Even with technology improvement, models that represent the carbon cycle (see *THE CARBON CYCLE*) project that the BAU scenario would lead to an increase in the atmospheric CO_2 concentration to just over 700 ppmv. This level would be nearly 170% above the preindustrial value, as compared with being approximately 37% above preindustrial levels at present. Although variants of the BAU emissions scenarios (in terms of population, technology improvement, etc.) led to projected concentrations in 2100 that range from approximately 600 to 850 ppmv (each with an uncertainty of around 15% due to assumptions regarding the carbon cycle), the international negotiations leading to the Kyoto Protocol focused on addressing the BAU scenario, mainly because there is actually little difference among the scenarios for the 10- to 15-yr period of the proposed agreement.

For IPCC's Third Assessment Report, new emissions scenarios were developed. To provide a basis for constructing them, four storylines (that branched into six scenario groups) were developed to project how the world might change from 1990 to 2100.[36] Integrated assessment models (IAMs) of various types were used in this effort to generate 40 emissions scenarios. IAMs[61,62] typically include component parts that deal with the global and regional economy, choices among energy technologies and the pace of technological improvement, amounts of fuel available at various prices, emissions of GHGs and aerosols, changes in land use and demand for land, simplified climate models, and the impacts of climate change.

Prescribing various types of policy restraints (including none at all), these models generate the economically optimal selection of energy technologies through the 21st century for the regions of the world that they represent (see ref 36, Appendix IV). The resulting emissions scenarios, often referred to as the *Special Report on Emissions Scenarios* (SRES) scenarios after the title of the report, were grouped into four families, ranging from one that shifted predominantly to non-fossil fuels to ones that are even more fossil-fuel (i.e., coal) intensive than at present. In outline form, these scenarios are:

- In its central scenario (A1B) the A1 storyline envisions a world of very rapid economic growth with global population peaking mid-century, the rapid introduction of new and more efficient technologies, increased cultural and social interaction internationally, and a substantial reduction in regional differences of per capita income. Mid-range emissions of CO_2 for this scenario (and the mid-range value is similarly given for the other scenarios) climb to approximately 17 PgC/yr and then start slowly declining to approximately 14 PgC/yr by 2100. The fossil-fuel-intensive variant of this scenario (A1FI) has emissions increasing to approximately 29 PgC/yr by late in the century before slowly starting to decline. Emissions from the non-fossil-fuel-intensive variant (A1T) are projected to increase to approximately 12 PgC/yr by mid-century and then decline to approximately 5 PgC/yr by 2100.
- The A2 storyline envisions a very heterogeneous world with considerable variations in fertility, economic development, economic growth, and technological change. In this scenario, CO_2 emissions climb to approximately 28 PgC/yr by 2100, at which time they are still rising.
- The B1 storyline envisions a world like A1, but with rapid changes in economic structure, shifting towards a service and information economy in which there is an emphasis on solutions, sustainability, and equity, but without specific climate initiatives. Emissions for this scenario are projected to be similar to A1T.
- The B2 storyline envisions a world that emphasizes local solutions and approaches and intermediate rates of growth in population, economic development, and technological change, but coupled with attention to environmental protection and equity. Projected emissions for this scenario rise more slowly than for the A1T and B1 scenarios to mid-century, but then keep on rising slowly instead of declining towards the end of the century.

These emissions scenarios project that total CO_2 emissions from 1990 to 2100 will range from 770 to 2540 PgC, leading to an even wider range of concentrations than for the 1992 emissions scenarios and an even lower likelihood that the actual emissions will be outside the projected range. The authors chose not to assign probabilities to the scenarios given the significant uncertainties about the future of global society. Although this decision may make sense scientifically, it simultaneously makes the problem more difficult for policy-makers because of the wide range of possible outcomes, and therefore policy steps, needing to be considered.

Since the SRES effort, several authors have sought to assign probabilities to the various postulations made in the IPCC storylines. Among the most thorough of the subsequent analyses is a report prepared by Clarke et al.[63] for the U.S. Climate Change Science Program. The baseline scenarios generated by the three IAMs participating in their study are shown in Figure 4. These scenarios are typical of what is expected to occur in the absence of specific policy actions to limit greenhouse emissions, but allow for technology improvements, population changes, standard-of-living improvements, and other aspects of economic development. Interestingly, their central estimate ends up being very similar to the mid-range of IPCC's 1992 and 2000 studies, with fossil-fuel CO_2 emissions in the range of 20–25 PgC/yr in 2100.

Even though the range of the SRES emission scenarios was intentionally quite broad, extending from approximately 12 to 18 PgC/yr in 2050 and 4 to 30 PgC/yr in 2100, the recent acceleration in emissions due to strong economic development and the many new coal-fired plants coming online in southern and eastern Asia are causing emissions to increase at a faster pace than even IPCC's highest scenario.[64] The probability that the problem will go away by itself as a result of ongoing technological development thus seems very, very low.

Emissions from the United States

To have the information needed to limit emissions under the U.N. Framework Convention on Climate Change (UNFCCC), which is the 1992 international agreement setting the objective of reducing overall global emissions and limiting climate change, nations are required to submit increasingly detailed compilations of their emissions.[65] These compilations typically cover a fixed set of climate-affecting gases that are inter-related on the basis of their relative influence on radiative forcing as compared with CO_2, as explained under Finding 2. To provide

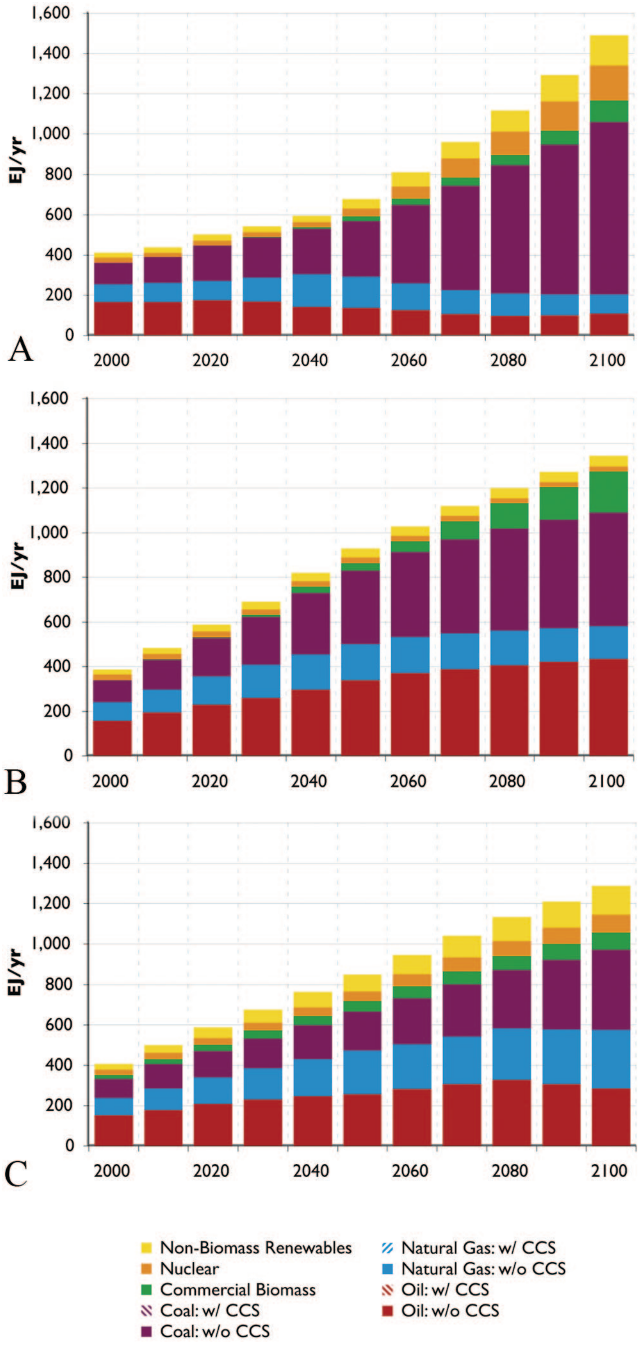


Figure 4. Baseline projections from three IAMs of the components of global primary energy consumption out to 2100 assuming that policies to limit GHG concentrations are not enacted, so sequestration (carbon capture and sequestration [CCS]) is not required. Total energy consumption varies among models mainly because of differing assumptions about the potential for efficiency gains. Variations in the mix of technologies occur because of differing assumptions about the availability of liquids and natural gas from tar sands and oil shales (source: Clarke et al.[63]).

context for this discussion of U.S. emissions, Table 2 provides the multiplicative factors recommended by IPCC (ref 15, chapter 2). Once this conversion is made, the emissions are referred to as being CO_2-equivalent and so are given as $PgCO_2$-equiv/yr.

Note also that referencing emissions to the mass of CO_2 means that the mass of the two oxygen atoms as well as the mass of the carbon atom is being included. As a result, given the relative molecular weights, the emission totals given in the national and international inventories[66,67] and being discussed in developing policy are a factor of 3.67 times larger than the emissions totals reported in PgC/yr (i.e., the current global emissions of ~8 PgC/yr are equivalent to ~25.4 $PgCO_2$/yr). Although presenting the mass of CO_2 emissions can be useful for following total mass flows, this approach requires extra calculations if carbon atoms are being followed through the carbon cycle.

In 2005, the U.S. Environmental Protection Agency (EPA),[68] reported that U.S. GHG emissions totaled 7.26 $PgCO_2$-equiv, which was approximately 16% higher than in 1990 even though the U.S. gross domestic product (GDP) had grown by over 55%. The comparison to 1990 is important because the UNFCCC, which was signed by President George H.W. Bush and unanimously acceded to by the U.S. Senate, included a voluntary commitment to bring year 2000 emissions down to 1990 levels; this still has not been accomplished. However, that emissions grew at a rate of less than one-third of that of the economy suggests that the United States is improving its carbon efficiency through a combination of improved economic efficiency, a switch towards a more service-oriented economy, and an increasing fraction of non-fossil sources of energy.

For 2005, EPA[68] found that approximately 84% of the CO_2-equivalent emissions resulted from CO_2 emissions, 7.4% from CH_4, 6.5% from N_2O, and 2.2% from halocarbons and perfluorocarbons. The relative roles of CO_2, approximately 94% of which is from fossil-fuel combustion, and halocarbons are rising, whereas the relative roles of CH_4 and N_2O are slowly declining.

Of the U.S. CO_2 emissions, 33% result from transportation (more than 60% from use of personal vehicles), 27% are from industry (split between direct use of fossil fuels and use of electricity derived from them), 21% are from residential use (70% from use of electricity), and 18% are from commercial sources (78% due to electricity). The electric generation sector uses 93% of the coal in the United States, and because combustion of coal leads to higher CO_2 emissions per unit energy than other fuels, 41% of the CO_2 emissions result from generation of electricity. Overall, U.S. CO_2 emissions, which total 1.66 PgC/yr, are approximately 21% of the global total, and per capita emissions are approximately 4.5 times the global average value. Largely because of its extensive petroleum industry, the state with the highest emissions is Texas, with California in second place, emitting roughly half as much even though it has a population approximately twice as large. On a per capita basis and ignoring cross-boundary transfer of electricity and the energy used to make products, Wyoming has per capita emissions approximately 6 times the U.S. average because of the energy required for coal mining and the CO_2 released because of generation of electricity for others. At the other extreme, New York and California have per capita emissions that are about half of the national average, in large part because they have very little heavy industry, import electricity, and have strongly encouraged conservation and efficiency.

Table 2. Global Warming Potential (GWP) for a few of the most important atmospheric gases.[15]

Species	Lifetime Used for GWP Calculation (yr)	GWP for Given Time Horizon (yr)		
		20	100	500
CO_2	[a]	1	1	1
CH_4	21	72	25	7.6
N_2O	114	289	298	153
CFC-11	45	6730	4750	1620
Other halocarbons	A few to many hundreds of years	Generally several thousand	Generally several thousand	Generally several thousand

Notes: [a]The response function used by IPCC to represent the persistence of the increase in the CO_2 concentration created by human-induced CO_2 emissions is the sum of a constant (0.217, meaning 21.7% of the perturbation will not disappear) and three exponential decay terms: 18.6% with a decay time of 1.186 yr; 33.8% with a decay time of 18.51 yr; and 25.9% with a decay time of 172.9 yr.

Despite increased economic activity and waste generation, CH_4 emissions have not been rising because controls of CH_4 emissions are relatively inexpensive, and in some cases lead to cost savings. Historical data indicate that capture from garbage dumps, reduced leakage of natural gas, and recovery from agricultural operations have reduced emissions since 1990. For N_2O, emissions have also been slowly dropping as a result of better agricultural management and reduced emissions from mobile sources. Therefore, for the United States, reducing CO_2 emissions is the biggest challenge, and this challenge is growing and will continue to grow in the absence of policy actions limiting such emissions.[63] Depending on whether per capita emissions can be reduced from approximately 6 tC/person/yr or end up doubling, U.S. emissions are projected to grow to 30–175% above their year 2000 levels by 2100.

FINDING 2: THE EARTH'S NATURAL GREENHOUSE EFFECT IS BEING ENHANCED

The Earth's climate is different from that of the moon largely because of the presence of the Earth's atmosphere. Rather than incoming solar radiation directly striking the surface, with the absorbed fraction warming the surface until balanced by emission of infrared (IR) radiation, the atmosphere intervenes. Atmospheric intervention includes reflecting and absorbing some of the incoming solar radiation, and absorbing and emitting back towards the surface much of the upward-directed IR radiation, thereby impeding the natural cooling of the planet (see supplemental data). Altering atmospheric composition modifies the intensity of this process, affecting the resulting surface temperature, overall climate, and sea level.

The Global Energy Balance

Although the balance of net incoming solar radiation and total outgoing IR radiation determines the average *planetary* radiating temperature, the Earth's *surface* temperature is dependent on fluxes within the atmosphere and exchanges of energy between the atmosphere and the surface. Together these make up the Earth's energy balance (see ref 15, FAQ 1).

Average solar radiance at the distance the Earth is from the Sun is approximately 1368 W/m^2. Spread over the planetary sphere, the annual global average of incoming solar radiation at the top of the atmosphere is one-quarter of this amount, or approximately 342 W/m^2. Of this amount, clouds, particularly low-level stratus clouds that are highly reflective, and scattering by particles and air molecules lead to approximately 77 W/m^2 being reflected back to space; the Earth's surface, which is generally darker than the clouds, reflects approximately 30 W/m^2. As a result, the ratio of the total reflected energy from the Earth to the total incoming solar radiation (defined as the Earth's albedo) is approximately 31%. To achieve a balance, the Earth warms until 235 W/m^2 are being emitted back to space by the atmosphere and surface. By the Stefan–Boltzman equation, this gives an annual global-average planetary radiating temperature of 255.25 K or -18 °C, which by chance turns out to be very near 0 °F. Were this the average temperature of the Earth's surface, the world would be a very different place, being frozen from roughly the subtropics to the pole in each hemisphere if one assumes local temperature is determined solely by the incoming solar and outgoing IR radiation and that day–night and seasonal cycles and atmospheric and oceanic transport of heat have no influence.

That the Earth's average surface temperature is observed to be approximately 15 °C, approximately 33 °C higher than the planetary radiating temperature, is a result of how the atmosphere functions. As the incoming solar radiation passes through the atmosphere, approximately 67 W/m^2 ($\sim$20%) is absorbed. Stratospheric O_3 absorbs the first 3%, mainly in the ultraviolet (UV) wavelengths that drive stratospheric chemistry. Solar radiation making it to the troposphere is then selectively absorbed by water vapor and other gases and by cloud droplets and other aerosols. Approximately 168 W/m^2, or just under half of the solar radiation incident at the top of the atmosphere, is eventually absorbed by the surface. Were this the only energy warming the surface, the surface's radiating temperature would be 233 K, or about -50 °C.

But the atmosphere also radiates energy to the surface. Because of the absorption bands of the atmospheric gases, most of the IR radiation emitted upward is absorbed, with the height of absorption being dependent on wavelength and amount of the absorbing gas. In layers where the temperature is high enough that the atmosphere can have a significant water vapor content (i.e., mainly in the lowest few kilometers), much of the absorption is by atmospheric water vapor. Higher in the troposphere and when conditions are cold and the air is dry, absorption by CO_2 and other gases is very important. These other gases include CH_4, N_2O, O_3, and halocarbons, each of which has absorption bands that increase the atmosphere's energy gain. In addition, cloud droplets are highly absorbing, so all IR radiation encountering clouds is rapidly absorbed; impacts of particulate aerosols on IR radiation are generally small. In the atmosphere, the same gases that absorb also emit radiation, doing so in both the upward and downward directions at the temperature of the air or cloud surface where they are. Radiation emitted upward is subject to further absorption and re-emission upward and downward until upwardly emitted radiation passes through to space. Radiation emitted downward is absorbed by gases below and by the surface, causing further warming and additional emission of IR radiation, which is in turn subject to absorption and emission in the atmosphere.

Further complications arise because the atmosphere moves, and this movement carries energy in the form of heat and water vapor (water vapor transport equates to energy transport because condensation leads to release of the latent energy used in evaporation). If the atmosphere did not move and its temperature were governed solely by the absorption and emission of solar and IR radiation interacting with atmospheric composition, the Earth's surface would become much warmer than the lower atmosphere. However, surface warmth leads to both evaporation (transferring latent heat to the atmosphere) and direct warming of the atmosphere (transferring sensible heat). Atmospheric warming makes the air buoyant, causing it to rise, expand, and cool; this convection cools the surface and warms the atmosphere, creating the troposphere. As the upward moving air expands and cools, condensation occurs, releasing heat that drives further upward movement. By forcing air outside the rising convective column back down, thereby compressing and warming it, the energy released in the rising cloud column is spread out. Averaged over the Earth, air temperature cools with altitude at near the moist adiabatic lapse rate (which averages about −6.5 °C/km). With radiation and convection tightly coupling the surface with the troposphere, altering the energy balance of one domain will alter the other.

The trapping of IR energy, with a significant fraction radiated back down to further warm the surface, is popularly referred to as the "greenhouse effect," even though a greenhouse is kept warm because the enclosure is mainly containing the water vapor, so suppressing the cooling effect of evaporation. For the Earth, the greenhouse process contributes to surface warming until the temperature of the troposphere, on average, radiates energy to space reaching 255 K, thus balancing out the absorbed solar radiation with the IR radiation being emitted to space.

Calculation of the greenhouse effect requires great care to properly treat the spectral absorption bands of each species and their overlaps, and the altitudinal changes in absorber amount, absorption and emission of radiation, cloud cover and characteristics, and temperature and pressure. The U.S. Department of Energy (DOE) has established several observatories to validate and improve understanding of the many dependencies.[69] Accounting for these factors, radiation of energy to space occurs at approximately 6 km above the surface. For the temperature of this layer to reach 255 K, the surface temperature needs to be elevated by approximately 33 K, creating the surface warming that is essential to life on Earth.

At its elevated temperature, the surface radiates approximately 390 W/m^2 upward. Of this amount, only approximately 40 W/m^2 (~10%) passes directly to space through windows in the absorption bands of the atmospheric species. The surface also transfers to the atmosphere approximately 24 W/m^2 as sensible heat and approximately 78 W/m^2 as latent heat, an amount equivalent to annual precipitation of approximately 0.98 m/yr. The 310 W/m^2 of upward-directed IR radiation that the atmosphere absorbs is just over twice the amount of energy the atmosphere gains from incoming solar radiation, latent heat release from condensation, and from direct warming by the surface. Downward radiation to the surface of approximately 324 W/m^2 from atmospheric gases and clouds is equivalent to blackbody radiation coming from a layer approximately 13 K cooler than the surface, or at an altitude of approximately 2 km using the average global lapse rate. For the surface, energy gain from the downward IR radiation, integrated over the globe and over day and night, is just over twice the amount of solar energy absorbed at the surface.

Processes Governing the Atmospheric Response to Changes in Atmospheric Composition

Changes in atmospheric composition and surface characteristics alter the energy balance, and thereby affect the climate. This effect is quite evident at night: under clear, dry conditions, atmospheric absorption and downward re-emission of IR radiation is relatively low and nights can get quite cold, whereas when the humidity is high and clouds are present, downward IR emission is increased and little cooling occurs. An increase in highly reflective low clouds increases planetary albedo, leading to less absorption of solar radiation and surface cooling, even though the change does not significantly change emission of IR radiation to space. High cirrus clouds tend to warm the planet because they let most solar radiation through, but strongly absorb upwelling IR radiation and then re-emit half of this energy downward. Viewed from space, cirrus clouds reduce upward IR radiation because the radiation appears to be coming from a higher and colder level than would be the case if the clouds were not there. Deep convective clouds are highly reflective, but they are not very extensive; because their tops radiate to space at much colder temperatures than their bottoms radiate to the surface, they tend to warm the planet, especially at night. Although these relationships are varied, complex, and not yet well understood, that the climate has been stable suggests that the many processes act in concert to try to stabilize the climate rather than create large, nonlinear outcomes and runaway effects.

Because the IR radiation terms are roughly twice as large as the solar radiation terms, changes in the concentrations of IR-absorbing (i.e., greenhouse) gases can have a very large influence. With respect to climate change, what matters is how changes in composition affect the energy fluxes across the tropopause because it is these changes that affect the coupled surface-troposphere system. Collectively, the effect of higher concentrations of GHGs, particularly of gases like CO_2 that are mixed vertically through the atmosphere, is to make the atmosphere less transparent to IR radiation, which leads to an increase in the average altitude of the atmospheric layer that is emitting radiation to space and a lowering of the average layer radiating to the surface. In addition, because the higher atmospheric layers can now absorb more of the upward-directed IR radiation, these layers require less convective heating from below to maintain their temperature, leaving that energy near the surface to contribute to surface warming and an intensified hydrologic cycle.

But even more than this heating effect is occurring near the surface. Because the vapor pressure of water, which is governed by the Clausius–Clapeyron equation, increases by approximately 7% per degree, the initial increase in surface temperature due to the additional CO_2 leads to an increase in the water vapor concentration of the lowest atmospheric layers. Because water vapor is a very strong GHG, this leads to absorption of upward-directed IR radiation lower in the atmosphere, and in turn, radiation back to the surface by water vapor (and other gases whose concentration has increased) from lower, and therefore warmer, altitudes. These changes tend to increase the downward radiation at the surface by several times as much as the reduction in emission to space caused by the increase in CO_2 alone, creating an amplifying effect that is referred to as water vapor feedback.

Other feedbacks also contribute to the climate's response to changes in atmospheric composition, and many are amplifying, or positive, feedbacks. Surface warming tends to melt snow and ice cover, which darkens the surface and increases the amount of solar radiation absorbed at the surface, amplifying the original warming. Increases in the extent of low stratus clouds reflect more solar radiation and exert a cooling influence; such clouds, however, are typically associated with ocean waters that are relatively cool, especially in regions where deeper ocean waters are upwelling and where near-surface inversions form. As a result, it is unlikely that the extent of low clouds will increase as the world warms; indeed, reduced extent might well contribute to further warming. With extent and intensity of convection generally increasing with temperature, higher temperatures would seem likely to lead to greater convection, perhaps contributing to additional moisture and cirrus clouds in the upper troposphere; this type of response would also tend to amplify overall warming.

Cooling influences (often referred to as negative, or dampening, feedbacks) have also been identified. Warming that leads to drying of the land tends to increase surface albedo, decreasing the absorption of solar energy. Increased lofting of dust and the sulfate aerosols that result from oxidation of SO_2 from coal combustion (this is really a human-induced forcing rather than a feedback) also tend to reflect solar radiation, contributing a cooling influence. Because the presence of sulfate aerosols can increase the concentrations of cloud condensation nuclei, their presence in clouds tends to lead to smaller, but more numerous, cloud droplets, which tends to increase cloud albedo and, in some cases, to increase the lifetime of clouds; both effects tend to reduce the amount of energy available to warm the planet.

Although this discussion has focused on the energy balance of the surface-troposphere system, what happens in the stratosphere also matters. The stratosphere absorbs the highest frequency radiation from the Sun. This energy, which is primarily absorbed by O_3, warms the stratosphere and maintains the layer as a relatively stable air mass only loosely connected to the troposphere. Although the stratosphere represents only approximately 15% of atmospheric air, the average residence time of an air molecule in the stratosphere is a few years. The absorbed UV radiation also contributes to the formation of stratospheric O_3. Unable to lose its heat by mixing with the troposphere, the stratosphere needs to radiate its heat away. However, being very dry, there is little water vapor, and O_3 is at such a low concentration that emission is also low. Indeed, it is the CO_2 in the stratosphere that is present in a high enough concentration to radiate sufficient energy out of the stratosphere, either out to space or down to the troposphere. As a result, stratospheric temperatures are determined mainly by the balance between O_3 absorption of solar energy and CO_2 radiation of IR radiation, thus coupling the O_3 depletion and climate change problems, although not very tightly. With CO_2 determining the rate of energy loss, an increase in its concentration makes it easier for the stratosphere to radiate away its energy, causing it to be cooler—and because stratospheric O_3 chemistry is temperature dependent, this represents another linkage of the two issues.

Overall, however, conceptual analysis of the energy balance and recognized feedback processes strongly favor warming as a consequence of the trapping of IR energy—the challenge is to determine the climate sensitivity, which is a measure [in units of $°C/(W/m^2)$] of how much warming will result from a specified change in radiation at the tropopause.

Empirically Based Estimates of Climate Sensitivity

Laboratory studies of the IR absorptivity of CO_2 and other GHGs provide one indication of their ability to alter the climate (and such measurements were first done for CO_2 in the mid-19th century). The climates of nearby planets and the time history of the Earth's climate can also be used to estimate the intensification of the greenhouse effect in response to changes in atmospheric composition.

The Earth's neighboring planets provide excellent tests of scientific understanding.[70] The surface temperature of Venus is much higher than the Earth, but not primarily because Venus is closer to the Sun. Because of the very bright clouds that make Venus so visible in the night sky, solar absorption by Venus is less, on a per square meter basis, than what occurs on Earth. Instead, the very high concentrations of GHGs in its atmosphere recycle the limited solar energy that is absorbed over and over to create the planet's high surface temperature. Although the Martian atmosphere is mainly CO_2, Mars is farther from the Sun; lacking water vapor, its surface temperature is only slightly elevated by the greenhouse effect of its atmosphere. Once adjustments are made for the very different composition and pressure of these planetary atmospheres, the same radiation models that explain solar and IR radiation fluxes in the Earth's atmosphere explain the conditions observed on Venus and Mars, expanding the set of conditions that any alternative explanation of atmospheric behavior needs to explain.

Understanding of the greenhouse effect can also be checked against Earth's climatic history. Using all sorts of geological, geochemical, isotopic, and biological indicators, significant efforts have been made to reconstruct past climatic conditions. Paleoclimatic analyses are then done to relate changes in climate to changes in the amount of incoming solar radiation, surface geography, and atmospheric composition, each of which has undergone substantial changes.[58,71] Although there is still much to learn, especially about the rate of change of climate in the past, that most of the changes are associated with changes in factors that can affect the climate is quite evident. Over the Earth's 4.6 billion-yr history, its climate was not random, but was driven to different states by various forcing factors. Only a few examples will be discussed here.

During the late Cretaceous period (the period of dinosaurs that covered tens of millions of years and almost certainly ended with a major asteroid impact 65 million yr ago), geological evidence suggests that the CO_2 concentration was likely close to 1800 ppmv and there are indications that the world was much warmer, particularly in high latitudes, where there are indications of near-tropical vegetation. During other epochs since that period, the CO_2 concentration has also been high with warmer conditions: Eocene (58–37 million yr ago [Ma]; CO_2 concentration ~1200 ppmv); Miocene (25–9 Ma; 760 ppmv); and Pliocene (9–2 Ma; 450 ppmv). Maps of prevailing climatic conditions by Soviet scientists, paired with estimates of CO_2 concentration from geological time histories, suggest that a doubling of the CO_2 concentration is associated with an increase in global average temperature of approximately 3 °C, although the uncertainties are significant.[71,72]

The ice age cycling over the last few million years provides another period for attempting to empirically derive an estimate of climate sensitivity. Data from the ice core extracted by a French-Russian team at the Vostok station in Antarctica[49–51] provide the most detailed record, although earlier indications were available from ocean sediment records. The time history, now extending back approximately 800,000 yr,[51] shows quite correlated variations in temperature and in CO_2 and CH_4 concentrations (see Figure 5). The overall timing is well correlated with the combined effects of the cycling of three of the Earth's orbital elements,[73] the major features of which involve: (1) the ellipticity of the Earth's orbit, which varies between near circularity and slight ellipticity with a frequency of approximately 100,000 yr; (2) the tilt of the Earth's axis, which varies between approximately 22 and 25° with a period of approximately 41,000 yr; and (3) precession, which cycles the time of year of closest approach to the Sun through the seasons with a period of approximately 26,000 yr. When the major and minor terms of these cycles, which are a result of the time-varying pull of the Sun and planets, are properly combined, the periodicities that emerge, particularly for the amount of solar radiation reaching high latitudes, match quite well with the periodicities determined from the ice cores.[74–76]

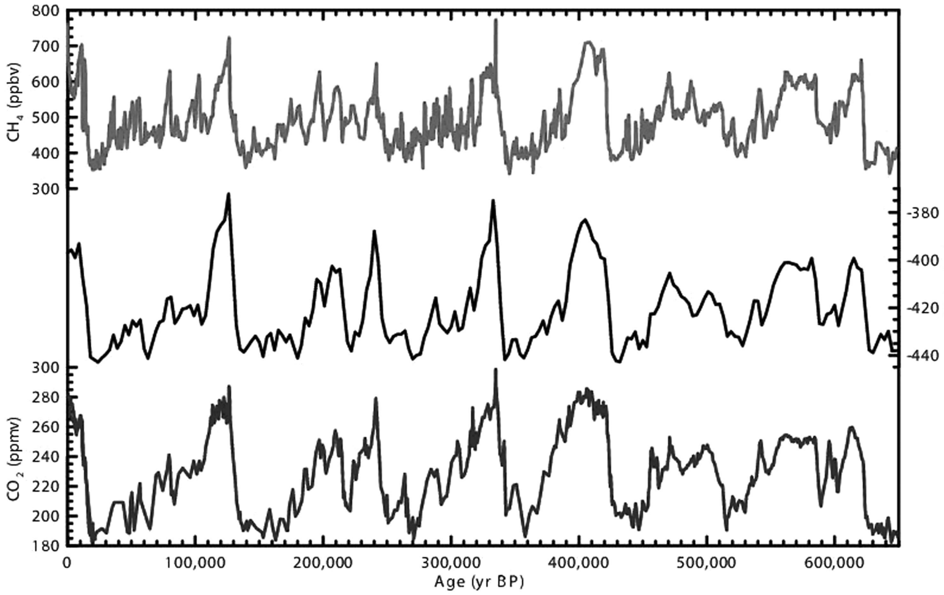


Figure 5. Time history over the last 650,000 yr of the concentrations of CH_4 (top, in ppbv) and CO_2 (bottom, in ppmv) derived from air trapped in bubbles in the Dome C ice core drilled in East Antarctica. The center curve shows the change in the deuterium isotope concentration (in parts per thousand), which is a linear proxy for the change in local air temperature. On the basis of a survey, an increase (i.e., less negative) departure of 9 parts per thousand is proportional to a 1 °C increase in temperature, indicating about a 7 °C range. The peaks approximately every 100,000 yr represent interglacial periods and the minima indicate the times of maximum glaciation. Reprinted with permission from Petit et al.[49] Copyright 1999 Nature Publishing Group. Also reprinted with permission from Siegenthaler et al.[51] Copyright 2005 American Association for the Advancement of Science.

What is most striking is that the largest climatic changes derived from the ice cores occur with approximately 100,000-yr periodicity. However, this is also somewhat perplexing because the ellipticity cycle causes the smallest variations in the latitudinal and seasonal redistribution of insolation at the top of the atmosphere. Working with a two-dimensional (latitude-vertical) climate model that has been completely overhauled since I built the first such model for my dissertation on ice age hypotheses,[77] simulations can now be run over hundreds of thousands of years. Through such studies, Berger[73] and his colleagues have made significant progress in quantifying the contributions of various factors to glacial-interglacial cycling. His results indicate that the combined effects of multiple forcings must be considered, including not only the orbital forcings and albedo effects caused by the ice sheets, but also the effects of changes in atmospheric composition (i.e., in CO_2 and CH_4); changes in vegetation that alter surface albedo, subsidence and rebound of the land surface due to changing masses of ice sheets, and changes in sea level (at glacial maximum, sea level is depressed 100–150 m below present, exposing additional land areas). When these forcings are imposed based on paleoclimatic reconstructions, Berger's model generally reproduces the climatic changes observed in the ice core record with a derived climate sensitivity of approximately 3 °C. As an interesting sidenote, if Berger imposes a CO_2 concentration above approximately 400 ppmv, there is no glacial cycling.

Although the correlation of temperature and CO_2 concentration is very high, close examination of the ice core record indicates that the temperature starts to rise about 1000 yr before the CO_2 concentration. Even though this difference is close to the temporal resolution of the data and an offset might occur as a result of the temperature record being derived from ice isotopic changes whereas the CO_2 measurement involves air that is trapped in the air bubbles that eventually form, the offset does appear to be real. Some of those criticizing the IPCC findings suggest that this phasing refutes the finding that the increasing CO_2 concentration is the cause of current warming; such claims, however, rest on a fundamental misunderstanding. For the case of glacial cycling, the 5–6 °C warming that marks the transition to an interglacial state is initiated by particular changes in orbital forcing. The initial warming is then amplified by a positive carbon cycle feedback that contributes to the ultimate warming and full transition to interglacial conditions.

The best hypothesis at present for explaining how this feedback works is that the initial orbital conditions not only increase warm season melting of Northern Hemisphere ice sheets, but also simultaneously melt Southern Hemisphere sea ice cover, exposing very cold waters that have high concentrations of dissolved CO_2.[78] With reduced sea ice, ocean waters warm, forcing an increasing amount of CO_2 into the atmosphere (just as warming a carbonated beverage forces out CO_2), initiating a rise in the global atmospheric CO_2 concentration. This rise then leads to further warming, melting of more sea ice, additional warming of ocean waters, and a further push of oceanic CO_2 into the atmosphere. Thus, through the glacial cycling, the natural carbon cycle serves as a positive feedback to the orbital forcing, exerting a warming influence equivalent to approximately 3 °C per doubling of the CO_2 concentration.

In the case of the human-forced changes in climate now underway, the increase in atmospheric CO_2 is occurring by a different mechanism (primarily fossil-fuel combustion), but the effect will be the same—namely, to cause additional warming of the ocean and land surface and the initiation of water vapor, sea ice, and other positive feedbacks that together will lead to additional warming at a pace equivalent to approximately 3 °C per doubling of CO_2. What is particularly significant about identification and quantification of the positive feedback mechanism created by the natural CO_2 feedback is that recent changes in climate suggest that this natural feedback mechanism, which is only starting to be included in global climate models, is already starting to contribute to present warming.[79] For example, there are indications that global warming is leading to less uptake of CO_2 by the ocean, just as likely occurred in the glacial-interglacial transition, and this is leading to additional warming.

Thus, rather than the offset of temperature and CO_2 increases in the ice core record being an indication of IPCC overestimating the climatic response to the ongoing rise in the CO_2 concentration, as some critics have suggested, the offset is an indication that there is a strong natural carbon cycle feedback mechanism, something that had only been hypothesized. To make matters even more serious, the ice core records also suggest that there is a natural positive feedback mechanism involving CH_4, likely relating to increased release as frozen soils (i.e., permafrost) warm and greater production occurs in swampy areas.

Changes in Radiative Forcing

Because the Earth's surface and troposphere are energetically coupled, both vertically by convection and horizontally by atmospheric circulation, the net change in the energy flux across the tropopause, or "radiative forcing" (RF, defined as net change in downward minus upward radiation in W/m^2), has become the metric for indicating the potential climatic influence of different perturbations to atmospheric composition. Unfortunately, this quantity cannot be directly measured, but instead must be calculated using radiation models.

Because of the large heat capacity and circulation of the oceans, whether a perturbation in atmospheric composition causes a change in RF that is globally and seasonally uniform or not seems to have relatively little influence on the change in global average temperature. Model results are indicating, however, that the vertical pattern of the forcing can make a difference. For example, by absorbing solar radiation aloft, aerosols allow less solar energy to reach the surface, thus weakening the hydrological cycle and water vapor feedback. The limiting case of this effect was found in the study of the potential effects of large amounts of dark smoke hypothesized to be lofted as a result of fires started by a major nuclear war. Although more solar radiation was absorbed, because the energy was absorbed in the upper troposphere above most of the atmosphere's water vapor, the natural greenhouse effect was diminished and resulted in a "nuclear winter."[80]

So that feedback effects are not included in the calculation, RF is calculated before any adjustment in tropospheric conditions (i.e., the climate) is allowed to occur. By convention, however, the calculation of the RF allows adjustment of stratospheric temperatures because this adjustment is purely radiative and occurs quite rapidly as compared with overall adjustment of the climate system. Both radiative and convective processes act to spread the influence of the RF to the surface and throughout the troposphere. However, because of the large heat capacity of the oceans and ice sheets, global average temperature only slowly adjusts to the change in RF. As a consequence, an imbalance remains in the planetary energy balance—and it is this imbalance that carries the warming forward. Although there remain uncertainties, satellite observations of the changes in the spectral distribution confirm that the increasing concentrations of GHGs are exerting a warming influence in this way.

The fourth column of Table 1 provides IPCC's estimate of the contributions of human activities to RF since 1750 (ref 15, chapter 2). Increases in GHG concentrations are all positive, but the RF per unit increase in forcing is very different across species. For example, calculations indicate that the RF of the increase of 100 ppmv in CO_2 concentration has risen to 1.6 W/m^2, whereas the RF for the CH_4 increase of approximately 1 ppmv is approximately 0.48 W/m^2, or 30 times as much per part per million by volume as CO_2 since the start of the Industrial Revolution. Note that the aerosol results have large uncertainties, reflecting their diverse sources, complex composition, and significant spatial and temporal variability. Indeed, even the uncertainty limits are uncertain. For example, a recent study[81] has suggested that soot aerosols are contributing to a warming influence of as much as 0.9 W/m^2, which is much larger than the estimate of 0.3 W/m^2 indicated in IPCC (ref 15, chapter 2) as coming from direct aerosol absorption and darkening of snow albedo. Note that emissions contributing to air quality problems, especially emissions of carbon monoxide (CO) and nitrogen oxides (NO_x), also affect RF, mainly by affecting tropospheric O_3. These interactions are beyond the scope of this review and those interested are referred to the IPCC assessments for further detail (e.g., ref 11, chapter 4).

To account for differences in the relative radiative influences of the various GHGs, as well as the effects of their different lifetimes in the atmosphere, the global warming potential (GWP) has been developed as a metric to use in converting across species. By definition, the GWP for CO_2 is set to 1, and the RFs of the other gases, integrated over selected time intervals, are calculated with reference to the effect of an increment in the atmospheric concentration that would result from emission of 1 kg of each gas (by convention in the policy community, the mass of a gas in the GWP calculations includes its full molecular weight, so for CO_2, the masses of both the carbon and oxygen atoms are included). Table 2 provides the latest estimates of the GWPs for the major GHGs. Note that for each of the gases, in addition to the direct effects of the gas on the fluxes of radiation, there can also be indirect effects (e.g., halocarbons deplete stratospheric O_3, which further affects the fluxes of radiation). Except for the effects of CH_4 on stratospheric water vapor and O_3, these indirect GWP contributions are not included in the estimated values. Although generally small, such indirect effects do, however, need to be considered in comprehensive projections of climate change and evaluations of the effects of various emission control strategies.

Total RF from the increases in GHG concentrations since 1750 is just over 3 W/m^2; this is equivalent to an increase of approximately 1.25% in the amount of solar radiation absorbed by the Earth system. Increases in atmospheric aerosols, including their indirect impacts on cloud properties, reduce the total energy gain by about 1 W/m^2, thus canceling out about one-third of the warming influence of the GHGs. Other influences, including contrails and changes in surface albedo through land-cover change, are generally smaller and induce their effects over very local areas. Natural factors have also been found to have relatively small or short-lived influences. In particular, satellite observations suggest that changes in solar irradiance amount to only approximately 0.1 W/m^2 since 1750. Although there have been several strong volcanic eruptions since 1750, the injected stratospheric aerosols are removed with a lifetime of about 2 yr, so there is no persistent, long-term change.

Limiting climate change is made particularly difficult because the increases in GHGs tend to have persistence times of decades to centuries or beyond, whereas the increases in loading of the aerosols tend to have persistence times of less than 2 weeks. As a result, reducing emissions will lead to much faster reductions in the cooling influence of aerosols than in the warming influence of GHGs, meaning that the net warming influence will persist for decades even though intense efforts have been made to reduce GHG emissions. It is for this reason that, in addition to limiting emissions, various "geoengineering" or "hedging" approaches to counterbalance the warming influence by reducing solar radiation reaching the Earth or by drawing down atmospheric GHG concentrations by enhancing sink processes are being considered (see supplemental data on geoengineering).

Questions often arise about the relative warming effects of the heat and water releases from combustion as compared with the effects of exhaust products like CO_2. Assuming a heat of combustion of 10 kcal/g, combustion of 8 PgC/yr (the present rate of fossil-fuel combustion) leads to a heat release of approximately 0.02 W/m^2 spread over the globe. Accounting for sink processes, the observed annual increase in global atmospheric CO_2 concentration from this much combustion is approximately 2.5 ppmv. Scaling from Table 1, the annual CO_2 increase leads to a RF of approximately 0.04 W/m^2. Thus, as a rough approximation, the heat of combustion each year is equivalent to the trapping of energy by CO_2 that takes place over approximately 6 months, making their climatic significance seem similar. However, the CO_2 increase persists in the atmosphere, heating the planet at this rate for centuries after the combustion has occurred. Clearly, what is so important about the emission of CO_2 is that the perturbation persists for so long.

With respect to the amount of added water vapor, combustion of 8 PgC/yr leads to annual emission of a few petagrams of water vapor. The average amount of water vapor in the atmosphere at a given time is on the order of 13,000 Pg, so the human-induced increment is small in comparison, especially given that precipitation causes the annual cycling of water vapor through the atmosphere to be approximately 40 times larger. In addition, by changing the gradient of water vapor pressure, the additional water vapor tends to suppress local evaporation. So, quite clearly, the global-scale effects of addition of water vapor to the atmosphere by combustion are very small. It is true, however, that there can be local influences; for example, in desert environments, whereas evaporation of water from irrigated lands and golf courses can lower the surface temperature, the local atmospheric burden can be increased and this can trap additional IR radiation. However, on a global basis, and even regionally, this effect is very small.

FINDING 3: CLIMATE CHANGE HAS BEEN DETECTED AND CAN BE ATTRIBUTED TO HUMAN ACTIVITIES

Given that the Earth's climatic history provides significant evidence of conditions that have been different than the present, the critical question is the extent to which recent changes are a consequence of human activities as opposed to natural causes. The first step, often referred to as the "detection" step, is to document that the changes in climate are persistent rather than short-term fluctuations. This requires developing extended records for both the instrumental period, which for surface temperature, for example, extends back to the mid-19th century, and the preinstrumental period, which extends back through human history and Earth history. Because records of past conditions rarely cover the entire Earth, are of varying length, often come from changing types of instruments and measurement protocols, and can be affected by a wide range of biases (e.g., urbanization, etc.), great care must be taken in homogenizing the datasets. Analysis of the resulting records can allow estimation of trends, variations, shifts, extremes, and other statistical measures of past and recent behavior of the Earth system, including of the climate, which is, by convention, taken to be the average over the last 3 complete decades.

The second step, referred to as the "attribution" step, requires an analysis of the most likely causes of the indicated changes, checking for consistency in both magnitude and timing. Drawing a parallel from forensics, the tests use climate models or other means to develop a characteristic "fingerprint" for each hypothesized cause of climate change. With those fingerprints, rigorous statistical tests are used to estimate the relative likelihood and magnitude of each factor's contribution to the observed result. As an example of the differences between fingerprints, an increase in solar radiation would be expected to warm both the stratosphere (because of more absorption by O_3) and the surface-troposphere system (because of more absorption at the surface and in the atmosphere), whereas an increase in GHG concentration would be expected to cool the stratosphere (because of increased emission of IR radiation) while warming the surface (because of increased trapping of IR radiation). Similarly, distinct fingerprints can be developed for volcanic aerosols in the stratosphere and fossil-fuel-generated sulfate and soot aerosols in the troposphere. With these different patterns, the temporal and spatial characteristics of which are quantified through use of climate models, careful statistical analyses can be used to extract estimates of the time-varying contributions of each factor to changes in various climate variables—and the more variables, the greater the confidence in the conclusions.

Much of the contention over the climate change issue arises from a failure to understand the need to complete both the detection and attribution steps. For example, expecting the temperature and CO_2 records to match exactly fails to understand that multiple factors, both natural and human-induced, are affecting the climate. As a result of the "climatic noise" created by natural variability, the influence of various factors will become distinguishable at different times. Assertions of correlations of global average surface temperature with the time history of a single causal factor remain a too frequent basis for claims that the climatic effects of increasing concentrations of GHGs are overstated.

A viable explanation today needs to account for the contributions of each factor in a quantitatively consistent way—energy is energy. Now that quantitative means exist to analyze climate interactions, unless a more detailed set of quantitative couplings and processes is demonstrated, it is the equivalent of "voodoo economics" to assert, for example, that small changes in solar radiation are the cause of large changes in global average surface temperature, whereas much larger changes in energy due to changes in IR radiation cause virtually no change in temperature. Gaining insights regarding areas to investigate can come from both interesting correlations and unexplained deviations of an explanation from observations, but for an argument to gain the stature needed to counter the IPCC's extensively supported findings, rigorous quantitative arguments, carefully peer-reviewed, must be required, given the very significant risk to the Earth system being created by the increasing atmospheric concentrations of GHGs.

Evidence that Global Average Temperature Is Increasing

The variability of the weather, the cycling of the seasons, and year-to-year variability can make it hard to detect changes in decadal average conditions. To protect against mistaken conclusions, carefully and consistently taken measurements are needed, and records must be available that cover wide areas and extended periods. These requirements tend to limit the breadth and set of variables that are adequate for convincingly detecting that changes are occurring.

Figure 6 presents the time history of changes in annual global mean surface air temperature from 1850 to 2005 (ref 15, chapter 3). This record has been constructed by area-averaging the annual temperature departure from its long-term average in grid squares around the word for which there are data (see *CALCULATION OF CHANGES IN GLOBAL AVERAGE TEMPERATURE*). The black dots give

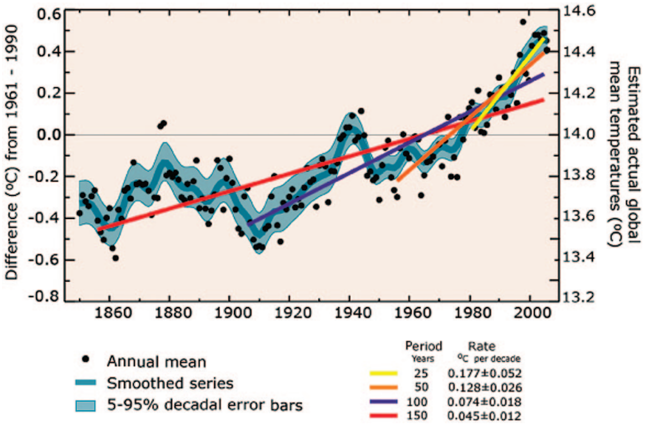


Figure 6. Observed changes in global average surface temperature. The black circles show yearly values and the smoothed curve represents running decadal averages. The shaded areas shows the 5–95% confidence interval estimated from a comprehensive analysis of known uncertainties. The straight lines show the slope over periods of different periods back from 2005. Reprinted with permission from the IPCC[15] (chapter 3). Copyright 2007 Cambridge University Press.

the annual estimate and the line presents the running decadal average value, which is designed to average out years with short-term variations caused by features such as El Niño events and volcanic eruptions. The width of the shaded area indicates the uncertainty in the 10-yr average value arising from changing areal coverage, observational uncertainties, and any inadequacies in removing biases because of such factors as urbanization around stations.

Overall, the global average increase in near-surface temperature has been approximately 0.8 °C since the mid-19th century, with most of the warming occurring during the second half of the 20th century. There appears to be an upward trend in the rate of warming, with the rate for the last 25 yr being almost 0.18 °C/decade, which is approximately 4 times the rate over the entire 150-yr record.

The warming has not been uniform over the Earth. As expected based on how atmospheric processes work, warming in the Arctic and the northern parts of the surrounding continents over the last 100 yr has been about double the global average, whereas warming in low latitudes has been less, damped in part by a larger fraction of the energy going into evaporation. Warming over continents generally has been greater than warming over ocean areas, as expected because of their different heat capacities. There are a few areas where warming has been quite limited, generally because of either higher-than-average burdens of aerosols, which exert a cooling influence by reflecting some of the solar radiation, or enhanced mixing of surface ocean waters with deeper layers.

That global warming is really occurring is made clear by noting that 12 of the last 13 yr are among the 13 warmest years in the instrumental record (updated from ref 15, chapter 3). In addition, the cooling just before this period following the Mt. Pinatubo volcanic eruption in 1991, likely the largest eruption during the 20th century, took global average temperatures down only to levels that are nonetheless among the warmest temperatures since the early 1940s (see more comments on this period below), and so well above the significantly colder conditions following volcanic eruptions during the late 19th century.

Looking across the entire record, at least some of the year-to-year variability in the early record appears to be due to the effects of major volcanic eruptions (Krakatoa in 1883, and several large Caribbean eruptions around 1903). However, the main reason for the larger variability in the 19th-century record is likely because the limited coverage of the network is not sufficient to average out the influences of spatial variations. In addition, some types of measurements taken during World War II (WWII) have large biases that make homogenization difficult, especially because we do not have, as is the case since approximately 1950, observations of tropospheric temperatures that can be integrated and cross-compared using current techniques to ensure overall consistency. As an example of the types of problems that arose during WWII, measurements of nighttime marine air temperature were made near the door to the ship's wheelhouse to take advantage of a sliver of light when the door was ajar rather than to use a flashlight at the bow of the ship, the light from which might attract a torpedo from a vigilant submarine. This change in procedure led to biases of up to a couple of degrees in the measurement as a result of the heat radiated off a ship's metal superstructure.

In addition, during WWII, the spatial distribution of measurements changed as ships took different routes, seeking to avoid interception. Meteorological and oceanic information was also considered especially valuable and sensitive, for it could indicate a ship's location. The unusual nature of the temperature anomaly record during WWII thus makes me continue to wonder if all of the biases have been removed. To get a sense of the possible significance of this problem, place a finger over the record for that time period and note how the century-long record then appears to show steadier warming, especially if the apparent decadal variations during the 19th century (which are not evident in the record of the last 50 yr when data coverage is much more extensive) are considered as mainly because of the limited spatial coverage of the dataset.

Because the instrumental record only goes back to the mid-19th century, a longer record of global average temperature is needed to allow evaluation of the significance of the trends that have taken place over the last 150 yr. A wide range of proxy indicators have been identified that, by calibrating to records over the instrumental period, can be used to estimate changes in local temperature from a baseline period. These include measurements of tree-ring width, changes in abundance of various types of pollen, dates of flowering and harvests, bands created in caves and by corals, isotope records in ice, and many more.[80] Historical records have also been used and are often cited by IPCC critics, but such records must be used carefully because most are from the North Atlantic region, which is among the most variable and its fluctuations are not necessarily indicative of simultaneous worldwide changes (e.g., the warming in the North Atlantic during the early 20th century was not evident in northwestern North America, the Arctic and over to Asia, much less around the Southern Hemisphere).

CALCULATION OF CHANGES IN GLOBAL AVERAGE TEMPERATURE

Although local, and so possibly unrepresentative, records in a few regions go back further, a broad-scale thermometer network was not established until the mid-19th century. Even then, there was little coverage in the Southern Hemisphere, in the Arctic, and over the oceans. The network was set up mainly for the purpose of gathering the information needed to forecast the weather for the benefit of agricultural production, national security, transportation, and economic development. Unfortunately, the network and measurements were not set up for monitoring the climate, so the observations are not ideal. To best achieve the intended objectives, many station locations were set up near cities, airports, and agricultural fields, rather than in unperturbed regions where long-term changes could more easily be identified. In addition, as new instruments or approaches that might improve the weather forecasts have become available, they have typically been rapidly introduced with only limited evaluation of any offsets that might arise with respect to the previous record. Along with changing station locations and station environments (e.g., extent of development of surrounding lands), these changes create challenges for convincingly identifying changes related to long-term changes in the Earth's climate.

As a first step to identifying changes in temperature, dealing with changing spatial coverage of observations and accounting for the spatial heterogeneity of the temperature itself, compilations have been focused not on the temperatures themselves, but on the change in temperature from a baseline at each location. Data quality checks, including checking for consistency in differences between nearby stations, are then used to identify and adjust for biases that might arise, including jumps when stations are relocated, when instruments are changed, or when time of measurement is shifted.

Because measurements of the daily minimum and maximum are more common than hourly measurements, average daily temperature for a given day at a given location is created by averaging the maximum and minimum daily temperatures (and one does have to be careful of what span of time is considered so as not to double count particularly low or high values, and for the type of surface, type of shelter from the Sun, and type of instrument).

Averaging is then done over months, seasons, years, and ultimately decades to get a baseline value at each location around which to calculate changes and then trends. For each station, care also has to be taken to ensure local changes (e.g., buildings or pavement or relocation) or regional development (i.e., urbanization) are not contributing to biases; this is generally done by checking for and ensuring consistency of differences in temperature with other stations, etc.

Similar procedures have had to be followed over the ocean, where many measurements are from ships. Older measurements were taken by throwing a canvas bucket overboard and measuring the surface water temperature with a thermometer as slow evaporative cooling occurred. As diesel-powered ships replaced sailing ships, ocean water temperature observations were instead made of the temperature of cooling water coming into the engine room—so water came from a different depth and through a heated ship, leading to the need for an adjustment to ensure consistency in the record.

Nighttime marine air temperatures, which were typically taken at the bow of the ship, required an adjustment to account for the changing height of the observation as ships got bigger. Because ships move, the frequency and location of observations in a given grid square can change, creating a further need for carefully checking the observations.

Once a set of station values is arrived at, spatial averaging is done. A typical approach is to first average all of the results in a given latitude-longitude box (say 5 by 5 °), and then area-weight the resulting values for the available grid locations. Because grid boxes in polar regions tend to have temperature increases that are larger than the global average and grid boxes in the low latitudes and over the ocean tend to undergo changes that are less than the global average, care must be taken to avoid generating a bias that might arise from a changing latitudinal distribution of grid boxes.

Such efforts to homogenize and validate the data are involved, detailed, and essential. Increasingly, records are being drawn from reference stations where careful quality-assurance procedures have been followed. That useful results come out at all might be surprising, which is why pattern and fingerprint analyses and trends in other variables are also used to document changes in climate.

Several scientists have used various combinations of the available proxy records to generate estimates of the changes in Northern Hemisphere temperature to as far back as 2000 yr ago[82] (see also ref 15, chapter 6). Analyses during the instrumental period suggest that, to a reasonably high correlation (and with the exception of such regional forcings as sulfate aerosols), the two hemispheres tend to show similar multiyear average trends, so the records are often referred to as indications of global change. Although there are variations in the details (and some controversy about the methods used in particular early analyses of the data), caused, for example, by the different seasonal sensitivities of the various proxies, the different spatial coverage of the proxies, and different approaches to extending point measurements to regional average conditions, all of the results show a similar overall pattern.[82]

As shown in Figure 7, a slow cooling occurred for most of the preindustrial period, probably since the end of the last glacial, approximately 6000–8000 yr ago, with the coldest period near the start of the Industrial period (when Europe, for example, was particularly cold). Beginning in the 19th century and continuing strongly through the 20th century, there has been significant warming, giving the long-term curve a "hockey stick" shape. Looked at more closely, however, the warming has been interrupted by cooling in the years after major volcanic emissions and during the mid-20th century, as discussed further below. Nonetheless, the recent warming appears to be unmatched by any similar event at other times in the record of at least the last few thousand years, including during the so-called "Medieval Optimum," when the European region was roughly as warm as at present, but other global locations were not.

Evidence that Confirms Climate Change Is Underway

Although the instrumental record of changes in global average surface temperature is the longest, there are several types of limitations, including that it begins after humans had started modifying the environment, both in the area surrounding many of the observation sites and globally. For this reason, there have been extensive efforts to look for other records and at trends for other than the daily average value of temperature. Even though each record has its own peculiarities and limitations, these other records collectively show broad agreement with the observed trends in surface temperature, adding significant confidence to the conclusion that the climate is changing.

The records examined in IPCC (ref 15, chapters 3–5) included:

- Maximum and minimum temperatures: Minimum temperatures over land are generally rising faster than maximum temperatures, which is expected because the increase in downward IR radiation has a larger relative influence when the Sun is down.
- Ground temperature: Measurements on every continent (other than Antarctica) indicate that surface warming is modifying the near-surface gradient of temperature from the Earth's hot interior to the surface. Although land surface modification can also cause such effects, the best observations in drilled holes in rock obtain the same result.
- Tropospheric temperatures: Balloon-borne (i.e., radiosonde) observations of tropospheric temperature have only been available since the mid-20th century and inferences of changes in tropospheric temperature on the basis of satellite observations of microwave radiance have only been available since 1979. Because a series of corrections has been required to account for changes in the height and timing of satellite orbits and in intersatellite calibration, early indications that the satellite observations showed less warming than the surface (and even perhaps some cooling) have not held up to close scrutiny.[83] The recent assertion by Douglass et al.[84] that the set of IPCC-cited models does not reproduce the observed changes in tropospheric temperature has recently been extensively evaluated by Santer and many colleagues[85] and found to be based on a flawed statistical analysis that failed to properly account for natural variability. The most detailed analyses of the satellite and radiosonde data thus now indicate that the troposphere is warming in a manner "broadly consistent with surface temperature trends provided that the stratospheric influence. . . is accounted for" (ref 15, chapter 3).
- Stratospheric temperatures: Both radiosonde and satellite microwave measurements indicate that the stratosphere is cooling reasonably steadily, as expected, with sharp warming for a few years

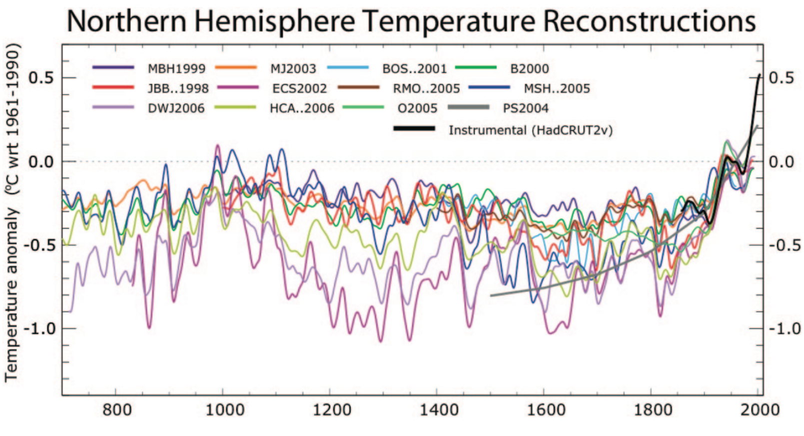


Figure 7. Reconstructions by different investigators of Northern Hemisphere average temperature variation over the last 1300 yr from proxy indicators. Most of the curves are derived from tree rings and other high-resolution indicators; the relatively smooth curve from 1500 to the present is from subsurface temperature, so is much less variable. The curves are all normalized to 1856–1980, which is the period that proxy results overlap the instrumental record shown in the dark line. Reprinted with permission from the IPCC[15] (chapter 6). Copyright 2007 Cambridge University Press.

following major volcanic eruptions when the injected aerosols increase stratospheric absorption of solar radiation.

- Amount of precipitation: Precipitation is highly variable in space and time, so estimating change is quite problematic, especially over the oceans. Over land areas, however, there are some large regions experiencing increased precipitation (e.g., eastern parts of North and South America, northern Europe) and other areas experiencing reduced precipitation (e.g., the Mediterranean, Sahel, parts of southern Asia), suggesting that large-scale shifts in precipitation bands are underway.
- Intensity of precipitation: Over most land areas, the fraction of rain coming in the heaviest categories is increasing, which is consistent with model simulations and with the type of change seen in moving from high to low latitudes. In addition, the amount of rain in light events is decreasing, a combination that, along with warming, tends to encourage drying because a greater fraction of rainfall in heavy events runs off than for lighter rains. As a result, global warming can, seemingly paradoxically, lead to tendencies for both more flooding and more frequent (or at least faster transition into) drought conditions.
- Sea ice: The extent and thickness of Northern Hemisphere sea ice is decreasing sharply.[86] The change has been much more rapid than projected by models, and has led to significant thinning as well as decreases in area. In the Southern Hemisphere, the deeper and more extensive mixing of the upper ocean has limited its warming and apparently limited a sea ice response.
- Glaciers: Surveys of mountain glaciers around the world indicate sharp retreat in virtually all locations,[87] the exceptions generally being in regions that were very cold and so some warming can increase snowfall amount. During the so-called "Climatic Optimum" that extended from approximately 5000 to 7000 yr ago, glaciers in some mountain ranges of the Northern Hemisphere were smaller than at present, likely due to the particular alignment of orbital parameters that led to increased summer insolation and warming in the Northern Hemisphere. By contrast, glaciers over the entire world are melting back today at a time when orbital parameters are causing diminished summer insolation in the Northern Hemisphere, conditions that in the past have been associated with glacial growth.
- Snow cover and permafrost: Both are decreasing around the Northern Hemisphere.
- Ice sheets: Although the narrow range of sea level variations over the Holocene suggests that there have not been large changes in the amount of ice tied up in the ice sheets covering Greenland and Antarctica, they appear to be starting to respond to the increases in atmospheric temperatures (or at least to the increases in downward IR radiation). Changes are occurring so rapidly that IPCC's analyses are rapidly becoming dated. Traditional estimates of ice sheet behavior have had to be based on estimates of change in surface height, first by surveys and more recently using satellite-based radar. These observations have generally suggested that the ice sheets might be growing in volume. More recent observations with the GRACE satellites (which use two satellites to determine changes in gravitational pull, so can indicate actual change in ice sheet mass) indicate that both ice sheets are losing mass.[88–90] With volume possibly increasing and mass decreasing, this suggests density is decreasing, quite possibly as the melt water forms ponds, finds cracks and crevasses, and drains into and carves moulins (tunnels) through the ice. Although the Greenland Ice Sheet (GIS) apparently melted around the edges during Viking times, what is happening now is much more extensive, being associated with widespread Arctic warming that has been allowing, and pushing, many new plant and animal species into the Arctic region—species for which the very observant indigenous peoples of the Arctic have no words in their language.
- For Antarctic, changes are also underway. Much attention has been given to the calving of ice shelves from the edge of the Antarctic Peninsula,[91] especially as a result of some very large calving events. The most recent event calving of the Wilkins Ice Sheet added an additional 570 km^2 to the much larger losses in the region over the past decade.[92] Because ice shelves are already floating, their calving does not affect sea level. However, the breaking up of the ice shelves does unblock glacial streams extending inland, allowing them to flow faster into the ocean, contributing to sea level rise.[93] More important, there are increasing signs that the West Antarctic Ice Sheet (WAIS)[94,95] and even parts of the East Antarctic ice sheet are starting to lose mass, in contrast to the snow build-up that had been projected in the model results (ref 15, chapter 11).
- Ocean temperatures: Observations since 1961, mostly with dropsondes, indicate that the ocean is warming down to as far as 3000 m. Although the record cited by IPCC (ref 15, chapter 5) shows some unexplained multidecadal variations (and even a sharp drop in energy content at the end of the record), more recent studies have found that accounting for the changing mix of instrument types and for biases in rates of sinking of the dropsondes lead to a steadier warming that is in better agreement with the rate of warming of surface temperature.[96] Because the amount of heat stored in the ocean is over 80% of that added to the climate system, achieving agreement is critical to building confidence in the records.
- Sea level rise: With glaciers and ice sheets adding water to the oceans and with ocean warming causing the waters to expand, sea level is rising at what appears to be an accelerating pace. That sea

level did not change much over the 2 millennia before the 19th century is evident across the Mediterranean, where Roman and Phoenician coastal structures are just starting to be inundated. Tide gauge observations from around the world (adjusted for ongoing upward and downward land movement prompted by the changing weights of the ice sheets since the Last Glacial Maximum ~20,000 yr ago) indicate that global sea level rose by approximately 150–200 mm (1.5–2 mm/yr) during the 20th century. Recent satellite measurements indicate that the rate over the last decade is roughly twice this amount, suggestive that strong warming is underway.

- Ranges of plants and animals: Observed changes in biological systems over the past few decades indicate that substantial changes are underway. Of the datasets summarized in support of the recent IPCC assessment, nearly 9 of 10 are consistent with what would be expected in response to global warming. Even though development pressures are certainly having impacts, plants and animals are showing a very high sensitivity to the climatic conditions (a result that should not be surprising to gardeners and mountain climbers, who observe many of the sensitivities in the course of their activities and excursions).

These, and other observational results make clear that the climate, broadly defined, is changing at what appears to be an increasing pace. To provide context, substantial efforts have been underway to extend the records back to earlier times. Records of isotopic variations can be very useful indicators of, for example, ice extent on land (because $H_2{}^{18}O$ takes more energy to evaporate than the predominant $H_2{}^{16}O$, so sediments and other records show an increasing $^{18}O/^{16}O$ ratio during cold periods). Because similar temperature-dependent distillation processes affect the ratio in ice, glacial cores can give an indication of the time history of changes in local temperature. For some variables, historical records can be useful (e.g., observations of the edge of sea ice from whaling ships; presence and flowering dates of some crops), whereas for others, indirect (or proxy) indicators have proven useful (e.g., tree rings, changes in plant assemblages derived from pollen ratios, coral banding).

Particular attention was paid in IPCC's recent assessment to changes evident over the last 1–2 millennia with respect to climate, and during the last (Eemian) interglacial that peaked approximately 125,000 yr ago (ref 15, chapter 6). With respect to constructions extending back about 1000 yr, the second half of the 20th century (i.e., starting with the relatively cool 1950s and 1960s to the present) are likely to be the warmest period of that length in at least the past 1300 yr (i.e., extending back past the historically documented Medieval warm period that was apparently centered in the North Atlantic region). This conclusion probably covers an even longer period, although records are quite limited. Although shorter periods are subject to greater variability, with the late 20th century being much warmer than the mid-20th century and with the 21st century continuing to be warm, the confidence in these comparisons is increasing rapidly. Just as recent concentrations of GHGs appear to be unprecedented in at least many thousands of years, so are global average temperatures.

The Eemian interglacial is of interest as a potential analog to a warmer world because this few-thousand-year period, ending approximately 125,000 yr ago, is the last time that reconstructions suggest that global average temperature was higher than at present. The cause of this interglacial period was a particular alignment of the Earth's orbital parameters that led to significant enhancement of summer insolation in the Northern Hemisphere. Reconstructions suggest that summer temperatures in the Arctic were likely up to 5 °C warmer than at present and global average temperatures were approximately 1 °C above present. Cores drilled in northern Greenland find ice older than the Eemian, but this is not the case in southern Greenland or on Baffin Island, suggesting that roughly half of GIS had melted, a result that, along with mountain glacier retreat, would have caused sea level to be 3–4 m higher than at present. Independent estimates of beach height on some low latitude islands that have not been pushed up or down by glacial buildup and retreat suggest that global sea level was apparently higher by 4–6 m. Such a large rise would likely have required some loss of ice from the WAIS, which would likely have been affected by the rising sea level because much of it is grounded below sea level and so very vulnerable to increases in ocean temperature.[97]

Attributing Climate Change Primarily to Human Influences

The similar "hockey stick" shape and strong correlation of changes in emissions, concentrations, and temperatures, reinforced by the changes in other variables, make a very strong, but circumstantial, case that the unprecedented changes in climate are due to human activities. Determining the degree to which these changes can be specifically attributed to human activities, however, requires a comprehensive and internally consistent explanation that distinguishes the relative roles of each factor over time and space in a quantitative manner. To accomplish this, climate models (see *CLIMATE MODELS*) are used to calculate the separate and interacting roles of each natural and human-induced forcing.

Figure 8 shows the estimates for changes in RF at the tropopause extending back to 1850 for natural (volcanic aerosols, solar radiation) and human-induced (GHGs and sulfate aerosols) influences. Estimates for GHGs have the lowest uncertainty because the time history of concentrations can be determined from ice cores. Variations in solar radiation remain controversial; the values shown here are based on satellite observations that extend back for almost 3 decades. These results indicate comparatively small changes in solar flux over the 11-yr sunspot cycle; values at earlier times have been estimated in a proportional manner. Other mechanisms for estimating changes in the solar (or, more generally, extraterrestrial) influence have been attempted, including relating the changes to changes in solar radiation resulting from sunspot cycles or of a magnitude seen in other variable stars, changes in UV radiation that it is suggested have a special influence on climate through changes in stratospheric O_3, changes in

CLIMATE MODELS

With observations indicating that the climate is changing, two key questions arise: (1) Why is it changing? (2) What is going to happen in the future? Determining why change has happened is complicated by the complexity of the Earth system and many suggested variables, from GHGs to cosmic rays and instrument bias to limited records of sunspot number and volcanic aerosols. Determining what will happen is complicated by the chaotic nature of the atmosphere-ocean system evident in the record of Earth system history over time scales of seasons to millions of years.

Were the Earth system simpler, conducting experiments on a model of the system constructed in the laboratory would be a preferred approach, but laboratory and field experimentation has only proven useful for investigating how specific processes work (e.g., GHG absorption of IR radiation). Arrhenius[98] demonstrated that mathematical analysis could be useful in gaining a sense of how the system would respond, but only after significant simplification. Earth system history provides many indications of changes in climate and in some of the possible forcing factors, but there is no period in the past with such rapid changes in atmospheric composition that it could serve as an analog for the present. Although the recent past does include the effects on climate of human influences, it also includes the influences of natural factors, so trend extrapolation not only could be misleading, but also cannot account for different possibilities in the future.

Recognizing that many aspects of the Earth system are governed by physical laws, and building on the earliest work of Richardson,[99] the remaining option is to use all of the knowledge that we have available to construct numerical models of the Earth system on the computer, test the models against situations in the past, and then use these models as an experimental tool to explore the future. Indeed, the world is so complex that the numerical model cannot represent everything, and we will have to contend with the inherent chaotic nature of the system, such that no global state ever completely repeats itself, but, done carefully, the models should be useful in understanding the past and providing insight into the future.

Although models of just the atmosphere and simplified models of the climate have played an important role in gaining insights (see supplemental data on early history), the most rigorous and comprehensive simulations are now done with climate models that represent the atmosphere, oceans, land surface, ice, and vegetation in considerable detail. The atmospheric component, for example, is constructed by subdividing the world horizontally into latitude-longitude cells that now typically cover approximately 1.5–3° in latitude and longitude, with resolution becoming finer as computer speed increases, and vertically into several tens of layers (i.e., typically 1–2 km deep). Each cell is characterized by properties such as temperature, water vapor and GHG concentration, liquid water concentration (related to cloud characteristics), wind speed and direction, geopotential height, aerosol loading, and more. Changes in the various properties in each cell over time are governed by both fundamental equations that ensure, for example, conservation of mass, momentum, energy, and species amount, and by empirical relationships (often referred to as parameterizations) that have been derived from and tested against a wide range of observed conditions. Each of the equations treats several processes; for example, the energy equation accounts for the effects of solar and IR radiation in both clear and cloudy skies. As scientific understanding keeps improving, the modeling groups seek to represent the fullest extent of scientific understanding possible (e.g., see ref 8, chapter 4; ref 11, chapter 7). Compromises, however, are unavoidable because of limits in understanding and computer resources. Each modeling group must thus make a tradeoff between the level of spatial and temporal detail and the practical need to complete simulations of interest within reasonable time periods and within the limits of computer budgets. That multiple investigators make these tradeoffs in different ways leads to a diversity of models, and thus an opportunity to evaluate the robustness of the model results to the types of tradeoffs that are made. A range of different model approaches giving a similar outcome tends to increase confidence; a range of model results from models with similar or different approaches suggests that deeper understanding and inquiry is required.

With each component being a theoretical construct, evaluation of how well the models emulate the real world is essential. For atmospheric models, such tests include evaluation of their ability to simulate:

- Model treatments of particular process are often evaluated against specific situations that have been highly documented with intense measurements;
- Day-to-day evolution of the weather, measuring model tendency and skill against the theoretical limit imposed by the atmosphere's chaotic nature and the practical limit created by the finite set of observations available to initialize the model simulation;
- The annual cycle of the seasons, which, over the Earth and because model representations are not tuned to match local conditions, provides for evaluation of model representations against a very wide range of conditions;
- Interannual variability, which includes the ability of models to generate year-to-year and season-to-season variability that is similar to observations (and when oceans are coupled to the atmosphere, to provide some seasonal to interannual variability);

CLIMATE MODELS (cont.)

- Recent decades, which involves running the atmospheric model with the observed surface boundary conditions (typically including sea surface temperature and sea ice extent);
- Climatology, to determine if the equilibrium state of the model is stable and conditions are close to long-term average conditions; and
- Perturbations of opportunity, such as major volcanic eruptions.

Each component undergoes a similar set of tests. Improvements and adjustments are made to work out problems, and some tuning is typically done to calibrate constants in empirical relationships that cannot readily be measured. For example, with an atmospheric grid cell being roughly the size of the state of Ohio (formerly more like Colorado), a coefficient in the relationship that governs surface drag for all grid cells around the world (so the same relationship is used everywhere) is tuned, for example, to get the optimal simulation of the average intensity and latitude of the jet stream. Rough estimates of the coefficients are available from drag experiments that observe boundary layer development as wind flows over trees of various heights placed out on smooth ice, for example, but values for a diverse types of landscapes just cannot be measured in the field, so tuning is required. There are not many of these parameters, and once tuning is done against a selected dataset, tests go on to evaluate performance of the parameterization against other datasets. In addition, in a much grander effort involving coupled models, tests have gone on using random combinations of the set of tunable parameters to evaluate model performance and robustness of the simulations (e.g., see http://www.climateprediction.net/science/).

Once model components are tested separately, they are coupled together. Given their different temporal and spatial characteristics and time constants, this can be interesting and challenging. Although the early atmosphere and ocean components each did well when driven by observations from the corresponding component, early attempts to couple them led to each drifting off to unrealistic conditions. It was learned, for example, that it is easy to get the atmosphere about right under winter conditions with surface conditions specified because that type of surface serves as essentially an infinite source of energy. On the other hand, getting summer conditions right is more difficult because the increased solar radiation must be properly distributed.

The converse is true for the oceans; it is easy to do well in the summer when heat enters only the upper ocean, but it is hard in the winter when the upper and deep oceans are convectively coupled. To keep early simulations realistic, some groups resorted to somewhat ad hoc flux adjustments, which, after testing, were found to have relatively little influence on the outcome of climate sensitivity experiments with models. Progress in understanding, improved spatial resolution, and more frequent model coupling have now, however, replaced the need for ad hoc adjustments, and all major modeling groups are now running with coupled ocean-atmosphere models. Although shortcomings remain, particularly in representing some tropical processes and oscillations that seem to require using very fine spatial resolution (and so much more computer time), most models provide quite realistic representations of the global system. Climate model intercomparison projects have been a quite strong impetus for progress[100] (see also ref 8, chapter 5; ref 11, chapter 8; ref 15, chapter 8). An interesting result has been that the set

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cloud cover because of cosmic ray-induced changes in the generation of cloud condensation nuclei, and more. Although interesting and sometimes showing multidecadal correlations, none of these changes shows a good correlation over the entire record and it would be rather an odd coincidence if the Sun just happened to start having a strong influence on the climate at the same time the Industrial Revolution took off.

Volcanic eruptions are also capable of changing the climate. Eruptions over the past 2 centuries are generally well documented in time, but the amount of injected aerosol and the resulting reductions in radiation are not well established because of limitations in early measurements. Because of the poorly known time history of the emissions and changeover from surface to elevated emissions, the relatively short lifetimes and the dependence on height of emission, the complex mix of materials and the resulting uncertainty about the radiative properties of the particles, and the very heterogeneous temporal, spatial, and chemical distributions that result, the forcings due to human-influenced sulfate and other tropospheric aerosols are poorly known. In addition, not only do human-induced aerosols have direct effects on solar radiation through their backscatter, forwardscatter, and absorption, but the hygroscopic aerosols can also affect the radiative properties of clouds directly (by affecting the droplet number distribution, and therefore cloud reflectivity) and indirectly (by altering the lifetimes of clouds and cloud droplets). Although uncertainties in the early record are important, the high-quality observations over the past few decades make clear that changes in the RF by GHGs are the dominant factor.

Using these forcings as input, modeling groups around the world have evaluated the comparative influence of natural versus human-induced forcings and the overall fit to observations when all forcings are applied. Most of these simulations started their calculations in 1750 or 1850, although Tett et al.[105] report on a study covering the period since 1550. Because the observed sequence is just one pass of the Earth system through

CLIMATE MODELS (cont.)

of models together typically provides a better representation of the climate than the results of any single model, consistent with results in other fields.[101]

With numerical climate models constructed and tested, they can be used as tools to conduct a range of experiments. Early studies using atmospheric models coupled to surface-ocean models instantaneously doubled the CO_2 concentration and then ran several decades until a new stable state was established. Such "sensitivity" experiments are useful to get a sense of what the ultimate response to a particular change in forcing will be, but must be carefully interpreted because the simulations generally are carried out changing only a single variable, so do not include the simultaneous influence of other forcings, and they do not represent the gradual shift of climate and the lags that would be expected for real world situations. Although it made good sense to conduct such studies, the first impressions of such experiments have resulted in some unfortunate generation of climate change myths.

The most fundamental result of these studies was recognition that models with slightly different formulations could give different results for the climate sensitivity, which by convention is defined as the change in global average temperature in response to a CO_2 doubling. A summer study in 1979 used the earliest model results and available information about Earth history to suggest that the climate sensitivity was 3 ± 1.5 °C, with roughly a 50% likelihood the actual sensitivity was within this range.[102] The most recent IPCC estimates suggest, with roughly a 90% likelihood, that the range is 2–4.5 °C with a most likely value of approximately 3 °C (ref 15, chapters 8–10).

The newest model experiments are greatly improved, seeking to emulate the time-dependent evolution of the climate in response to the most important natural and human-induced forcing factors. Most of the model simulations start in 1850, initialized with equilibrium climatic conditions that the model generates with preindustrial atmospheric composition. Simulations then typically run to 2100 or beyond, with or without historic or projected human-induced or natural forcings being imposed over different intervals. To account for the chaotic nature of the climate system, an ensemble of simulations is conducted, each simulation starting from a slightly different atmospheric state (so with different weather conditions). The result is a set of possible time histories, the set of which is designed to provide a representation of the envelope of possibilities to a particular statistical degree. Although the envelope gives the impression of a smoothly varying evolution of the climate, the individual model simulations are very similar to the natural world in exhibiting year-to-year variability.

In using the models to project the future, simulations from 1850 to the present are continued, using the concentrations resulting from one of IPCC's emissions scenarios having been used to drive a carbon cycle or other geochemical model (the newest climate models are starting to directly incorporate these relationships). Again, an ensemble of simulations leads to an envelope of possible outcomes, and again, the average across the simulation gives an impression of steady and gradual change that should be expected only over very long-term averaging. For comparing with observations, it is important to remember that particular model simulations (and actual conditions) will exhibit variability, and so have periods when the temperature does not rise or even falls for a few years.

time, the complex couplings that exist lead to a particular sequencing of the simulated weather and of internal oscillations such as El Niño and La Niña events that is unique and that cannot and will not be exactly matched by any model simulation—that is the nature of a chaotic system.[106] And it is because of the chaotic nature of the system that it makes no sense at all, as popular author Michael Crichton called for in his 2004 book *State of Fear*,[107] to be expecting to see the conditions at each station to show only the influence of the rising CO_2 concentration. Furthermore, given the chaotic nature of the weather and climate on annual to decadal scales, it is not reasonable to evaluate the skill of climate models by evaluating their year-by-year predictions of anomalies at each station over the next 10 yr, especially with model simulations started based on conditions in 1850 or earlier.

What can be expected is that the range of results from an ensemble of model simulations, each starting from slightly different initial conditions and each responding to the imposed natural and human-induced forcings, will generate a band of conditions spanning the possible responses of a chaotic system. Then, the expectation is that the actual observed path taken by the real world through the 20th century will, within statistical limits, fall within this band. Figure 9, from IPCC (ref 15, chapter 9), shows that this is largely the case. The blue band represents the range of results in various areas of the world when the models are driven by only natural forcings. The black line represents observations (with the dashed parts representing times with limited data) generally near or within this band out to the mid-20th century, but observations are far above the blue band thereafter. The pink band shows the results of model simulations when both natural and human-induced forcings are applied; observations are generally within this band for the entire 20th century and for all regions, with the one exception being for the oceans during the period of WWII, a period during which, as indicated earlier, it is difficult to ensure that all of the biases have been adequately removed from the observations.

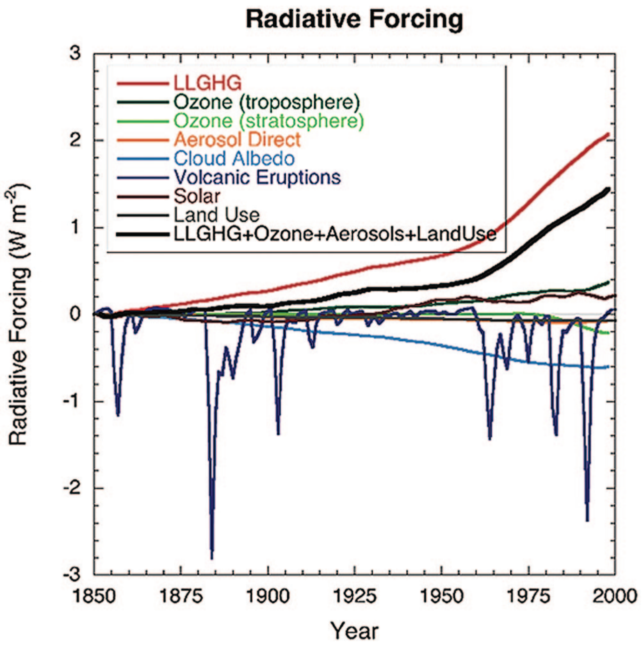

Figure 8. Globally and annually averaged temporal evolution of the instantaneous all-sky RF (in W/m^2) at the tropopause due to various agents, with a positive value indicating a warming influence. Note that the volcanic influences are large, but short-lived; the solar influence is small; and the long-lived GHGs (LLGHGs) have a very strong warming influence. This result, which is typical of other models, is derived from the MIROC+SPRINTARS model.[103,104] Reprinted with permission from the IPCC[15] (chapter 2). Copyright 2007 Cambridge University Press.

Overall, what these results indicate is that the effects on climate of both natural and human-induced forcings must be accounted for to achieve a good match with observations. In addition, the results make clear that the global warming of the late 20th century can only be accounted for by including human influences, especially because natural forcings alone during this time would have led to a slight cooling as compared with the mid-20th century. The good results from the range of models, assuming the forcings are adequately represented, also suggest that the model-determined climate sensitivities (~2–4.5 °C per doubling of CO_2) must be roughly correct.

To further explore this fit of models with observations, simpler models in which the climate sensitivity can be specified have been used to explore the possible range of various factors and influences (e.g., in the RF because of sulfate and soot aerosols) that determine the climate sensitivity while still providing a statistically acceptable fit to the observed record. Those results indicate that, on the low end, a sensitivity of at least 1.5 °C per doubling of CO_2 is needed to represent the changes in global average temperature that have occurred. On the high end, however, the upper bound is not as well defined because it is possible that strong aerosol effects are offsetting the warming influence of a higher climate sensitivity. Indeed, there are several studies suggesting that the climate sensitivity could exceed 4.5 °C, perhaps by as much as 50%. Although such a high sensitivity remains a possibility on the basis of analyses of forcing and climate change over the past 250 yr, considering changes in climate over geological times, including the Cretaceous period, which was, on average, only 5–8 °C warmer than at present although having approximately 5 times the preindustrial CO_2 concentration, it seems quite plausible that 4.5 °C per doubling of CO_2 is the upper bound for the climate sensitivity.

Achieving relatively close agreement between model simulations and the observed changes in temperature during the 20th century is only one of several "fingerprint" analyses that have been carried out. Analyzing the relative contributions of forcings (including the effects of CFCs on stratospheric O_3) that can cause changes in the temperature in the troposphere and stratosphere, also rules out a significant role for solar radiation over the past few decades—basically, the stratosphere is cooling, except immediately after volcanic eruptions, and increasing solar radiation would be expected to be causing it to warm. Similarly, these studies rule out a reduction in volcanic eruptions as a factor in recent warming. Other studies have looked at patterns of oceanic heat uptake and trends in Arctic sea ice extent and sea level pressure in middle versus high latitudes. In general, there is a significant consistency of observed and simulated changes only when human influences are playing a dominant role over recent decades.

In addition to looking at changes in long-term mean conditions, increasing attention is being devoted to the effects of climate change on the intensity and frequency of weather and extreme events. Analyses of the return

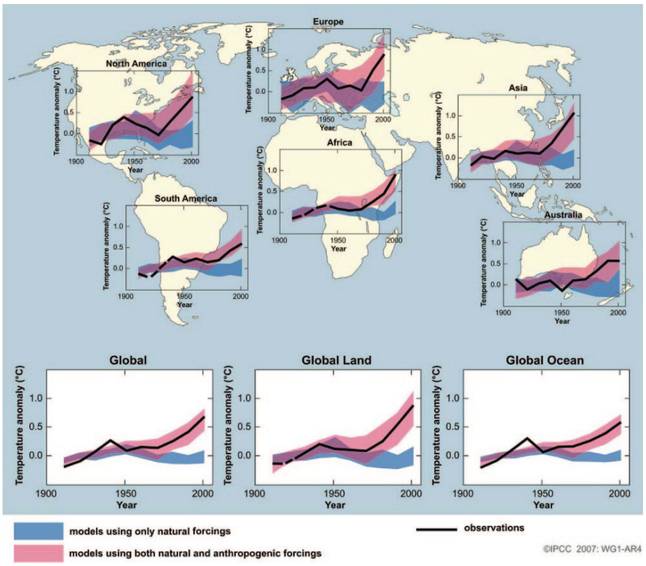

Figure 9. Comparison of observed continental- and global-scale changes in near-surface air temperature (solid line) with the envelope of possible climatic states constructed from ensemble simulations by multiple climate models using just natural forcings (blue band) and natural and anthropogenic forcings (pink band). The observed data are decadal averages plotted at the center of each decade from 1906 to 2005, and all changes are normalized to the period 1901–1950, during which the anthropogenic influences of increasing GHGs and sulfate aerosols tended to counterbalance each other. Reprinted with permission from the IPCC[15] (Technical Summary). Copyright 2007 Cambridge University Press.

period of rare events in simulations done using the Canadian climate model indicate that, for example, the return period for severe precipitation events decreases significantly, such that events that have in the past been once-in-100-yr occurrences (which is the design standard for significant community infrastructure in the United States) might occur as frequently as once every 30-yr by the end of the century[108] (also see ref 15, chapter 10). Given that warming is advancing, the multidecadal trend towards more intense precipitation events appears to be consistent with the changes projected by that model, and other models give similar results.

Similarly, traditional statistical analyses of the likelihood of the 2003 European heat wave, which led to over 30,000 excess deaths, indicated it was a 1-in-500-yr event. However, projections of future climate change suggest that by 2050 such conditions would be expected on roughly an every-other-year basis, making it at least likely that there was a human influence on the 2003 event.[109]

For hurricanes and cyclones, statistics indicate that although their global total is not changing, there appears to be an increase in the fraction that are in the higher intensity categories and that these storms are releasing more energy, persisting longer, and causing more damage.[110,111] Because climate change is leading to warmer ocean waters and to an increase in atmospheric water vapor, thus making available more energy for the storms, the observed trend in storm intensity appears consistent with the type of change that is expected.[112]

Because climate is just the average of the weather, changes in weather are also expected as a result of climate change. Although analyses of changes in weather are still in their early stages, some very unusual weather events have started occurring (e.g., tornadoes in Wisconsin in January 2008).[113] The rapid melting-back of Arctic sea ice is likely one important driver of the changing weather, because the very cold air masses that strongly influence weather over North America are created there. Although most attention has been on the minimum extent of sea ice in September, that actually has little effect on the surface temperature felt by the air above because melting sea ice and open ocean have nearly the same temperature. What really matters is how long into autumn it takes for meter-thick sea ice to form, because it takes ice roughly this thick to insulate the atmosphere from the heat of unfrozen ocean waters. Until an ice layer forms, the heat conducted up from the ocean water below will tend to keep surface air temperature near 0 °C rather than allowing it to drop to −40 °C.

With North America being the only Northern Hemisphere continent extending from the Arctic to the tropics without an east-west mountain range to separate the cold, dry, and warm, moist air masses, the cold and warm air masses collide over North America, creating the continent's very active and violent weather.[114] With less sea ice extent in fall, the warm, moist air will push north and the collision of air masses will occur in the upper Midwest, generating severe winter rain and snow there rather than along the Gulf Coast, where the traditional result has been rain. The delayed onset of winter also leads to freezing conditions coming later to the upper Great Plains, allowing the ground to stay warm longer, which in turn leads to less persistent snow cover and increases the risk of freezing rain and sleet. With the Great Lakes being warmer, their ice cover forms later, thus paradoxically extending the period when lake-effect storms dump large amounts of snow on the Northeast.

It might well even be that once the high latitudes freeze over, causing air temperatures and atmospheric water vapor concentrations to plummet, that the increase in the CO_2 concentration is increasing the cooling rate of cold anticyclonic air masses (for the same reasons that increased CO_2 cools the lower stratosphere). If this is the case, the increased CO_2 concentrations could paradoxically be responsible for record cold temperatures being set during particular winter weather situations during the same year that record-high temperatures are being set in the summer.

FINDING 4: MUCH LARGER CHANGES IN CLIMATE ARE PROJECTED FOR THE 21ST CENTURY

Weather is the instantaneous state of the atmosphere. Climate is the time-averaged state, including means and higher moments of the atmosphere and more generally of the oceans (including sea level), cryosphere (including snow and ice cover, glaciers, ice sheets, and permafrost), and vegetated and moistened land surface. We live and experience the weather; we create the climate as a mathematical way to describe the totality of what we experience—the envelope for the weather (i.e., as the adage goes: climate is what you expect, weather is what you get). Evolution of the weather in a given location is dependent primarily on the state of the earlier weather—it is said to be an initial value problem. Beginning with a representation of present weather conditions, the detailed evolution of the atmosphere is theoretically predictable out to several days (e.g., rain tomorrow afternoon in eastern Tennessee), and large-scale weather features (e.g., the general paths of high and low pressure systems) are theoretically predictable, under some situations, for up to a few weeks. This is especially the case when the systems are being influenced by anomalous states of the oceans, land, or snow and ice cover because fluctuations in these systems typically have time constants of weeks to months or seasons.

The climate, however, being the range or envelope within which weather occurs, is determined not by the initial state of the system, but largely by the boundary conditions. For example, the seasonal cycle is strongly influenced by the changing zenith angle of the Sun, and global circulation over seasons is controlled by conditions in the ocean (e.g., the presence of an El Niño event) or on land (dry or wet soils, forest cover, etc.). Global cooling occurs following major volcanic eruptions, although there are also finer-scale seasonal and land-sea patterns. Earth system history indicates that the long-term climate responds to changes in factors such as the Earth's orbital parameters (which shift the seasonal and latitudinal pattern of incoming solar radiation), changes in atmospheric composition (which shifts the Earth's IR radiation balance), and long-term changes in positions of the continents and their altitude (which deflect and channel ocean and atmospheric circulations). This is not to suggest that there is no effect of natural air-sea interactions and other internally generated variability; only that our understanding of how the Earth system works makes clear that boundary conditions are the dominant factor in determining the prevailing multidecadal climate.

Building on the success of the climate models in simulating changes in climate over the 20th century, the period for which we have reasonable estimates of changes in boundary conditions (expressed as changes in RF), climate models can be used to conduct numerical "experiments" that calculate their response to a variety of emission and RF scenarios (see *CLIMATE MODELS*). Because the future is hard to predict, especially with respect to societal, economic, technological, institutional, and policy evolution, climate models use of a set of plausible emissions scenarios to allow exploration of possible outcomes. Although some scenarios may appear more likely than others, the chance that conditions will come out exactly as an emissions scenario suggests and as climate models project is virtually zero.

To account for the chaotic nature of the Earth system, an ensemble of model simulations starting from different initial conditions is typically carried out for each of the scenarios. Although each of the model simulations explicitly attempts to calculate the evolution of the weather, it is, at best, only the statistics across the set of simulations (i.e., changes in the mean, higher moments, frequencies, etc.) that are appropriate to use to project the range of future climatic conditions.

Because the calculations are based on plausible scenarios of societal development, the results of model simulations are not referred to as "predictions." Instead, the model results are generally labeled "projections"—indicating that if things happened to work out as the scenarios suggest, the set of model calculations would provide an estimate of the expected range of what is likely to happen. The term projection is also used to make clear that the outcome is conditional, being subject to change if actions are taken to alter future emissions or other boundary conditions. As an example, policy-makers might decide that the severe impacts that are projected merit a policy response, and so the emissions path would be changed; then, so would the expected climate outcome. By contrast, nothing policy-makers can do, at least at present, affects the weather, so a weather forecast need not be conditioned on an emissions or other scenario.

Projections of Change in Global Average Temperature

Until the early 1990s, global climate models were most often used to simulate the equilibrium response of the climate to a sustained doubling of the atmospheric CO_2 concentration. This simplification was necessitated by limited capabilities for simulating the climate system and by limitations in computer resources that prevented the carrying out of few-hundred-year, time-dependent simulations with full representation of the oceans. By not treating the evolution of the climate over time or the full range of factors influencing the climate, these model simulations were really sensitivity tests rather than projections of likely changes in the climate.[5]

Unfortunately, this distinction has often been lost in interpretations of model results. As a result, misimpressions developed that the warming would be steady and that the time sequence of coming climate change could be derived by interpolation. As an example of a misleading result, because the doubled CO_2 simulations caused substantial warming and melting of sea ice in mid-winter, interpolation generated the impression that mid-winter warming would be largest, whereas more nuanced interpretations of conditions over the first few decades of the change recognized that what should really be expected over time was a shortening of the cold season and lengthening of the warm season, with the largest temperature changes being in autumn and spring (as is being observed). As another example, because the early doubled-CO_2 simulations were run with models with simplified oceans, the models generated changes in the sea ice around Antarctica; later simulations incorporating the full ocean circulation and the slow rise in the CO_2 concentration have made clear that vertical mixing of ocean waters in that region delays the onset of melting of Antarctic sea ice, as is being seen in the observations. Similar changes in the simulations arose in mid-latitudes, where the doubled-CO_2 simulations projected a jump in the locations of storm tracks; the transient simulations had shifts that were gradual.

The new IPCC assessment (ref 15, chapter 10) presents projections from fully time-dependent model simulations treating the full set of climate forcings. Not surprisingly, the projections are different than the initial, but still remembered, model results that assumed an instantaneously doubled CO_2 concentration. In the latest simulations, coupling of the upper and deep oceans slows the warming because of the large heat capacity of the deep ocean, retreat of snow and ice takes time, and warming during the early stages is greatest in the transition seasons rather than in mid-winter. Natural variability introduces variability in the near-term projections, with some years and decades warming a lot, some not warming much, and others showing cooling. Tropospheric aerosols exert a significant cooling influence, slowing the pace of warming until, for some emissions scenarios, their loading drops and the warming effect of the longer-lived GHGs becomes fully evident.

Figure 10 presents time-dependent projections of the increase in global average temperature for the 21st century (more correctly, projections of the annual average of the area-weighted increase in temperature at grid points around the globe) for three of IPCC's six emissions scenarios. The bars to the right show the uncertainty ranges for the projections for all scenarios. Each of the curves is an average across a set of ensemble simulations from each of the approximately 20 models that carried out the standard IPCC simulations. The simulations generally started in the mid-19th century or earlier (although past results are shown only for the 20th century) and some of the simulations ran out several centuries into the future. To gain insight about the commitment to future warming caused by past emissions, an additional simulation was carried out assuming constant forcing after the year 2000.

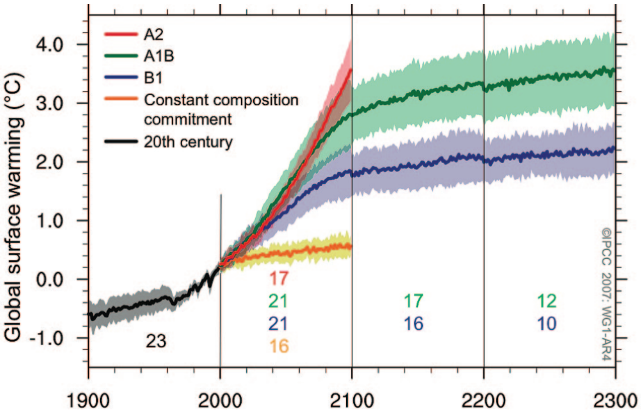

Figure 10. Multi-model mean projections of the increase in global average temperature from 2000 to 2100 for three of the SRES[36] emission scenarios (red, green, and purple) and assuming that the concentrations of GHGs and loading of aerosols are held constant at their year 2000 values (orange line). The dark line shows the average across models and the shading indicates the ±1 standard deviation range for annual-average results from individual models. As context, the black line shows the change in temperature during the 20th century relative to the year 2000 value. The colored numbers indicate the number of models that have run a given scenario. The apparent discontinuities between different periods have no meaning, being a result of changes in the number of contributing models. Reprinted with permission from the IPCC[15] (chapter 10). Copyright 2007 Cambridge University Press.

With observed variations in solar radiation being comparatively small and with volcanic eruptions having intermittent effects for only a few years, the potential influence of these forcing factors on calculation of the multidecadal pace of climate change is likely to be small and so has been neglected.

Averaging the instantaneous results over 2 decades to generate a climatic norm, the models simulated a warming of approximately 0.6 °C from the preindustrial period to 1990 (strictly, the period 1980–1999), which is close to the value estimated from observations. For the 21st century, the models project a further overall global warming of approximately 2–4 °C above the increasing global average temperature to approximately 2.5–4.5 °C above its preindustrial level. Although this may seem modest compared with seasonal variations or the change experienced in relocating from New York to Arizona, it is a shift imposed not just on society, but also on the environment, and not just to an individual, but also on everyone and everything. Such a change is equivalent to about half of the difference in global average temperature from the peak of the last ice age to preindustrial temperatures. That the glacial to interglacial transition led to the melting of the 2-km thick continental-scale ice sheet that covered much of the northern part of North America and Europe and to a sea level rise of approximately 120 m should make clear that the warming being projected can be expected to have very significant consequences.

Looking at the results more closely, the projected temperature increase of 1.4 °C by 2050 shows little dependence on emissions scenario, in part because the energy system is so pervasive and slowly changing that the emissions scenarios only slowly depart from each other, and in part because much of the warming over the next couple of decades will be a result of the climate continuing to adjust to the RF caused by past emissions. This would be equivalent to a warming of between 0.2 and 0.3 °C per decade, which is about twice the pace of warming over the second half of the 20th century.

Beyond 2050, projected warming is dependent on the emissions scenario, making clear that society's choices about emissions can and will make a difference, although with a lag of approximately 50 yr if changes in emissions are gradual. For the B1 emissions scenario, which is nominally the lowest, or most optimistic, emissions scenario in the absence of emissions controls, the projected increase in global average temperature, averaged across the set of models, is approximately 0.4 °C from 2050 to 2100 (i.e., slowing to the warming rate of the second half of the 20th century), with little more warming thereafter. For the A1B scenario, which assumes a slower transformation to alternative and high-efficiency solutions, an additional degree of warming is projected by 2100, so maintaining the decadal rate of warming of the first half of the century and leaving a commitment to further warming thereafter. For the A2 emissions scenario, which foresees a very heterogeneous world with only slow and spotty adoption of new technologies, the pace of warming continues to accelerate into the 22nd century.

Recognizing that the thermal inertia of the oceans slows the pace of climate change and thereby hides the full warming implications of past emissions, the modeling groups carried out a calculation that assumed, quite arbitrarily, that the value of RF in the year 2000 persisted indefinitely, allowing the climate system to adjust to this degree of perturbation. The model results project further warming of approximately 0.6 °C ± 50%. Although this is the commitment to future warming for year 2000 levels of GHGs, this increase understates the warming that would result if actions were somehow taken that led to near-term stabilization of GHG concentrations. This is the case because, to stabilize the atmospheric CO_2 concentration, emissions of CO_2 would need to be cut by approximately 75%. This would inevitably lead to reductions in aerosol emissions, both of SO_2, which leads to sulfate aerosols with their cooling influence, and of soot, with its warming influence. Because these aerosols have lifetimes in the atmosphere of at most 2 weeks, their radiative effects would be quickly lost and further warming of perhaps 0.5–0.7 °C or more would result.

Although the change in global average temperature is a useful metric, what matters to people and the environment is what is happening where, and how fast are the changes occurring. Figure 11, also from IPCC (ref 15, chapter 10), shows the global distribution of the projected changes in annual average warming in the year 2100 for the IPCC's A1B scenario, thus the middle of the three emission scenarios presented. As is already evident in recent warming, the changes are projected to be larger over land than the ocean (due to the different heat capacities and potential for evaporative cooling) and larger in mid-to-high latitudes than in low latitudes (due to the amplifying effects of snow and sea ice albedo feedback and to the different potential for evaporative cooling). Although not shown, warming is generally greater in winter than in summer because of the increased potential for

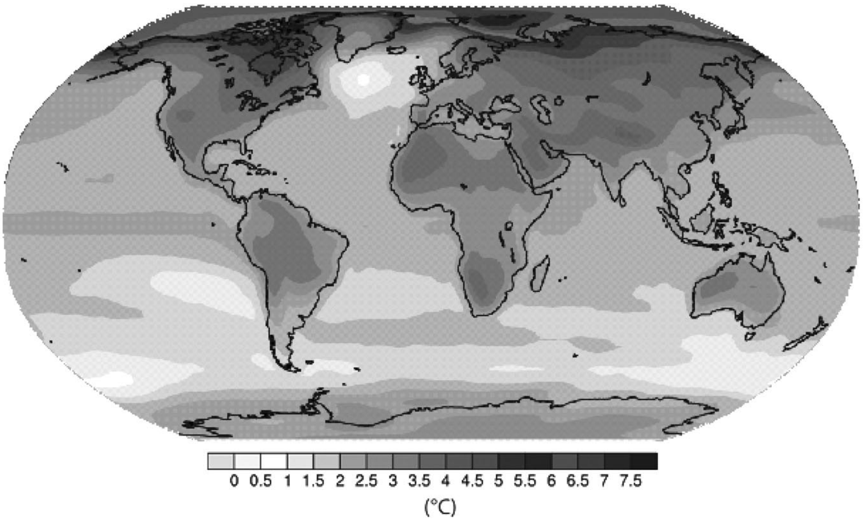

Figure 11. Multimodel mean of the projected increase in annual mean surface air temperature from 1980–1999 to 2080–2099 for IPCC's A1B emissions scenario, which envisions a world of very rapid economic growth with global population peaking in mid-century, the rapid introduction of new and more efficient technologies, increased cultural and social interaction internationally, and a substantial reduction in regional differences of per capita income. For this mid-range scenario, CO_2 emissions climb to approximately 17 PgC/yr and then start slowly declining to approximately 14 PgC/yr by 2100. The global average temperature increase is approximately 2 °C, with larger changes over land and in high latitudes and smaller changes over low-latitude oceans. Reprinted with permission from the IPCC[15] (chapter 10). Copyright 2007 Cambridge University Press.

evaporative cooling with higher temperatures and because it takes less energy to warm during colder times when inversions are typically stronger and more frequent. There will, however, be special cases: if a moist land area dries out, its temperature increase can become quite large; if a dry area becomes wet, its temperature increase can be reduced. Essentially what is happening is that the warm season is becoming slightly warmer and much longer, and the cold season is becoming warmer and much shorter.

Although many of IPCC's critics suggest that climate models are likely overestimating future warming, a much stronger case can be made that the model results project too limited and smooth a warming. During glacial periods and during the emergence from the Last Glacial Maximum, ice core results document large shifts in the temperature over Greenland over time intervals of less than a decade, suggesting that hemispheric and perhaps global average shifts of up to several degrees could happen very quickly.[115] Since recognizing this possibility, there have been increasing efforts to try to identify the mechanisms involved and to search for possible tipping points that might be triggered as warming continues.[53,116] Among the types of changes that could trigger relatively sudden and abrupt warming and other types of change are unusually rapid melting of Arctic sea ice, accelerated release of CH_4 from melting of frozen ground, and a slowdown in oceanic uptake of carbon that would indicate the triggering of the natural carbon feedback mechanism that in the past amplified the changes in climate caused by the changing orbital elements.[117] Disturbingly, each of these mechanisms already looks to be starting to amplify the projected warming beyond the projections of most climate models.

In addition, the pace of several related impacts could be amplified, including an acceleration in the rate of deterioration of the GIS and WAIS, slowing of the overturning circulation of the global ocean, intensification of tropical cyclones and hurricanes, shifts in the global pattern of monsoons, loss of the Amazon rain forest, and northward extension of the boreal forest. It is also likely that there will be changes in the natural modes of oscillation of the atmosphere-ocean system, although model projections are not yet providing definitive projections on what the changes will be. For example, there are projections of both intensification and reduction of the El Niño/Southern Oscillation; further work will be needed to determine the outcome.[118]

Each of these types of events, and others, has the potential to not only wreak significant havoc on vulnerable regions and populations, but to amplify the pace of change in particular regions around the world by altering surface albedo. On the basis of the increasing pace of global warming, including the potential for an abrupt acceleration, and the potential seriousness of intensifying regional changes and the further global consequences they would create, the risk appears to be increasing that a tipping point leading to "dangerous," or perhaps even catastrophic change could surprise us in the years ahead.[53,116,119,120]

Projections of Changes in the Hydrologic Cycle

That evaporative cooling is limiting warming over the ocean and in moist regions does limit the temperature increase, but this benefit comes at the price of putting more water vapor into the air. The increase in water vapor concentration not only amplifies overall warming through the positive water-vapor feedback mechanism, but also provides the energy that drives storm systems, including especially tropical cyclones (e.g., hurricanes, typhoons, etc.). Model projections are that such storms will become more intense (leading to faster winds and lower central pressure), which will increase their destructive power. Although the higher GHG concentrations increase trapping of IR radiation in the upper troposphere, tending to slightly stabilize the atmosphere, this effect is overcome by the increased energy drawn from increased condensation, which is available because of the higher water vapor concentrations resulting from the warmer ocean temperatures. Model simulations project that an increase of approximately 2 °C in sea surface temperature will lead to an approximately 5–8% increase in peak wind speed (and damage potential is roughly proportional to the cube of wind speed, up until a structure collapses) and an approximately 20% increase in peak 6-hr rainfall.[121] Because the lower central pressure and increased winds also drive the storm surge, and because peak rainfall in recent major storms has been of order an inch an hour for 24–48 hr, the potential for increased damage and loss is enormous even though these severe storms are more intermittent than the persistent warming.

Over land, increased rain intensity can, depending on river basin configuration and base river flow at time of occurrence, increase the potential for flooding (even flash flooding), because the proportion of rain that becomes runoff increases with rainfall rate and the fraction going to groundwater decreases. Simulations using the Canadian climate model suggest that the return period of severe storms will decrease, leading to what are now 100-yr storms occurring as often as every 30-yr. Because significant transportation and other civil infrastructure are typically designed to withstand 100-yr storms, having such intense storms so much more frequently would be expected to lead to significant additional costs and disruption, not to mention the psychological impacts that repeated flooding imposes on communities.

Mid-latitude storm tracks are expected to shift poleward as larger areas of warmed air push against a diminished supply of cold air. Thus, climate change will lead to shifts in the locations where precipitation is occurring, likely affecting water resources. Warmer conditions will accelerate the drying of soils and onset of drought conditions.[122] Drier conditions will increase stress on plants, even though the higher CO_2 concentration will help improve their water use efficiency. Higher temperatures and increased frequencies and extent of dried vegetation will increase the likelihood of wildfire. In addition, projections indicate that the duration of time above various threshold temperatures will increase, thus leading to more intense and longer heat waves, which, in turn, increase the likelihood of elevated O_3 concentrations and poor air quality (ref 16, chapter 8).

Sea ice cover will continue to decrease in thickness, extent, and duration. Although the model simulations project rapid retreat of Arctic summer ice, the observed rate of retreat over the past few years has been significantly more rapid than projected, suggesting that the models are not adequately representing melting processes. Simulations with more detailed regional sea ice models indicate that this accelerated pace is likely to continue. Because the expelling of salt during sea ice formation creates the very salty, and therefore high-density water that sinks into the ocean depths and contributes to the overturning circulation of the global ocean, changes in sea ice can play a global role.

Although precipitation in high latitudes will generally increase (right now it is generally too cold for significant precipitation), snow cover will retreat, both in extent and duration, as more of the precipitation falls as rain. Given that snow cover in many regions plays a role in insulating the soil during times of freezing, its retreat will have effects on ground temperature, including leading to a reduced extent of permafrost. In the mountainous regions of the western United States where spring snowpack is so important in managing water resources, the higher snowline will result in earlier melting, which will reduce the amount of water stored as snow in the spring, especially because mountain areas above particular elevations tend to decrease rapidly with elevation.

Projections of Change in Sea Level

Although the global climate models have been successful in simulating the increase in temperature over the 20th century, including on a regional basis and for ocean heat uptake over the past 50 yr,[123] the models and analyses have not yet been successful in explaining the observed increase in sea level (ref 15, chapter 5). Of the observed rise in sea level of approximately 77 ± 21 mm from 1961 to 2003, model-based estimates of thermal expansion and the surface water balance of ice sheets along with surveys of changes in mountain glaciers account for only 47 ± 21 mm, leaving a rise of approximately 30 ± 30 mm unexplained (either as errors in these terms or unaccounted processes such as release of water from underground aquifers or from the GIS and Antarctic ice sheets).

For the briefer period from 1993–2003, the accounting is better, explaining approximately 31 ± 8 of the 34 ± 8 mm rise over this period. This close agreement is possible, however, only because the models seem to be assigning virtually all of the thermal expansion and most of the ice sheet contribution to the period since 1993. This suggests that acceleration in the rate of change is occurring. On the other hand, the residuals suggest an average rate of rise of approximately 0.5 mm/yr from 1961 to 2002, which is far below the average rate of 1.5–2 mm/yr for the 20th century as a whole. Indeed, with the observed rate of rise now up to almost 4 mm/yr, compared with the model-simulated rate of approximately 3 mm/yr from 1993 to 2003 and 0.5 mm/yr for the 3 decades before that, there remains a good deal of uncertainty about what has been causing past increases and what this means with respect to projecting future increases.

IPCC's Third Assessment Report (ref 11, chapter 11) accounted for the uncertainties in understanding of sea level rise by suggesting that the increase from 1990 to 2100 could be as low as 90 mm or as much as 880 mm (~4–34 in). Reviewer comments from prominent glaciologists led IPCC to include an additional caveat acknowledging "this range does not allow for uncertainty relating to ice dynamical changes in the WAIS." It is turning out that this same caveat applies even more urgently to IPCC's 2007 projections.

More detailed model simulations formed the basis for projections of the sea level rise in IPCC's Fourth Assessment (ref 15, chapter 10). However, because the assessment failed to present a time history for the 20th century comparing model simulations for sea level rise with observations, there is little basis for confidence that the model simulations are adequately representing all of the important terms—and considerable room for concluding that the IPCC projections for the future are too low.[124] Averaging across emission scenarios, IPCC projected that sea level rise from the late 20th century to the late 21st century would amount to approximately 350 ± 150 mm (the full range was from 180 to 590 mm, depending on emissions scenario), which is a generally lower and narrower estimate than from IPCC's Third Assessment (ref 15, chapter 11). Thermal expansion and melting of glaciers and ice caps were the dominant contributions to the increase. Accumulation of snow on the Antarctic Ice Sheet was estimated to more than make up for any loss of mass from the GIS. Although IPCC again indicated that the effects of dynamical changes in flow of the ice sheets were not included in the estimates, they estimated this term at between 100 and 200 mm, and then added, in response to reviewer comments, that even higher values could not be excluded.

Because glacial stream behavior, satellite observations, ice sheet base heights, and paleoclimatic evidence all suggest that change could be more rapid than IPCC projects, there remains a significant possibility that the future rate of sea level rise could be much higher than indicated in the latest IPCC assessment. With respect to ice stream behavior, there are glacial streams in both Greenland and Antarctica that are moving more rapidly than glacial stream models can explain, and ice fronts that had apparently been stable for centuries are now in rapid retreat. In contrast to previous radar and lidar observations suggesting that ice sheet volumes were increasing, new satellite observations indicate that the mass of the ice sheets is decreasing, suggesting that the density of the ice is decreasing and consistent with observations of meltwater carving moulins through the ice sheet.

Although the WAIS was always recognized as especially vulnerable because it was grounded below sea level, analyses have generally assumed that the GIS is resting on mountains that would separate its ice from the warming ocean waters and thus slow the loss process. New data indicate that not only has the ice sheet pressed the interior of Greenland down to well below sea level, but there are also several deep and long fjords that extend into the interior of the ice sheet.[125] These fjords could well accelerate the loss of ice by allowing the ice sheet to move and drain dynamically—and this effect is yet to be included in the ice sheet models or the IPCC projections.

Getting a rough estimate of the potential importance of the dynamical term is thus critical. Unfortunately, historical records of variations in ice sheets provide little insight. As indicated by the values given in Table 3, paleoclimatic records of past climatic states can be used to provide a very rough estimate of the equilibrium relationship between global average temperature and sea level departure from its present value. For warmer conditions, an equilibrium response of perhaps 5–15 m of sea level rise per degree of increase in global average temperature is suggested. The Eemian interglacial was at most a few thousand years long and there are some suggestions much of the rise in sea level may have occurred over just a few centuries, with rates of sea-level rise being as much as 1.6 m/century.[126] However, the Eemian may be a special case, because this was a time when the orbital elements led to a significant increase in summer solar radiation, and this may have accelerated the rate of rise by more than would happen with the more uniform increase in forcing caused by increased GHG concentrations. Although results from the U.K. climate model, which assumed a few degree elevation in annual temperature, suggest it would take a few thousand years for about half of the GIS to melt, that sea level rise averaged about 1 m per century in the 12,000 yr following the Last Glacial Maximum, suggests that quite high rates of melting are possible.

What about the coming century? IPCC projections have global average temperature going up by approximately 2–4 °C, which paleoclimatic analogs suggest might be associated with an equilibrium increase in sea level of 10–20 m or more. Observations indicate that the increase of approximately 0.8 °C has already started the deterioration of parts of the GIS and Antarctic ice sheets; that some of their glacial streams are moving more rapidly than can be explained suggests significant sea level rise could happen relatively quickly (over several decades to centuries). In my view and that of others,[127] those living in low-lying coastal regions should not be complacent and coastal zone managers should be assuming that the rise will be substantially faster than the quantitative estimates made in IPCC (ref 15, Summary for Policy-Makers).

Projections of Changes in Climate beyond 2100

Most of IPCC's focus has been on climate change out to 2100, essentially out a few generations. But, unless strong action is taken, global warming for most scenarios will continue thereafter, and for sea level, it is likely to take a few thousand years for the full ramifications of ocean warming and melting of ice sheets to be felt.

Table 3. Estimates of sea level and change in global average temperature from paleoclimatic records.[128]

Geological Period	Years before Present	Difference in Global Average Temperature from Present (°C)	Equilibrium Sea Level Departure from Present (m)	Estimated Sensitivity Relative to Present (m/°C)
Last Glacial Maximum	~20,000	−5 to −6	−120	~20–24
Eemian interglacial	~125,000	+0.5 to 1	+4 to + 6 (perhaps not at equilibrium)	~4–12
Pliocene	~1.8–5.3 million	+2	+30	~15
Eocene	~34–56 million	+4	+70	~17

With respect to the amount of warming, projections are that it would continue for several decades once emissions are limited sufficiently to keep the RF from increasing. The increase would be approximately 0.5 to 1 °C, and this would be augmented by a similar amount as aerosol loadings dropped following reduction in emissions of GHGs. The adjustment time could be lengthened somewhat as a result of vegetation feedbacks—it takes many decades for new vegetation systems to come into balance with altered climatic conditions. Even if GHG emissions are halted completely and the concentrations of relatively short-lived gases (e.g., CH_4) start to drop, there will be some future warming as the deep ocean warms (thus reducing the cooling influence of upwelling waters) and as the aerosol loading simultaneously drops.

For sea level, the equilibrium time following a cessation of emissions is many centuries—it takes time for the deep ocean to warm and it takes time for glaciers and especially ice sheets to melt. As a result, even though the rate of sea level rise is increasing, we are still seeing only a small fraction of the eventual equilibrium rise. In addition, melting of the ice sheets will allow the land presently under the ice sheets to rise and nearby areas that were pushed up to balance will now start to subside, so present coastlines will change. These processes have very long time constants; the Chesapeake Bay area was pushed up by the ice sheets to its north during the Last Glacial Maximum, and now, 20,000 yr later, is still subsiding at approximately 1.5 mm/yr, causing relative sea level for this area to be about twice the global rate because of human activities. With subsiding land and sea level rise both likely for many centuries into the future, many low-lying coastal regions face an ominous future, especially if the rate of rise continues to accelerate.

FINDING 5: IMPACTS OF CHANGES IN CLIMATE ON THE ENVIRONMENT AND SOCIETY WILL BE SIGNIFICANT

The natural distribution of ecosystems, their change with altitude, migrations of species, impacts on society of severe storms and anomalous weather, the sensitivity of agricultural production, the intensity and frequency of wildfires, floods and drought, and many other indicators make clear that both the environment and society are very dependent on the state of the climate. If impacts of climate change are going to be the basis for investing substantial effort and resources to transform the global energy system, then the impacts involved need to be of similar scale and significance. This section provides a broad-brush summary of the major categories of the impacts identified by the IPCC[16] (see Figure 12), and also includes a brief overview of the most important impacts on different regions of the United States from its National Assessment.[20,21]

Although the available assessments do a generally effective job in assessing potential impacts, all such studies to date remain very limited in their identification of effective adaptation options—in large part because, for many types of impacts, there are simply not ways to adapt to or avoid many of the adverse impacts. Although some adaptation to some of the impacts will be possible in some regions, suffering and adverse consequences will in some situations be unavoidable.[53]

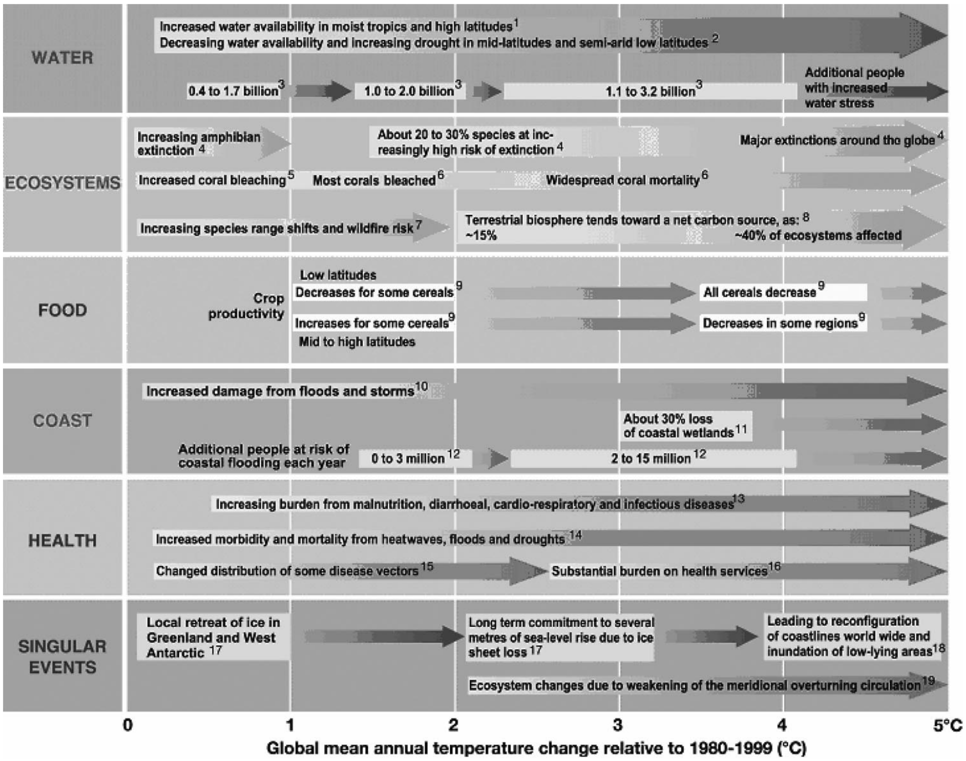

Figure 12. Examples of global impacts in key sectoral areas projected to result from changes in climate associated with the indicated increase in global average temperature, and, where relevant, increases in sea level and atmospheric CO_2 concentration. Reprinted with permission from the IPCC[15] (Summary for Policy-Makers). Copyright 2007 Cambridge University Press.

The Direct Effects of the CO_2 Increase

For humans, CO_2 at high enough concentrations (>100,000 ppmv) can be a near-term asphyxiant, and, indeed, CO_2 emissions from volcanoes and from lake overturning have, under special circumstances, caused illness and death.[129] For 30-day exposures for submariners and other healthy individuals, the long-term standard is 7000 ppmv. With a wider mix of people, the Occupational Safety and Health Administration has set a standard of 5000 ppmv for 8-hr exposure in buildings. However, for susceptible people over longer periods the standard would be expected to be considerably lower given the types of health effects that can arise.

To ensure limits on a mixture of pollutants present in buildings, the ventilation criterion for buildings (American Society of Heating, Refrigerating and Air-Conditioning Engineers Standard 62.1) has been based on keeping the CO_2 concentration at no more than 700 ppmv above the ambient outside level (near 1000 ppmv when the standard was first developed). Although the concentration was over 1500 ppmv when mammals evolved near the end of the Cretaceous period, the period of human development took place with the CO_2 concentration below approximately 400 ppmv, suggesting that unconstrained emissions scenarios taking the ambient concentration to 1000 ppmv or above in 100 yr would be very problematic, leading to exposures well above 1500 ppmv in enclosed places. Similar concerns arise generally for wildlife, as the ambient CO_2 concentration has likely not been above 1000–1500 ppmv in over 50 million years (ref 15, chapter 6).

Higher CO_2 concentrations allow plants to take in needed CO_2 without their stomata being as open; this has the dual benefit of not letting as much air pollution in and not allowing as much water to escape, thus improving the water use efficiency of the vegetation.[130] Field and chamber experiments have been undertaken to explore these relationships for various types of plants, including crops and trees on which society particularly depends (ref 9, section A). An increasing number of free-air-CO_2 experiments (FACE) are being conducted to explore the response to a higher CO_2 concentration of various species under various temperature, moisture, and nutrient conditions. Many types of trees and crops show productivity increases of up to a few tens of percent, providing there are not limits imposed by soil moisture and nutrients (ref 16, chapter 5). The response in less than ideal situations is more complex, especially because the different responses of different species affect the competitive balance of ecosystems, especially given the strong response of many weeds and pests. Wildlife is also affected, because the nutrient value of vegetation is somewhat reduced when the CO_2 concentration is increased.

Simultaneous changes in temperature, evaporation, temperature-light relationships, and other factors can also lead to reduced plant productivity and success. With the combined effects of CO_2 and changing climate, the latitudinal bands for optimal growth of species tend to shift—differently for different species. As a result, the balances in existing ecosystems will be disrupted and new couplings and balances will need to develop. Were the climate shifting slowly to a new stable state, the process might go unnoticed, as for the slow shift of the center of the maple sugaring industry from Maryland to upper New England over the past few centuries. With a rapidly changing climate, much more stressful situations are likely to develop. A very important example has been the devastation of many of the lodgepole pine forests in western Canada and the northwestern United States as a result of winter temperatures not getting below −40 °C, thus allowing the pine beetle to survive and multiply.[131] With trees dead, the risk of wildfire increases and forests no longer provide reliable lumber harvests, disrupting local economies.

For marine systems, the prospective impacts are even more serious. As the atmospheric CO_2 concentration rises, it forces a new chemical equilibrium with the ocean waters that leads to a reduction in the concentration of carbonate ions and lowers ocean pH, leading to what is called "ocean acidification." In the surface waters of the open ocean, the mean pH ranges between 7.9 and 8.3, having dropped by approximately 0.1 from 1750 to the mid-1990s and by another 0.1 since the peaks of past glacial periods when the CO_2 concentration was approximately 200 ppmv (ref 15, chapter 5). Projections are that the pH will drop another 0.3–0.4 units by 2100, leading to undersaturation of the carbonate ion, initially in the coldest waters and then later in low latitudes. In the past, when the atmospheric CO_2 concentration was high, the increase in concentration occurred over long enough periods that weathering of rocks served to limit any significant change in ocean pH. Because of this process, analyses by Caldeira and Wickett[132] indicate that, although the CO_2 concentration was as much as approximately 2000 ppmv, the pH has not been more than 0.6 units lower than present over the last 300 million yr. The recent and projected rate of increase, however, is far faster than can be buffered by weathering (although there are some geoengineering proposals, quite likely very expensive, that envision actively stimulating this process).

Changes in ocean pH during the 20th century have already been observed to lift the carbon compensation depth—the depth at which calcareous sediments like coral dissolve. This suggests that organisms that have skeletons or shells made of calcium carbonate are likely to be threatened. Coral reefs are likely to be particularly affected. Assuming that the CO_2 concentration rises as projected, the ocean chemistry of virtually all the regions that were favorable to coral reef formation in preindustrial times will be marginal by 2050; many regions will have calcium carbonate saturation levels that in preindustrial times allowed for no development of coral reefs.[20,21]

Ocean acidification also threatens the overall marine food chain and the calcareous plankton on which it is based. The effect is most imminent in high latitudes where water temperatures are lower and more CO_2 can be taken up, potentially threatening many regional fisheries. Given the potential consequences and the very limited time for marine species to adjust (or evolve), this threat alone, which depends only on the increase in the CO_2 concentration and not on climate change, is likely reason enough to rapidly reduce emissions of CO_2 from fossil-fuel combustion.

Impacts on Water Resources

Freshwater is vital for life on Earth. Natural systems depend on the regular occurrence of precipitation, and many cities depend on vast reservoir and piping systems to ensure sufficient water. Climate change affects the entire hydrologic cycle, including shifting the tracks, timing, and intensity of storms, increasing evaporation rates, changing of snow to rain, melting mountain glaciers, changing the timing of lake and river ice, altering the demands for water for irrigation and consumption, raising sea level, and changing estuarine salinity. Although variability continues, its baseline is shifted and new extremes are created. For virtually all regions studied as part of the U.S. National Assessment,[20,21] water was the number one issue. A similar level of concern for regions around the world is expressed by IPCC.[16]

The weather is largely determined by the comparative temperatures of different air masses, with cold, high-density air masses formed in high latitudes spreading out and undercutting warm, moist, low-density air masses formed in lower latitudes. This undercutting leads to the lifting of air masses to lower pressures, causing expansion and cooling, condensation, and release of latent heat that powers further lifting. Where polar and tropical air masses collide, which occurs especially in central North America, large frontal systems result that are characterized by strong convection, thunderstorms, and even tornadoes. With moist tropical air pushing further and further north during winter as Arctic air masses become less cold and extensive, the result in the United States is a shift of their winter interaction, with the associated large increase in heavy precipitation, into the middle to upper Mississippi River Valley from the traditional location along the Gulf Coast. Examples of the unusual northward penetration of tropical air masses include the storms that caused the historic floods that occurred in the central Midwest in March–April 2008.

In very warm low latitudes, the atmospheric circulation is powered by latent heat release in convective storms. As atmospheric water vapor increases, more energy is available to power such storms, and precipitation rates increase. Air that goes up (and has given up its moisture in rising) must come down, and this occurs in the subtropics, with the more powerful upward motion in the tropics forcing the air in the subtropics down over wider regions, spreading out the warming and suppressing precipitation over wider regions.

When whirling air is generated, for example over the Sahara Desert, warmer ocean waters promote greater intensification if the atmospheric circulation is properly aligned, leading to stronger and longer-lasting tropical cyclones (i.e., hurricanes and typhoons). Higher water vapor concentrations lead to greater condensation, providing the extra energy needed to drive these systems, even in the face of the slight increase in atmospheric stability. The result is higher wind speeds (causing more building damage), increased precipitation (leading to greater flooding, which is a major cause of death from such storms), and higher storm surges (causing more extensive damage and increased coastal erosion). Although questions remain, particularly with regard to constructing trends to back before the weather satellite era began 3–4 decades ago,[133,134] the available data indicate that the fraction of storms that are in the most powerful categories is increasing,[110] and that storms are tending to persist longer, dissipating more energy and therefore doing more damage.[111]

For reasons that are not clear (perhaps related to the globally integrated energy flow toward the poles), the annual number of tropical cyclones globally has been fairly steady. The number in each basin, however, appears to be changing, with an increasing trend in the North Atlantic basin. Global warming is likely playing a couple of roles: warmer ocean temperatures help to increase the intensity of the storms, and a deeper layer of warm water limits the cooling effect of vertical ocean mixing due to hurricane-force winds. With passing storms not cooling the ocean waters as much, strings of storms can occur (as in 2005) and storms can occur later in the year than previously.

The amount of damage from tropical cyclones has been increasing nearly exponentially. A major factor is that more people and more buildings and other infrastructure are present in vulnerable coastal regions,[135] although there are many ways that climate change is adding to the risk.[136] In many areas, it is not clear where to live: the coastal plain is subject to inundation and high winds, the mountainsides are subject to heavy rain and landslides, and the valleys are subject to flooding and mud and debris flow. In addition to the devastation caused by Hurricane Mitch dumping up to 1900 mm (75 in) of rain in 2 days on Honduras and Nicaragua in 1998, wiping out decades of economic progress, a major impact for the United States was the increased push of refugees along the Texas border; given the devastation of their homelands, many were allowed at least temporary entry. Some suggest that the root cause of the disaster was poverty and money that might be used to limit GHG emissions would be better spent on development, but the 1-m deluge that Tropical Storm Alison dumped on the Houston area in approximately 30 hr in 2001 showed that development per se is not a protection against such downpours. Pretty clearly, increased precipitation and storm intensity will make things worse.

Although too much water is the problem in some places, too little is the problem in others. The 2003 heat wave in Europe was, as indicated earlier, roughly a 1-in-500-yr event, killing several tens of thousands of people.[109] Assuming people reduce their time outdoors as the frequency of such events increases, the health impacts of the intense heat could be alleviated by significantly increasing the fraction of buildings with air conditioning. However, very low river flows were an important additional effect, causing the closing of several power plants because of an insufficient supply of cooling water. With the power demand increasing and plant availability decreasing, adapting to the changing conditions is likely to be quite expensive.

Finally, warming is raising the snowline, reducing the spring snowpack, and melting mountain glaciers. In the western United States, the dam and reservoir systems depend on much of the winter precipitation being stored as snow well into spring. Not only does warming reduce the total amount of snow, but the potential for rain falling on the remaining snowpack is also the worst-case flood scenario for many dams. To meet flood protection requirements, which are generally the highest priority, reservoir levels need to be lowered well in advance of storms. Although predictions can help to some extent, if late-season storms do not appear, there is not only less water in the reservoirs, but also less snow on the mountains, causing a double hit on the water resources available to meet increasing warm season demand. With most water resources already allocated, global warming is therefore increasing competition for water.

Impacts on Highly and Lightly Managed Terrestrial Ecosystems

In addition to water, life depends on the food and fiber derived from croplands, pastures, and forests. Wildlife also depends on what grows, and the species that have survived are those optimally adapted to what nature provides, locally and, for many species, along long-established migration routes. Although it would seem that migrating species, which can move around, would be more adaptable than other species, their movements, and quite likely their dominant genetic coding, have resulted from very special climatic features and sequences, from the timing of seeds appearing to the timing of ice melt on rivers. Just the right set of plants and wildlife in just the right mix of field and forest have to produce in just the right amounts at just the right time for species, especially migrating species, to survive and reproduce.

In general, warming will push cold region species poleward, sometimes to extinction. Paradoxically, the number of different species may well go up in high-latitude regions as species push poleward, but global diversity is projected to drop sharply, because losses at the poleward edge and in niche environments will exceed the emergence rate of new species, and because interspecies linkages will be broken at a rate of change that is much faster than during past periods of rapid change (e.g., coming out of the last glacial cycle). That so many species are being impacted by the modest degree of climate change to date reinforces the projections of significant further change and disruption (ref 16, chapter 1).

Society depends on a highly tuned agricultural system—it has been estimated that the natural world without technological and chemical contributions to agriculture could only support 200 million people.[137] Although food production is generally meeting global caloric needs, problems in distribution and economic wherewithal lead to some having more food than they need and others less. Agriculture has generally been able to meet the increasing demands of the rising population because of ongoing improvements in seeds (including local tailoring of varieties to the climate); adequate amounts and well-timed application of fertilizer, pesticides, and herbicides; the increased skill and knowledge of farmers; and a relatively stable climate. In addition, although threatened by deforestation, the world's forests provide a vital set of products, from medicines to wood.

The ecosystems that have developed over many millennia are those most tuned to the prevailing climatic conditions. In addition, societies have developed based on the existing ecosystems. Global warming is likely to wreak havoc, working most devastatingly at the warm boundaries of ecosystems. Decreasing moisture leads to water stress, weakening plants and making them more vulnerable to pests and fire. As a consequence, transitions from one type of land cover to another are not likely to be smooth and gradual. More often, existing systems will be weakened and then burn, allowing undesirable species such as weeds and invasives to grow back first, taking advantage of the overstressed conditions. Only after many decades of a stable climate will more mature and desirable systems such as those from closer to the equator take over. Such disruptions of existing ecosystems and the services they provide, from water and air purification to recreation, are not a trivial concern. Estimates are that the ecosystems of the world provide benefits equivalent to roughly half of the global economy,[138] so the adaptive measures needed to replace lost services are likely to be costly.

As noted earlier, the CO_2 increase itself is likely to contribute to increases in global food and fiber production; the additional effects of climate change, however, are likely to be quite disruptive. Present cropping practices are closely tied to the prevailing temperature and precipitation. Although the efforts of those in land-grant colleges and seed companies have greatly helped tune crops to prevailing soil and climatic conditions, the process has taken decades. Climate change will force all of the tunings to be reworked on an ongoing basis. Accomplishing this will require greater efforts by researchers, increased knowledge and adaptability by farmers, and additional infrastructure investment to ensure compatibility with the changing crops. Differential rates of change will alter the decisions each farmer has to make (e.g., crop choice, time of planting, investment in fertilizers) as they work to succeed in the context of their capabilities and the marketplace created by the changing capabilities and choices of others. For those in large countries with significant intellectual and industrial support, adaptation is likely to be possible, assuming new plant diseases and weeds do not prevail; in developing countries where farmers have traditionally grown one crop, the challenge will be much more difficult and disruptive.

Impacts on Coastlines and Marine Resources

With virtually constant sea level from well before Roman times to the mid-19th century, the coastal environment has become hardened and stable. Human encroachment has certainly had a significant effect, but the impacts have generally been local. The rise in sea level over the 21st century is likely to be several times that of the 20th century, and the increased rate of rise seems likely to extend for centuries, posing an increasingly severe threat.

For many low-lying coastal regions, sea level rise will be the greatest threat. This is particularly the case for large river deltas such as the Ganges, Nile, and Mississippi River systems where there are many people and vast amounts of infrastructure. Areas subject to tropical cyclones will become more likely to be inundated, especially to the extent that storm intensity and storm surge increase. Around the United States, virtually the whole coastline is vulnerable, with many areas being very susceptible, including Boston, New York, Chesapeake Bay, the Outer Banks of North Carolina, Florida, the Mississippi Delta, and the Texas coast. Were a category 3 hurricane to push into New York harbor at high tide, the estimated storm surge would exceed 20 ft at current sea level, creating enough of a rise to flood many areas and cut Manhattan island in two.[139]

The United States is late in considering measures to limit vulnerability. Building continues in many low-lying coastal areas. For rivers and estuaries, storm surge barriers can limit the damage and help with sea level rise if properly designed. Learning from what has been done in other regions, a proposal has been made for protecting much of New York City.[140] Maps show the Sacramento-San Joaquin Delta as being made up of islands, but the late Marc Reisner[141] more accurately labels those islands as "empty reservoirs" because their interiors are several meters below river level. Collapse of the levies, whether as a result of an earthquake or sea level rise, combined with a spring flood, would draw in salt water from San Francisco Bay, seriously disrupting the system of waterways that is used to transfer northern California water to the Central Valley for irrigation and southern California for its communities; billions will be required to construct the barriers needed to protect the delta region and California's water transfer projects from both sea level rise and earthquakes.

Estuaries are one of the most productive of marine area environments, providing the conditions needed for reproduction and growth of many species fish, clams, birds, and more. Sea level rise pushing salt water in and changes in runoff (generally reductions in mean flow and increases in flood flows) will lead to changes in salinity, temperature, stratification, and flushing, quite possibly reducing oxygen concentrations. Changes in such conditions will dramatically affect many types of species, predator-prey relationships, pathogens, and the occurrence of disease-inducing harmful algal blooms. Coastal wetlands will also be affected, with inundation likely because accretion is unlikely to be able to keep up with the increasing rate of sea level rise.

Marine fisheries are already starting to shift poleward. Although fishing fleets can relocate, fishing rights will be affected because fish do not recognize national borders. Sea ice retreat will have very important biological effects. For example, many types of fish feed at the edge of sea ice as nutrients released during melting cause phytoplankton blooms, and the suppression of winter waves by sea ice benefits larvae and young fish. With the CO_2 rise and resulting acidification already likely to disrupt the food chain, climatic disruption of coastal and sea ice environments appears quite problematic.

Impacts on Human Health and Well-Being

Impacts on human health are likely to be of two general types: direct health impacts caused by heat waves, storms, and other extreme weather; and indirect health impacts resulting from the effects of climate change on air and water quality and vector- and rodent-borne diseases (ref 16, chapter 8). In addition, climate change can tend to reduce certain types of impacts, including those caused by intense cold. Although societal infrastructure and practices are designed to protect against the present range of extremes, what climate change will do is shift this range. The net effect is likely to be negative because the increasing intensity and duration of warm extremes will cause new and greater health impacts than will be alleviated by reducing cold extremes for which protection already exists. For most situations, adaptation is possible—the challenge is having the resources to take the needed actions.

Heat waves already pose threats to society, especially for those in areas where air-conditioning is not universal and adaptation to high summer temperatures and humidity must be re-established each summer. Building design is critical. Buildings in normally hot areas are already designed for air-conditioning (although electric costs will increase), and buildings in regions with cold winters are designed to be relatively airtight and retain heat, so air-conditioning can be added and operated at reasonable cost. By contrast, those in buildings not designed to ameliorate prolonged heat-wave conditions or not having the money to pay for air-conditioning can be severely affected, as was evident from the deaths during the European heat wave of 2003 and the Chicago heat wave of 1995. Climate change can push temperatures past thresholds that can severely impact health.

Even more important than the rise in temperature is the rise in absolute humidity, because it contributes to an amplified rise in heat index during nighttime hours. Calculations done for the U.S. National Assessment indicated that the increase in the mid-summer, 24-hr average heat index could be a few times as large as the temperature increase. Such changes would pose serious health threats, especially among the poor and those in old and deteriorating housing. With summer heat becoming so intense, outdoor activities will be limited. An adaptation measure might soon be to shift the outdoor vacation season for schoolchildren away from summer heat. Time spent in air-conditioned spaces is going to need to go up over much of the country and the cost for this is likely to significantly exceed the savings from reduced winter heating of relatively well-insulated homes. Although it is true that more people die during the cold than the warm season, the extent to which this is due to the cold itself versus the more frequent close contact with others (thus passing diseases) is not clear—increasing indoor time in summer may well have its own set of consequences.

The increasing intensity and longer duration of tropical cyclones, higher and more extensive storm surges, and other extreme weather events pose another threat to human health. Although improved warning systems should help to limit deaths from higher winds and flooding, this becomes more problematic as more and more people live near coastlines and as tropical storms carry their intensity longer and further inland. For regions such as Long Island and New York City, the infrastructure is just not available to allow full evacuation and relocation, especially if significant damage is done as a result of higher storm surges.

Other convective systems are also projected to intensify; with moisture laden tropical air pushing further north in the central United States as the duration and intensity of cold air outbreaks are reduced. Several regions that are not used to regularly coping with tornadoes, ice storms, and other severe conditions seem likely to experience more severe weather. Stronger buildings outfitted with safe rooms can be built, but it will take time and money to build resilience to and capabilities for dealing with the changes.

Warmer conditions tend to accelerate atmospheric chemical reactions, leading to higher O_3 concentrations.[142] Exposure can be reduced if people spend more time indoors and tighter emission controls are imposed or engines are changed to ensure air quality standards are met. Increased smoke from forest fires seems likely in many areas as traditional ecosystems become stressed and die—and then burn. Warmer conditions are also likely to lead to increases in allergens that then increase incidence of asthma, in part because species produce more pollen and in part because the types of weeds that are problematic are likely to be favored.[143]

Higher winter temperatures and a longer warm season are likely to allow greater survival and reproduction of insects and other disease vectors. With a capable public health system, thoughtful community design, strict building standards, and limited standing water, infectious vector-borne disease has been essentially eliminated from the United States, even where some vectors (e.g., types of mosquitoes) survive. As an example, the incidence of mosquito-borne Dengue is a factor of 1000 lower in Texas than in neighboring Mexico.[20] Keeping disease incidence low, however, will likely result in an increasing cost for infrastructure and helicopter-borne application of pesticides. Any weakening of resolve or limitation on resources is likely to lead to increasing health impacts.

Higher temperatures and reduced streamflows increase stream and river temperatures, potentially increasing exposure of fish (and people) to waterborne diseases and contamination. Increased flooding can sweep sewage, farm animals, and other debris into rivers and streams, contaminating water supplies while at the same time disabling sewage treatment capabilities. Food storage also becomes more important as temperatures rise, and this requires continuing access to electricity, which is likely to become increasingly vulnerable as storms intensify.

The United States and other developed nations seem sure to make available enough resources to maintain public health. However, the world is very intercoupled: people in the United States travel to many other places in the world where resources are not available to control health threats, and many from other countries come to the United States, potentially carrying diseases with them. Because isolating the nations of the world is neither realistic nor desirable, the health effects of climate change in every region will affect other regions, making it imperative that nations continue to work to strengthen the global heath care system, develop medicines and vaccines, and encourage good health practices. Already, insurance companies are recognizing the increasing risk, are having to pay out for increasing insured losses, and are bracing for potential surprises.[144] We will all bear the costs of the losses and suffering if adaptation is not proactive and sufficient.

Impacts on Society

In addition to impacts on food supplies, water resources, ecosystems services, human health, and coastlines, there will be direct impacts on communities, cities, and nations. At particular risk are the many components of societal infrastructure that sustain our modern standard of living. At the coastal edge, rising sea level and storm surges are the main threats to homes, hotels, and sewage treatment plants, whereas inland there is greater likelihood of flooding and fire brought on by more intense dry periods and drought. Hotter conditions will increase the need for energy and water, access to both of which can be affected by climate change.[145]

Significant amounts of transportation infrastructure are also very vulnerable.[146] In addition to the ports and waterways that are at the land-water interface, many roads, highways, railroads, and airports are only a few meters above sea level, therefore subject to eventual inundation as a result of sea level rise and more frequent flooding due to storm surges and high water. Levees can generally be used to protect the most valuable locations, but they need to be designed to protect against storms as well as sea level rise, and in regions such as Florida that are underlain by porous rock (e.g., limestone), levees will not work because water will simply seep underneath.

Inland, more frequent flooding episodes have the potential to scour channels and the supports holding up bridges and roadways. Hotter temperatures will weaken asphalt pavements, especially those with heavy truck traffic, necessitating more use of concrete and other new pavements. Very warm temperatures can cause expansion of steel rail lines and other materials, causing distortion and even breakage. Lower levels of rivers and lakes, especially the Great Lakes, will reduce capabilities for transporting bulk quantities of grain, fuels, and other resources.

Energy systems are also vulnerable. The efficiency of combustion will decrease as increasing temperature lowers air density. Reduced efficiency will thus affect power plants, vehicle mileage, the power of aircraft engines, and the lift of aircraft wings, requiring reductions in load, longer runways, or new aircraft. To the extent these engines are fossil-fueled, lower efficiency will require more fuel to meet the same demand for energy services. Electric wires also become less efficient as the temperature goes up and become more subject to breakage because of both rising temperature and stronger storms. Shifts in the amounts, timing, and location of rainfall and snow will affect the availability of cooling water for all types of power plants, whether powered by fossil fuels, biomass, or nuclear energy. Changes in rainfall and reservoir storage will also affect the amounts of water that can be used for biofuels.

Business, trade, and commerce will also be affected. Hotter conditions will make outdoor work such as construction and resource extraction more problematic in summer. Given international economic interdependence, impacts anywhere, whether drought and fire or downpours and flooding, will have much wider impacts. Preferred times and locations for tourism will shift, with tourism dependent on snow decreasing, and tourism related to warm (but not hot) conditions increasing. Increased intensity of storms and storm surges will put coastal resorts at greater risk as sea level rises, whereas inland, intensified drying will lead to restricted access to many areas that are vulnerable to fire.

Indigenous communities, many of which are located in regions that were special because of their environmental characteristics, will be especially disrupted.[19,21] In the Arctic, the melting back of sea ice is already allowing winter winds to whip up waves, eroding barrier islands that have served as home for millennia. In Alaska alone, the U.S. Government Accountability Office[147] estimates that 150 indigenous villages located on ocean and river coastlines will have to be relocated at a per capita cost of up to $1 million because homes, roads, utilities, community buildings, waste treatment plants, cemeteries, sacred sites, and other systems must all be relocated or constructed. In developing nations, the poor often have lived on low-lying lands subject to flooding or inundation, or have been crowded into other vulnerable areas on hillsides and steep valleys. As the intensity of severe events increases, more people are likely to become environmental refugees, relocating legally or surreptitiously, exacerbating regional tensions in ways that can threaten regional stability and international security (e.g., in Darfur), and increasing overall economic and environmental stress.

With all of the potential disruption around the world, there is increasing concern about the potential for not only disrupting the economy, but also for creating such hardship that the number of environmental refugees grows dramatically.[37] Increasingly, concern is being raised that impacts around the world may destabilize some governments, making climate change the most important threat to international security for the 21st century.[148,149] Already, the impacts of very severe hurricanes in Central America, which are likely to have an increasing human influence, have led to increased migration pressures along the border with Mexico.

Summary of Important Regional Impacts on the United States

Generalizations are not a basis on which actions can be taken to adapt—each location and situation needs to be examined. For North America, the IPCC WG II report (ref 16, chapter 14) concluded with high confidence that:

1. Warming in western mountains is projected to cause decreased snowpack, more winter flooding, and reduced summer flows, exacerbating competition for overallocated water resources.
2. Disturbances from pests, diseases, and fire are projected to have increasing impacts on forests, with an extended period of high fire risk and large increases in area burned.
3. Moderate climate change in the early decades of the century is projected to increase aggregate yields of rain-fed agriculture by 5–20%, but with important variability among regions. Major challenges are projected for crops that are near the warm end of their suitable range or that depend on highly utilized water resources.
4. Cities that currently experience heat waves are expected to be further challenged by an increased number, intensity, and duration of heat waves during the course of the century, with potential for adverse health impacts. Elderly populations are most at risk.
5. Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution. Population growth and the rising value of infrastructure in coastal areas increase vulnerability to climate variability and future climate change, with losses projected to increase if the intensity of tropical storms increases. Current adaptation is uneven and readiness for increased exposure is low.

The U.S. National Assessment[20,21] provided even more spatial detail. Table 4 presents a summary of the most likely impacts for different regions in the United States,[146] which, on a global basis, is likely one of the least vulnerable regions. In addition to the increasingly important impacts from sea level rise and storm surge affecting virtually all coastal regions, limits on water resources, drought,[122] and increases in fire frequency are likely the most important consequences for the western United States, increasingly severe storms and drought in the central United States, and stronger hurricanes and shifting ecological zones in the southeastern United States.

FINDING 6: STABILIZING THE CLIMATE WILL REQUIRE SUBSTANTIAL REDUCTIONS IN EMISSIONS

With the initial IPCC assessments[5,55] making clear that significant warming is likely and that this would induce many adverse impacts,[6] the nations of the world

Table 4. Examples of key regional consequences within the United States.[150]

Region	Environmental Consequences	Economic Consequences	Consequences to People
Northeast	Wetland and coastal inundation, changing forests	Reduced winter recreation, shifts in agriculture	Rising summer heat index
Southeast	Loss of coastal ecosystems, changing forests	Potential increasing productivity of hardwood forests	Increased coastal flooding; longer, hotter summers
Midwest	Higher lake and river temperatures alter fish species	Increasing agricultural productivity	Lowered lake and river levels, hotter summers
Great Plains	Warmer winters allow more invasive species	Initially, increasing grain production in moist regions	Worsened climatic extremes in spring/summer
West	Altered ecosystem types, and greater likelihood of fire	Rising snowline intensifies water problems	Shift toward warm season recreation, greater fire danger
Northwest	Stress to cold/cool water ecosystems and fish	Earlier winter runoff tightens water supplies	Shift to warm season recreation, coastal erosion

gathered at the Earth Summit[151] in Rio de Janeiro in 1992 to negotiate a series of environmental agreements, including the UNFCCC.[152] Its central objective is:

- Stabilization of the GHG 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.

Note that although stabilization is the objective, several important conditions were included. Increasing the chances that ecosystems can adapt naturally would seem to require that the stabilization level be relatively low and the rise to it slow. Similarly, ensuring that food production is sustained likely requires a slow adjustment process and a climate change that is quite modest as even small warming threatens low-latitude agriculture. Enabling economic development to proceed, however, would seem to mean that emissions cutbacks should be slow rather than rapid. This last provision seems to have dominated decision-making, slowing transition away from fossil fuels. However, the phrase "in a sustainable manner" could conceivably be interpreted in many ways, because climate change is likely to significantly interfere with fulfillment of the U.N.'s Millennium Development Goals, which were set up to help the poorer nations develop in a sustainable manner.[36,53] Other agreements reached at the Rio Earth Summit included the U.N. Convention on Biological Diversity; Agenda 21, which set goals for alleviating global poverty; and the Statement on Land Resources: Deforestation.[151]

Setting the objective as stabilizing GHG concentrations was a surrogate for stabilizing the climate. Because the climate is naturally variable and can be changed by volcanic eruptions and changes in solar radiation, achieving climate stabilization and confirming this would require statistical analyses of observations over several decades. In addition, because the oceans and ice create a large thermal inertia, the climatic conditions at any given time lag the forcing created by changes in atmospheric composition by a few decades. Indeed, were GHG concentrations to be stabilized now, and allowing for rapid atmospheric removal of aerosols, warming of roughly another 1 °C would occur over coming decades as the oceans warmed and snow and ice melted back further.

To keep the climate at near-present conditions, GHG concentrations need to be reduced to levels typical of several decades ago, not stabilized at present or some higher level. Indeed, because GHG emissions would be so low, sulfate aerosol loadings would also be down substantially, requiring even lower GHG concentrations because of the lack of the cooling influence of sulfates. Recognition that present climatic conditions are already threatening the GIS and Antarctic ice sheets, which would have catastrophic, if not dangerous consequences, is also indicating that the present climatic conditions are likely too warm to protect coastlines from significant inundation over coming decades and centuries. Getting GHG concentrations low enough to meet this additional requirement is even more challenging.[153] Quite clearly, the objective of the UNFCCC, which assumes stabilization at some higher concentration than the present will be acceptable, is going to be overwhelmed by increasing impacts, and so is going to have to be renegotiated, aiming to stabilize at a concentration below present levels.

Requirements for Stabilizing Atmospheric Composition

Achieving stabilization of GHG concentrations will only be possible by reducing emissions to match their removal rates by physical, chemical, and biological processes. Considering each species separately, the largest reductions in emissions will be required for those GHGs with the longest persistence times (e.g., CO_2, N_2O, CFCs, etc.), whereas smaller reductions will be required for gases (e.g., CH_4) with shorter persistence times. It is certainly reasonable, however, to consider the gases together, and then use the GWP as a way of accommodating greater cutbacks for gases with less expensive mitigation options and reduced cutbacks for gases with prohibitive costs for reducing emissions.

Stabilizing the CO_2 concentration, which is the primary cause of the increase in RF, must be a key part of any mitigation effort. Accomplishing this will require cutting emissions by approximately 80%. Because such a sharp cutback will take time, the CO_2 concentration will continue to rise to well above its current level of approximately 385 ppmv. Even the most optimistic of IPCC's SRES policy-free emissions scenarios results in the CO_2 concentration rising to over 500 ppmv (and effectively even higher because of the warming contributions of increases in the concentrations of other GHGs). Less optimistic scenarios are projected to lead to CO_2 concentrations from 700 to well over 1000 ppmv. As a result, returning atmospheric composition to a state compatible with the present or an earlier climate will likely require going to very near zero emissions for CO_2 and other long-lived gases.

An appreciation of the challenge can be understood by considering world population and per capita emissions. If the world population rises to 10 billion by 2100 and per capita emissions stay at approximately 1 tC/yr, approximately 800 PgC will be emitted during the 21st century (for comparison, the world's aboveground standing biomass is ~600 PgC). Such a release would increase the atmospheric CO_2 concentration by approximately 200 ppmv (assuming 50% remains airborne), leading to a CO_2 concentration roughly double the preindustrial concentration. Any rise in the per capita GHG emissions from those in the developing world would need to be offset by a cutback in or sequestering of emissions from the developed world. Because there will be approximately 6 times as many people in the developing world as in the developed world, each upward increment in per capita emissions in the developing world will require a cutback 6 times as large in the developed world. By a similar analysis, if average per capita emissions rise to 2 tC/yr, the

CO_2 concentration will exceed 700 ppmv (roughly double the concentration of the late 20th century).

Using carbon cycle models, IPCC (ref 11, chapter 3) provides quantitatively rigorous estimates for allowable emissions if the goal is to keep the CO_2 concentration from exceeding various levels from 450 to 1000 ppmv. Each of the cases requires that emissions start to be limited by 2050, with the 450 level requiring getting to near-zero emissions by that date. Given that a concentration of 1000 ppmv would result in global average temperatures comparable to values that in the past had greatly diminished ice sheets, implying sea level rise of tens of meters, the only real question about converting away from carbon-emitting technologies is how soon and how fast the world makes the changeover, because not doing so will lead to catastrophic impacts.

The UNFCCC, ratified by the United States and virtually all other nations, set a voluntary goal for developed nations of returning their emissions to 1990 levels by the year 2000. That goal was met by only a few nations and this happened for quite unique circumstances (e.g., the United Kingdom's switch from coal to natural gas from its new North Sea fields and Germany's reunification). Recognizing the limitations of voluntary efforts, the Kyoto Protocol was negotiated in 1997. It called for developed nations to reduce their net emissions to 5.2% below their 1990 level by the period 2008–2012. Negotiations led to different entities having different goals: Europe's goal was −8%; the U.S. goal was −7%; others such as Australia could even increase their emissions. Negotiations on details dragged on for 4 more years, following which approval by a sufficient number of nations was achieved (the United States did not sign and Australia has only recently agreed).

With the implementation phase of the Kyoto Protocol coming into force in 2005, permit systems and carbon markets have opened in Europe and regulatory and other steps are being taken to encourage efficiency in countries around the world. That so much contention (including U.S. rejection of the Protocol) has arisen from implementation of such a modest step (the equivalent, if continued through the 21st century with the United States joining in, of reducing projected world per capita mid-range emissions of ~2 tC/yr by only ~0.25 tC/yr), provides an indication of the challenges of reaching near-zero global emissions by 2100. But, to do nothing was deemed unacceptable by the 175 nations that have ratified the Protocol.

In looking to the next phase of the negotiations, the focus has come back to considering the impacts associated with various levels of warming (see, for example, ref 16, Technical Summary). Given the impacts of even moderate climate change and the potential for sudden shifts,[118,119] the nations of the European Union are suggesting that it is unacceptable to take the environmental risk associated with a warming of over 2 °C above preindustrial levels. The risks of most concern include significant sea level rise from melting of the ice sheets, and triggering of the natural carbon feedback as polar regions warm and additional CH_4 and CO_2 are released, causing further warming. Accounting for uncertainties in the climate sensitivity and carbon budget, ensuring a 50% chance of limiting global warming to less than 2 °C over the pre-industrial temperature is estimated to require keeping the CO_2 concentration below 450 ppmv.[154] Each increase of 50 ppmv above this level is estimated to lead to an additional warming of approximately 0.5 °C. Because the present CO_2 concentration of approximately 385 ppmv has led to a warming of approximately 0.8 °C even before equilibrium has been established and with sulfate aerosols moderating the warming influence, limiting the temperature rise to 2 °C will only be possible with early and very strong action.

The situation is actually more serious, because the combined warming influence of all GHGs is what matters. Accounting for the warming influences of CH_4, N_2O, and the other GHGs, the CO_2-equivalent concentration is already approximately 450 ppmv—it is only the cooling influence of the sulfate aerosols (roughly equivalent to reducing the CO_2-equivalent concentration by 70 ppmv) that is keeping the warming influence from exceeding the proposed limit. Because the loading of sulfate aerosols would quickly and sharply drop as the emissions of CO_2 from coal-fired power plants are reduced, keeping the CO_2-equivalent concentration below 450 ppmv and the warming below 2 °C is thus becoming very problematic technically, as well as politically. Although it would be controversial and would mean continuation of human-induced acidification of precipitation and high loadings of particulate matter, along with the impacts on ecosystems and human health that these changes induce, sustaining the current level of SO_2 emissions for several decades (e.g., by sequestering the CO_2 emissions, but allowing continued emission of SO_2 at the current rate) might actually make sense as an approach to restraining future warming, especially if the sulfates can be maximized over ocean regions with their dark albedo and clouds that could be brightened by increasing the number of cloud condensation nuclei.

The situation is not, however, without at least some opportunity. Although most attention has been paid to the challenge of limiting CO_2 emissions, significant reductions in the CO_2-equivalent concentration can be achieved by limiting the emissions of the non-CO_2 GHGs. For gases with long atmospheric lifetimes, actions being taken to limit halocarbon emissions under the Montreal Protocol and subsequent amendments have already played an important role in limiting the warming influence of these gases, and further cutbacks in emissions lie ahead and will contribute further.[155] Rather ironically, it is turning out, early recognition that the CFC emissions were causing O_3 depletion to such a degree that their emissions had to be virtually eliminated occurred in time to limit what would have been their very significant warming influence; had there not been a depletion effect that led to the Montreal Protocol limiting halocarbon emissions, present and future warming would have been significantly greater. Further commitments to limit emissions of the CFC replacement compounds can play an important role in limiting the overall warming influence of GHGs.

Limiting the emissions of CH_4 and soot and reversing deforestation can also be very important, especially as these actions would have a very rapid diminishing influence on the RF's warming influence. Human-induced emissions from the agriculture, energy, and urban sectors, among others, have been central in causing an increase in the CH_4 concentration to over 150% above its preindustrial value. Because the lifetime of CH_4 in the atmosphere is only about 1 decade, reductions in CH_4 emissions, which can be done quite cost effectively, would lead to relatively rapid drops in its concentration. Such drops in concentration would be very important because, as indicated in Table 2, on a per unit mass basis, CH_4 is over 20 times as effective at enhancing the greenhouse effect than is CO_2.

Reducing soot emissions would also have a near-immediate effect because soot's atmospheric lifetime is at most 2 weeks. Because soot is a sign of inefficient combustion, reducing soot emissions can generally be done at low cost, thus limiting warming that occurs both directly because soot aerosols absorb solar radiation and indirectly because soot darkens snow and ice and that leads to faster melting and further warming. Because biomass carbon would remain sequestered, cutting back on deforestation and encouraging reforestation would also reduce the increment to RF (and help enhance biospheric sequestration because of the higher CO_2 concentration), while at the same time improving environmental quality and the supply of key ecological services.

Near-Term Approaches for Providing Energy Services while Releasing Less Carbon

Most of the public discussion has been about how best to decrease CO_2 emissions by increasing their cost—whether by tax, carbon permit, regulation, or other means. But taxes and permits do not assure that adequate alternative energy supplies will be developed. If the standard-of-living is indeed going to continue to improve, then the carbon-free sources of future energy need to be identified. To date, no leading nation has figured out how to provide the environmentally friendly energy services needed to maintain a high standard-of-living. Indeed, until the United States gets on a workable path towards such a future, no nation will be convinced it can be done or is worth attempting. And until then, the United States has a very weak ethical basis for expecting, much less demanding, that the developing nations take early action.

Quite a number of comprehensive proposals have been put forward that would greatly reduce U.S. emissions.[156–159] The most straightforward first step is to dramatically improve the efficiency of our energy use. Because energy has historically been inexpensive, energy efficiency is much lower than it can be on both the supply and demand sides of the equation. For example, the efficiency of coal-fired electric power plants in the United States is around 35%; by comparison, the efficiency in power plants in Denmark, where cogeneration is common, is typically over 65%. Efforts to close this gap by expanding use of cogeneration are already underway.[160] Dupont and other companies working with the Pew Center on Global Climate Change[161] have demonstrated that emissions can be cut back while production is increasing—and money can be made while doing this.

In homes, switching to compact fluorescent bulbs and efficient appliances can make a tremendous difference. In California, the per capita use of electricity was near the U.S. average into the 1970s, but it is now about half of the U.S. average as a result of measures the state has taken (e.g., high-efficiency appliances, building standards, motion detecting light switches, shading of windows from summer sunlight, etc.).[162] Many individuals are voluntarily paying a premium for green energy or putting solar cells on their home—and some states are encouraging this with tax incentives. The cost, which has until recently been high, is starting to come down as new technologies are leading to more efficient and easier to install solar cells. One company, Citizenre, is seeking funding to basically rent out the solar cells that one needs to power one's home, with the 25-yr rental rate set at about the amount paid today for conventionally generated electricity. With such offers, both the transactional and incremental economic costs involved in rooftop solar drop essentially to zero and large-scale adoption should follow rapidly.

Much greater changes are coming. Driven in large part by the EPA and the U.S. Green Building Council, LEED (Leadership in Energy and Environmental Design) standards have been set for buildings. With buildings currently responsible for over 40% of U.S. emissions, the American Association of Architects[163] has set a goal of sharply reducing, or even eliminating, the contributions of buildings to global warming by 2030. The initial steps involve improved building design and focus on lowering energy use. To make this effort cost-effective, one approach is to generate savings to compensate for the improvement costs by reducing time lost to building-related illnesses; this is achieved by promoting improved employee performance by upgrading lighting, airflow, and other aspects of employee workspaces that affect productivity. Basically, by considering the lifecycle costs of buildings (construction, operation, etc.) and employee performance, it appears that overall energy-related and environmental impacts can be substantially reduced.[164]

A recent report by McKinsey & Company Analysis,[165] updating a similar analysis made originally for an earlier report of the National Academy of Sciences,[166] finds that U.S. emissions could be reduced by approximately 30% using available technologies that have an economic payback of approximately 3 yr or less. As shown in Figure 13, the approaches to reducing emissions of CO_2 range from more efficient lighting, motors, and appliances to better insulation, windows, and controls. Although a higher price for carbon would likely speed adoption, many of these steps are cost-effective now. To push adoption, proposals are emerging to encourage the greening of homes, with homeowners repaying the loans over a few years from their savings in energy costs. Such programs would provide multiple benefits: save money for the homeowner, reduce climate changing emissions, provide local jobs, help the local economy, and enhance energy security by reducing energy imports.

In the transportation sector, savings are also readily achievable, and the greatly increased cost of gasoline will drive many of them. Consumers choosing higher mileage vehicles will start to make a difference, but new hybrid technologies will be very important. Switching over to hybrid-electric cars has significant potential to improve mileage while improving performance, and this will especially be the case with plug-in hybrids once battery life

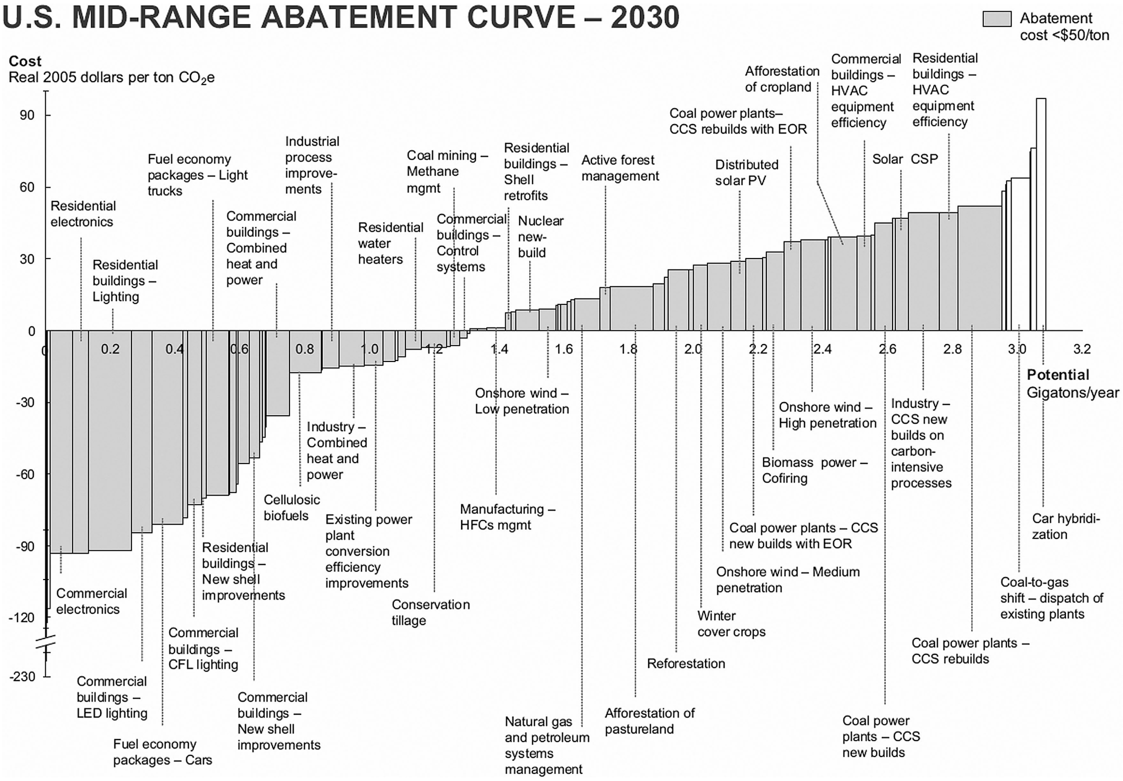

Figure 13. GHG abatement potential in the United States through 2030, showing the estimated cost in 2005 \$/t CO_2-equivalent abatement for mid-range estimates for implementation of a range of presently identified technologies and actions. Negative costs indicate that savings would occur; the width for each technology indicates the potential reductions in emissions. The shaded area extending out to 3 $GtCO_2$ equivalent/yr indicates that technologies having a cost of less than \$50/t of CO_2 equivalent are available to reduce current U.S. emissions by over 40%. With respect to the impact on the overall economy, the net cost of all of the actions indicated is near zero, with the savings matching the expenses. Reprinted with permission from McKinsey & Company Analysis and the Conference Board.[165] Copyright 2007 McKinsey & Company Analysis.

and cycling issues are resolved. Tests on such vehicles in Austin, Texas that recharge the batteries using nighttime wind power have a per-mile fuel cost equivalent to less than \$1.00/gal of gasoline.[167] With the present mix of electric generating plants (i.e., about half being coal-fired) and no improvement in automotive efficiency, switching over to electric-powered vehicles could reduce transportation-related carbon emissions because of reductions in the transport, refining, and distribution of gasoline, and, in effect, the substitution of natural gas for gasoline. Many other potential savings are also possible.

With the investor-based Carbon Disclosure Project[168] encouraging corporations to determine and then reduce their carbon footprints, with states and communities working in ways to do likewise, and with individuals becoming fired up, all sorts of approaches to savings are emerging. The traditional view has been that the economy is well tuned, and any savings of energy and emissions will generate extra costs. This appears, however, not to be the case; with inexpensive energy, the transactional costs of shifting away from traditional approaches were the major impediment. Now, with some leadership and incentives, there is significant potential to harvest the so-called "low-hanging fruit"—and what is proving interesting is that the low-hanging fruit seems to regrow as innovation is stimulated. In the years ahead, for example, light-emitting diodes (LEDs) will replace compact fluorescent lights, further reducing energy demand.

On the supply side, significant progress is also being made. That the production of wind-generating equipment and solar cells is running roughly 2 yr behind in a country with spare manufacturing capacity seems absurd. Strong leadership and a firm commitment to move away from carbon-emitting technologies are needed to convince businesses and the public to act. Certainly, the increasing U.S. population is raising the demand for energy services. However, the costs and incentives created by the oil embargoes of the 1970s helped to roughly double the rate of improvement of energy efficiency, and that was without a serious long-term commitment.

Long-Term Approaches for Providing Energy Services without Releasing Carbon

Although much can be accomplished by improving overall efficiency, taking advantage of existing and emerging technologies, and tightening regulatory standards, a key question remains about how best to replace fossil-fuel-derived energy over the long-term. That a long-term path forward can be found only comes with recognition that there will be no single fuel or energy source that will replace fossil fuels; instead a portfolio of approaches will be needed.[169] Such efforts will be challenging because they will require putting in place a different mixture of energy sources in different regions of the world.

In wet tropical regions, biomass and hydropower are likely to prove especially important. Brazil is already showing how sugar cane can be used to produce ethanol, and in the future cellulosic material is very likely to be used. Although an important research challenge, there is apparently no fundamental reason that "green" gasoline or other fuels could not be generated directly, thereby reducing the need to rework the existing fuel chain to deal with ethanol. Because of the efficiency of electric motors and because they recover energy in braking, hybrid-electric cars can be much more efficient than current vehicles. For electricity, hydroelectric systems can be combined with solar cells that are efficient in using the diffuse light coming through clouds. It may even be possible to beam electricity to the region from solar power satellites that collect the energy and microwave it to Earth.[170]

In the dry subtropical regions, wind and solar can be very effective, providing electricity for both buildings and transportation. The clear skies will allow incoming solar radiation to be redirected and concentrated by mirrors, creating the very high temperatures needed to generate electricity directly and to dissociate water to form hydrogen that could serve both for transportation and as an energy-storage medium. There are even suggestions that solar energy may be able to be used to harvest CO_2 from the air to generate liquid fuels.[171]

In the industrialized mid-latitudes, in addition to really pursuing energy efficiency and less energy-intensive lifestyles, there are a range of options, including wind, solar, biofuels, nuclear fission (and perhaps fusion in the longer term), and, in some locations, energy from tides and ocean currents.[172] Given the extensive infrastructure in place that relies on fossil fuels, retrofitting of coal-burning facilities with sequestration[39,173] will also be important if rapid reductions in CO_2 emissions are to be achieved.

This leaves as the real challenges what happens with China and India, where about one-third of the world population live. The answer is going to have to be all of the above—efficiency, renewables, fission and fusion, other new technologies, and more. Perhaps these are the two countries where plans should be developed to rely on solar-power satellites beaming energy down to them, or on approaches based on farming the ocean. Many ocean areas have low productivity that could be stimulated by drawing deeper, nutrient-laden waters to the surface and growing and harvesting biomass (fertilizing the oceans to sink carbon to the ocean depths seems to me a waste of a biofuel resource, even if it is potentially cost-effective and important to limit the growing CO_2 concentration). Pollution, costs, worker safety, land degradation, and energy security are already strong incentives for these countries to move toward greater efficiency and non-fossil-fuel-based energy—and both are doing so, although not rapidly enough. Were the developed world, and especially the United States, moving actively to limit emissions, I am convinced these nations would be doing so as well—likely manufacturing (and therefore interested in adopting) many of the products we would be using to improve our environmental quality and reduce the pace of climate change, impacts of which are likely to be devastating for these countries (e.g., disruption of the monsoon).

Although the technological potential is thus emerging, the challenge ahead is very large.[57] Assuming continuation of current trends, that is, carbon emissions growing at 1.5%/yr, primary energy consumption at 2%/yr, and gross world product at 3%/yr, Pacala and Socolow[174] developed 15 possible "wedges" to indicate the magnitude of what would be needed (see Table 5). Each wedge consists of a technology shift or limitation in emissions that would grow to a value of 1 PgC/yr over the next 50 yr. Accomplishing each would thus reduce total emissions over the 50-yr period by 25 PgC (equivalent to reducing the projected increase in the atmospheric CO_2 concentration in 50 yr by ~4–5 ppmv). Each wedge describes actions that would accelerate the historical rate of improvement of energy intensity, which is now approximately 1.5%/yr (on the basis of the rates of change given above) and which the Bush administration's strategy proposes to increase to 1.96%/yr. Not all wedges are independent or could be accomplished (technically or politically), and technology breakthroughs (such as developing the capability to convert cellulosic materials to ethanol, LED lighting, etc.) are likely to introduce new opportunities. What is important from their results is to get a sense of the magnitude of the challenge—and the importance of starting early and aggressively if substantial reductions in projected emissions are to be achieved.

The most recent IPCC Working Group III assessment[17] carried out an extensive review of approaches and technologies that could lead to reduced GHG emissions, looking also at their market and economic potential (which also accounts for social costs and benefits). To make sure their analyses were robust, they also looked both from the bottom-up (i.e., looking at the potential of specific technologies in specific situations) and from the top-down (so looking at the potential starting from the perspective of the global economy, and then subdividing into regions). Both approaches indicated "that there is substantial potential for the mitigation of global GHG emissions over the coming decades that could offset the projected growth of global emissions or reduce their emissions below current levels (high agreement, much evidence)" (ref 17, Summary for Policy-Makers). Taking actions that would put emissions on a path toward stabilization targets ranging from 445 to 710 ppmv CO_2-equivalents, the estimated costs in 2030 on a global basis range "between a 3% decrease in global GDP and a small increase, compared with the baseline, [although] regional costs may differ significantly from global averages."

Although the different approaches give rather similar results once the underlying assumptions have been reconciled,[175] significant controversy can arise because of how these numbers are presented, and this alone can create significant contention among decision-makers. To give an example, at a growth rate of 3%/yr, the global economy would roughly double by 2030 to near $80 trillion, so the maximum suggested 3% decrease in global GDP would be equivalent to: (1) reducing the GDP by about $2.5 trillion in 2030; (2) taking one extra year for the doubling of global GDP; or (3) reducing the annual growth rate from 3%/yr to 2.9%/yr from now to 2030. The first description makes the challenge of saving the world

Table 5. Potential approaches for reducing total carbon emissions by 25 PgC over an upcoming 50-yr period.

Option	Required Effort over 50 Yr
Increase energy efficiency and conservation	
1. Efficient vehicles	Increase the fuel economy for 2 billion cars from 30 to 60 mi/gal (or the same number of vehicles from 20 to 30 mi/gal)
2. Reduce use of vehicles	Decrease average car travel for 2 billion cars from 10,000 to 5,000 miles per year, substituting mass transit, telecommuting, and living closer to work
3. Efficient buildings	Reduce the carbon footprint of buildings by 25% by improving efficiency of lighting, appliances, computing machinery, etc.
4. Increase efficiency of baseload coal-fired power plants	Increase efficiency of all coal-fired power plants (roughly 1060 GW[a] in 1999) from less than 40 to 60% through more efficient design and cogeneration
Modify use of fossil fuels	
5. Shift from coal to natural gas for baseload power	Replace 1400 GW of 50% efficient coal-fired power plants with natural gas-based power (equivalent to 4 times current natural gas production) without forcing increased carbon emission in other sectors
6. Capture CO_2 emissions at baseload power plants	Introduce carbon capture and storage (CCS) at 800 GW of coal or 1600 GW of natural gas, sequestering the captured CO_2 underground or in the deep ocean or sediments
7. Capture CO_2 at hydrogen production plants	Use CCS at prospective plants producing 250 MtH_2/yr[b] from coal plants or 500 MtH_2/yr from natural gas (present production is 40 MtH_2/yr)
8. Capture CO_2 at coal-to-synfuels plants	Use CCS at prospective synfuels plants producing 30 million barrels of oil per day from coal (synfuels lead to greater emissions than does oil)
Expand alternative sources of energy	
9. Build nuclear instead of coal plants	Add 700 GW (about twice the capacity in 2004)
10. Build wind instead of coal plants	Add 2 million 1-MW[c]-peak windmills (about 50 times the capacity in 2004), requiring shared or exclusive use of about 30 million hectares
11. Build solar photovoltaics (PV) instead of coal plants	Add 2000 GW peak PV (about 700 times the capacity in 2004), occupying about 2 million hectares (including on roofs)
12. Substitute wind generated H_2 for gasoline in hybrid cars	Add 4 million 1-MW-peak windmills (about 100 times 2004 capacity)
13. Substitute biomass-derived fuels for fossil fuel	Requires 100 times the 2004 production of Brazil or the United States and use of 250 million hectares (about one-sixth world cropland), thus potentially limiting food production and/or impacting biodiversity as new areas are used
Restore forests and agricultural soils	
14. Reduce deforestation and increase reforestation and new plantations	Decrease tropical deforestation to zero from about 0.5 PgC/yr and establish 300 million hectares of new forest plantations (twice the 2004 rate)
15. Practice conservation tillage	Extend practice to all croplands (done on about 10% in 2004)

Notes: Adapted from Pacala and Socolow.[174] The approaches are grouped by broad category. [a]GW = gigawatt; [b]MtH_2/yr = megatons of hydrogen per year; [c]MW = megawatt.

from dangerous anthropogenic interference seem very expensive, especially because each year's GDP is similarly reduced, whereas the third description gives the impression that, globally, it is in the noise given the year-to-year swings in global growth rates. Although the range of potential impacts to the economy is slightly larger for 2050 and beyond (−5.5 to +1%), a time at which the economy would have nearly doubled again, there are some significant regional differences; as for the situation out to 2030, the numbers can be comparably expressed as being very large to being nearly negligible.

With the nature and impacts of climate change intensifying and with media and films giving the issue much more coverage, government leaders in many nations are pushing for much more aggressive action for the period after the Kyoto Protocol expires in 2012. Many are arguing that the potential impacts have become so serious that traditional cost-benefit analyses that discount the costs of future impacts to determine a present value for comparison with the costs of alternative energy technologies are not appropriate.[176] Ambassador John Ashton, the Special Representative for Climate Change of the United Kingdom's Foreign Secretary, commented recently that "fixing the problem will not cost us the Earth, whereas not fixing it will certainly cost us the Earth."[177] At the same time, critics such as Lomborg[178] argue that any money devoted to the issue would save more lives if spent on assistance to developing nations, focusing on short-term returns and assuming that safe water, human health, adequate food, climate change, and more are all distinct problems.

What is becoming increasingly recognized, however, is that all of the issues are really intertwined.[37,53] As a result, climate change needs to be considered as one of the issues that will increasingly affect the pursuit of sustainable development and achievement of the decadal Millennium Development Goals that have been set to try to improve the standard-of-living and well-being in the poorest nations. In support of the U.N. Commission on Sustainable Development's recent consideration of these issues, an expert panel on which I served, called for both *mitigation* to limit the warming influence and avoid catastrophic change and *adaptation* to assist in dealing with the climate change that is inevitable.[53]

An increasingly pressing question, however, is whether feasible mitigation and adaptation will be sufficient. Might the climate actually be changing so rapidly and persistently that some other human action might need to be taken to counterbalance the warming influence. Such approaches, often referred to as "geoengineering" to indicate that they are planetary efforts that would require substantial technical effort, have focused primarily on actions that could be taken to reduce the amount of solar radiation absorbed by the surface-troposphere system, leaving efforts to increase carbon uptake by reforestation or iron fertilization of the oceans to those focusing on mitigation. Because reducing solar radiation alone would not address all of the impacts, increasing attention is being devoted to determining whether both the climate and ocean acidification aspects of ongoing fossil-fuel use could be addressed by taking action to scavenge CO_2 from the atmosphere by accelerating oceanic uptake, enhancing the uptake by terrestrial vegetation, or initiating direct chemical removal.

Scoping out the effort required to counter the warming influence of GHGs gives an indication of the scale of the influence that these GHGs are having. As described in the supplemental data on geoengineering, possible approaches include using satellites to deflect solar radiation from striking the top of the atmosphere, or increasing the reflectivity of the Earth so that less energy is absorbed. Because some of these geoengineering approaches appear to be implementable at a reasonable cost, Wigley,[179] for example, has proposed adding geoengineering to the set of options for responding. A workshop last fall began exploring the cost and implementation challenges as well as the simpler questions of whether any of the approaches would actually work.[180] The types of thorny issues that arose included:

- How might such a project be undertaken on a global basis?
- How would it be decided how much might be done?
- What are the implications for future generations and how should their interests be considered, for once started, if geoengineering is then halted for any reason, the counterbalanced warming would occur relatively rapidly?

Although still contentious, an increasing number of groups are suggesting that a useful hedging strategy would be to sponsor research on geoengineering, doing as much as possible using models and other forms of analysis, and keeping any needed atmospheric testing as limited and reversible as possible.

MOVING TO A WORLD WITH A STABLE AND ACCEPTABLE CLIMATE

The evidence is overwhelming that human activities are changing atmospheric composition and that these changes are causing significant changes in the global climate—there is simply no other viable explanation. Given the current reliance on fossil fuels for most of the world's energy, further emissions are inevitable, and, without aggressive efforts that reduce emissions substantially over the next few decades, initiation of catastrophic changes seems very likely. We are likely already committed to more change than society and the environment can adapt to with low levels of cost and disruption. As indicated earlier, this problem was outlined to governments more than 2 decades ago,[181] and there has been little change in the main elements, even though details have been greatly elucidated. The time when slow and moderate action would be adequate has been wasted; aggressive action is now needed.

An international negotiating process is underway that would move beyond the Kyoto Protocol, which can only be considered a very modest first step. To an outside observer, the ongoing negotiations appear to be proceeding very slowly, looking a lot like a deadlocked labor negotiation. Neither the developed nor the developing nations seem willing to step forward and commit to taking strong action because, among other reasons, they each fear that the other side will simply accept their offer and ask for more. And so, negotiations are stretching out and the world's fever is rising at a faster and faster pace.

To resolve deadlocked labor negotiations, a mediator is often brought in to put on the table an agreement that gets done what must be done, spreading the pain and sacrifice in a way that neither side may be entirely happy with, but that both sides can and must accept. In my view, this is what needs to be said, and accepted:

On Behalf of the Global Environment. The climate is changing, glaciers and sea ice are melting and ice sheets are starting to deteriorate, sea level is rising at an accelerating rate, and the ranges of species that can move are shifting, whereas the populations of species that cannot are starting to drop. The rising CO_2 concentration is acidifying the oceans and threatening the base of the marine food chain that sustains humankind and other life. The pace of change is already too high and the world is headed towards dangerous and even catastrophic change. The nations of the world must rapidly shift to technologies that derive their energy services without severely disrupting the climate and the environment.

To the Leaders of the Industrialized Nations. Even if the GHG emissions from the developing nations went to zero tomorrow, the rate at which your nations are emitting will cause warming to exceed dangerous levels later this century, having gained only a few decades by the actions of the developing world. The industrialized nations are going to have to change their energy source, no matter what. You need to move expeditiously, especially because you bear a special burden because of your dominant role in causing past changes in atmospheric composition.

To the Leaders of the Developing Nations. Even if GHG emissions from the industrialized nations went to zero tomorrow, the projected growth in developing nation emissions will cause warming to exceed dangerous levels later this century, having gained a few decades by the actions of the industrialized world. The developing nations are going to have to change their path, no matter what, and need to move expeditiously, albeit in a differentiated way that allows for some growth in CO_2 emissions for a brief period to allow for the economic development needed to raise the standard-of-living of your people.

There Is a Way to Do This—But Action Is Required Quickly. It will not be enough to slow emissions and stabilize at some higher CO_2 concentration. Emissions must be cut so that the peak concentration is kept as low as possible and then emissions will need to be cut further so that GHG concentrations return to near or even below their current values. Government negotiators will have to agree on a combination of national and international regulations, taxes, permits, and incentives to make this happen. To save the Earth we share, action must be taken urgently:

- The industrialized nations must get on a path that reduces their collective GHG emissions by approximately 80% by 2050, and the path must continue to essentially zero emissions in the few decades thereafter. Limiting the emissions of all GHGs will be less expensive than focusing on just CO_2 emissions,[182] but reducing CO_2 emissions is absolutely critical, given their long lifetime.
- The developing nations need to join the process and demonstrate the seriousness of their commitment by: (1) quickly getting on a path to reduce their non-CO_2 emissions (particularly CH_4, soot, and CO_2 from deforestation) by approximately 80% by 2050, and (2) setting an aggressive goal for improving the efficiency of their economic activities so that increases in CO_2 emissions are kept to a minimum. Improving the efficiency of CO_2 use will be essential to remaining competitive with the improvements that will necessarily be taking place in the industrialized nations. Cutting back sharply on the non-CO_2 emissions is quite cost-effective and will contribute to improving air quality, water quality, waste treatment (both garbage and sewage are sources of CH_4), coal mine safety, energy efficiency, forest habitat, and the overall quality of life of your citizens. Of the warming emissions, soot is particularly important because its lifetime is short, it is a result of inefficient combustion, and it also darkens and therefore increases the rate of melting of mountain glaciers that are important to river flows in the Himalayas and other regions. CH_4 is important because the persistence of its increased concentration is only a few decades. And reducing deforestation keeps carbon out of the atmosphere.

  Seriously cutting back non-CO_2 emissions will provide the needed climate space to allow for the modest increase in CO_2 emissions over the next few decades. By the end of this period, your nations and the technologies should be sufficiently developed that it will be possible to afford cutting back on CO_2 emissions, joining the industrialized nations in heading toward zero emissions by the end of the century.
- Support for research, development, and demonstration of energy technologies must be very significantly increased.[183] In addition, there need to be agreements on sharing technology to accomplish the needed emissions reductions while providing sufficient energy. Cooperation should be possible because both the industrialized and the developing nations have strong incentives to achieve these emissions limitations—the alternative is catastrophe. It is past time to get on with these efforts. Industrialized nations need to demonstrate that a modern society can exist without emitting GHGs. Developing nations need to achieve the Millennium Development Goals and improve the lives of their people. Committing to this in writing will show the citizens of the developed nations that their efforts are being matched.
- Even with such sharp reductions in emissions, the climate will continue to change. Adaptation will be essential, and significant scientific and engineering efforts are going to be needed to limit adverse impacts. The developing nations have limited resources and capabilities for adaptation, so development needs to be done in ways that accommodate the coming changes in climate. The industrialized nations have extensive infrastructure at risk from sea level rise and they need to start planning for protection or retreat. For all, limits to water resources and the increased risks from floods and droughts merit special attention.
- Because these actions are nonetheless likely to allow global average temperatures to rise to a level that would lead to very damaging, even devastating, impacts (e.g., major deterioration of GIS or WAIS), research should be started to explore geoengineering approaches for limiting the peak warming and resulting impacts over what, it can be hoped, will only be an interval of a few decades.

CONCLUSIONS

The evidence is overwhelming that combustion of coal, oil, and natural gas and, to a lesser extent, land-cover change and emissions of halocarbons are rapidly increasing the concentrations of GHGs in the atmosphere. Past emissions have initiated warming of approximately 0.1–0.2 °C per decade since the 1970s, leading to accelerated loss of snow cover and Arctic sea ice, more frequent occurrence of very heavy precipitation, intensification of severe storms, rising sea level, and shifts in the natural ranges of plants and animals. The 2007 assessments of the IPCC make clear that changes are occurring more rapidly than projected in their previous assessments.

To limit the most adverse consequences, society needs to shift away from energy technologies that release CO_2, CH_4, and other GHGs—and do this over the next several decades. Global average warming above preindustrial levels is already approximately 0.8 °C, and present atmospheric levels of GHGs will, as equilibrium is established with current composition, lead to further warming of 0.5–1 °C. Warming of more than approximately 2 °C is very likely to cause severe impacts to key societal and environmental support systems. As a result, meeting the objective of the UNFCCC, namely to avoid "dangerous anthropogenic interference" with the climate, will require reducing emissions sharply by 2050 and to near zero by 2100.

If the world fails to act, future generations will inherit a world of accelerating climate change that requires them to devote substantial resources to adapting to the ever-changing environment. As Benjamin Franklin said: "It has been my opinion that he who receives an Estate from his ancestors is under some kind of obligation to transmit the same to their posterity." More recently, a local church bulletin board in Bethesda offered a starker view: "Life offers many choices; eternity only two." We can either work cooperatively to avoid catastrophe, or we will experience it.

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