CHAPTER 1

Introduction and Overview

INTRODUCTION

The Strategic Plan for the U.S. Climate Change Science Program (CCSP 2003) calls for the preparation of 21 synthesis and assessment products. Noting that "sound, comprehensive emissions scenarios are essential for comparative analysis of how climate might change in the future, as well as for analyses of mitigation and adaptation options," the Plan includes Product 2.1, *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations and Review of Integrated Scenario Development and Application*. This report presents the scenarios created in the scenario-development component of Product 2.1; the review of scenario methods is the subject of a separate report (CCSP 2007). The guidelines for the development of these scenarios are set forth in the *Final Prospectus for Synthesis and Assessment Product 2.1* (CCSP 2005). Consistent with the Prospectus and the nature of the climate change issue, these scenarios were developed using long-term models of global energy-agriculture-land-use-economy systems coupled to models of global atmospheric composition and radiation.

This report discusses the overall design of scenarios (Chapter 1); describes the key features of the participating models (Chapter 2); presents and compares the newly prepared scenarios (Chapters 3 and 4); and discusses emerging insights from these new scenarios, the uses and limitations of the scenarios, and avenues for further research (Chapter 5). Scenario details are available in a separate data archive.

The scenarios in this report are intended as one of many inputs to public and private discussions regarding climate change and what to do about it, and they may also serve as a point of departure for further Climate Change Science Program (CCSP) and other analyses that might inform these discussions in the future. The possible users of these scenarios are many and diverse. They include climate modelers and the science community; those involved in national public policy formulation; managers of Federal research programs; state and local government officials who face decisions that might be affected by climate change and mitigation measures; and individual firms, non-governmental organizations, and members of the public. Such a varied clientele implies an equally diverse set of possible needs, and no single scenario research product can hope to fully satisfy all of these needs. The Prospectus for this research highlighted three particular areas in which the scenarios might provide valuable insights:

- ***Emissions Trajectories.*** What emissions trajectories over time are consistent with meeting the four stabilization levels, and what are the key factors that shape them?
- ***Energy Systems.*** What energy system characteristics are consistent with each of the four alternative stabilization levels, and how might these characteristics differ among stabilization levels?
- ***Economic Implications.*** What are the possible economic consequences of meeting each of the four alternative stabilization levels?

It should be emphasized that there are issues of climate change decision making that these scenarios do not address. For example, they were not designed for use in exploring the role of aerosols in climate change. Also, they lack the regional detail that may be desired for many aspects of local or regional decision-making.

In addition, the scenarios in this report do not constitute a cost-benefit analysis of climate policy. They focus exclusively on the issues associated with reducing emissions to meet various stabilization levels; they do not consider the damages avoided through stabilization or ancillary benefits that could be realized by emissions reductions, such as reductions in local air pollution. Thus, although the scenarios should serve as a useful input to climate-related decision making, they address only one of several components of a benefit-cost analysis of climate policy.

Three analytical models, all meeting the criteria set forth in the Prospectus, were used in preparing the new scenarios. As also directed in the Prospectus, fifteen scenarios are presented in this document, five from each of the three modeling groups. First, each group produced a unique reference scenario based on the assumption that no climate policy would be implemented either nationally or globally beyond the current set of policies in place (e.g., the Kyoto Protocol and the President's greenhouse gas emissions intensity target for the U.S.). These reference scenarios were developed independently by the modeling groups, so they provide three separate visions of how the future might unfold across the globe over the 21st century without additional climate policies.[1]

Each group then produced four additional stabilization scenarios, which are departures from each group's reference scenario. The Prospectus specified that stabilization levels, common across the groups, be defined in terms of the total long-term radiative impact of the suite of greenhouse gases (GHGs) that includes carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). This radiative impact is expressed in terms of radiative forcing associated with increases from preindustrial concentrations of this suite of GHGs (Box 1.1).

Although stabilization is defined in terms of radiative forcing, the stabilization levels were constructed so that the resulting CO_2 concentrations, after accounting for radiative forcing from the non-CO_2 GHGs, would be roughly 450 parts per million by volume (ppmv), 550 ppmv, 650 ppmv, and 750 ppmv. The radiative forcing limits therefore are higher than the forcing from CO_2 alone at these concentrations. Based on this requirement, the four stabilization levels were chosen as 3.4 watts per meter squared (W/m^2) (Level 1), 4.7 W/m^2 (Level 2), 5.8 W/m^2 (Level 3), and 6.7 W/m^2 (Level 4). In comparison, radiative forcing relative to preindustrial levels for this suite of gases stood at roughly 2.1 W/m^2 in 1998. Details of these stabilization assumptions are elaborated in Section 1.3 and Chapter 4.

The production of emissions scenarios consistent with these stabilization goals required analysis beyond the study of the emissions themselves because of physical, chemical, and biological feedbacks within the Earth system. Scenarios focused only on emissions of GHGs and other substances generated by human activity (anthropogenic sources) can rely exclusively on energy-agriculture-economic models that represent human activity and the emissions

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[1] Although there are many reasons to expect that the three reference scenarios would be different, it is worth noting that the modeling groups met periodically during the development of the scenarios to review progress and to exchange information. Thus, while not adhering to any formal protocol of standardization, the three reference scenarios are not entirely independent.

that result. However, relating emissions paths to concentrations of GHGs in the atmosphere requires models that account for both anthropogenic and natural sources as well as the sinks for these substances.

Models that attempt to capture these complex interactions and feedbacks must, because of computational limits, use simplified representations of individual components of the Earth system. These simplified representations are typically designed to mimic the behavior of more complex models but cannot represent all of the elements of these systems. Thus, while the scenario research undertaken here uses models that represent both the anthropogenic sources (the global energy-industrial-agricultural economy) and the Earth system processes (ocean, atmosphere, and terrestrial systems), it is not intended to supplant detailed analysis of these systems using full scale, state-of-the-art models and analytic techniques. Rather, these scenarios provide a common point of departure for more complex analyses of individual components of the Earth system as it is affected by human activity. These might include detailed studies of sub-components of the energy sector, regional scenarios of climate change using three-dimensional general circulation models (GCMs) and further downscaling techniques, and assessment of the implications of climate change under various stabilization goals for economic activity and natural ecosystems.

The remainder of this chapter is organized into four sections. Section 1.2 provides an overview of scientific aspects of the climate issue as background for interpretation of these scenarios. Section 1.3 then presents the research design with a focus on the characteristics of the stabilization scenarios to be investigated in Chapter 4. Section 1.4 briefly discusses how scenarios of this type have been used to examine the climate change issue and the intended uses and limits of the new scenarios, focusing on interpretation of these scenarios under conditions of uncertainty. Section 1.5 provides a guide to the structure of the remaining chapters.

BACKGROUND: HUMAN ACTIVITIES, EMISSIONS, CONCENTRATIONS, AND CLIMATE CHANGE

Materials that influence the Earth's radiation balance come in various forms, and most have natural as well as anthropogenic sources. Some are gases which remain in the atmosphere from days to millennia, trapping heat. They are known as GHGs because, while transparent to incoming short-wave radiation (the visible spectrum that people commonly perceive as light), they capture and reflect back to Earth long-wave radiation, thus increasing the temperature of the lower atmosphere. These naturally occurring GHGs, plus clouds and water vapor (the most important GHG of all), are responsible for creating a habitable climate on Earth. Without them, the average temperature at the Earth's surface would be colder than it is today by roughly 55°F (~30°C).

GHGs are not the only influences on the Earth's radiative balance. Other gases such as oxides of nitrogen (NO_x) have no direct greenhouse effect, but they are components of the atmospheric chemistry that determine the lifetime of some of the heat-trapping GHGs and are involved in the reactions that produce tropospheric ozone, another GHG. Aerosols (non-aqueous particles suspended in air) may have positive or negative effects, depending on their relative brightness. Some present a white surface and reflect the sun's energy back to space; others are black and absorb solar energy, adding to the solar warming of the atmosphere. Aerosols also have an indirect effect on climate in that they influence the character and lifetime of clouds, which have a strong influence on the radiation balance and on precipitation. Humans also alter the land surface, changing its reflective properties, and these changes can have climate consequences with effects most pronounced at a local scale (e.g., urban heat islands) and regional levels (e.g., large-scale changes in forest cover). In addition, the climate itself has positive and negative feedbacks, such as the decrease in global albedo that would result from melting land and sea ice or the potential release of GHGs, such as CH_4 from wetlands.

Climate policy concerns are driven by the fact that emissions from human activities (mainly combustion of fuels and biomass, industrial activities, and agriculture) are increasing the atmospheric concentrations of these substances. Climate policy discussions have focused heavily on CO_2, CH_4, N_2O, and a set of fluorine-containing industrial chemicals – SF_6 and two families of substances that do not exist naturally, hydrogenated halocarbons (including hydrochlorofluorocarbons [HCFCs] and HFCs)[2] and PFCs. Some of these substances remain in the atmosphere for decades (CH_4 and most HFCs), others for about 100 years (CO_2 and N_2O), and some for thousands of years (PFCs and SF_6).

Other naturally occurring substances whose levels have also been greatly enhanced by human activities remain in the atmosphere for days to months. With such short lifetimes, they are not well mixed in the atmosphere, so their effects have a regional pattern as well as global consequences. These substances include aerosols such as black carbon and other particulate matter; sulfur dioxide, which is the main precursor of the reflecting aerosols; and other gases such as volatile organic compounds, nitrogen dioxide, other oxides of nitrogen, and carbon monoxide. All are important components of atmospheric chemistry.

This suite of substances with different radiative potency and different lifetimes in the atmosphere presents a challenge in defining what is meant by atmospheric stabilization. Specification in terms of quantities of the substances themselves is problematic because there is no simple way to add them together in their natural units, such as tonnes or ppmv. Thus, a meaningful metric is needed to combine the effects of different GHGs.

One approach is to define stabilization in terms of some ultimate climate measure, such as the change in the global average temperature. One drawback of such measures is that they interject large uncertainties into the consideration of stabilization because the ultimate climate system response to added GHGs is uncertain. Climate models involve complex and uncertain interactions and feedbacks, such as increasing levels of water vapor, changes in reflective polar ice, cloud effects of aerosols, and changes in ocean circulation that determine the ocean's uptake of CO_2 and heat.

For the design of these scenarios, the Prospectus called for an intermediate, less uncertain measure of climate effect. The Prospectus directed that stabilization "be defined in terms of the radiative forcing resulting from the long-term combined effects of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)." Radiative forcing (Box 1.1) is a measure of the instantaneous imbalance in the radiative energy budget of the Earth's climate system (energy in versus energy out) resulting from an externally imposed perturbation such as increasing GHG concentrations. It is measured in terms of W/m^2 at the Earth's shell and a positive value means a warming influence. For these scenarios, radiative forcing is measured against the concentrations of the GHGs considered in this research in preindustrial times, taken to be 1750.

Figure 1.1 shows estimates of how increases in GHGs, aerosols, and other changes have influenced radiative forcing since 1850. The GHGs considered in these scenarios are collected in the left-most bar and together they have had the biggest effect, with CO_2 being the largest of this group. Increased tropospheric ozone has also had a substantial warming effect. The reduction in stratospheric ozone has had a slight cooling effect. Changes in aerosols have had both warming and cooling effects. Aerosol effects are highly uncertain because they depend on the nature of the particles; how the particles are distributed in the atmosphere; and the concentrations of the particles, which are not as well understood as the GHGs. Land-use change and its effect on the reflectivity of the Earth's surface, jet contrails and changes in high-level (cirrus) clouds, and the natural change in intensity of the sun have also had effects.

Another important aspect of the climate effects of these substances, not captured in the W/m^2

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[2] For simplicity, all hydrogenated halocarbons will be referred to as HFCs in the subsequent text. The greenhouse gas methyl chloroform is often also grouped along with HFCs and HCFCs.

BOX 1.1 Radiative Forcing

Most of the Sun's energy that reaches the Earth is absorbed by the oceans and land masses and radiated back into the atmosphere in the form of heat or infrared radiation. Some of this infrared energy is absorbed and re-radiated back to the Earth by atmospheric gases, including water vapor, CO_2, and other substances. As concentrations of GHGs increase, there are direct and indirect effects on the Earth's energy balance. The direct effect is often referred to as a radiative forcing, a subset of a more general set of phenomena referred to as climate forcings. The National Research Council (NRC 2005) offers the following set of definitions:

> *Factors that affect climate change are usefully separated into forcings and feedbacks. . . . A climate forcing is an energy imbalance imposed on the climate system either externally or by human activities. Examples include changes in solar energy output, volcanic emissions, deliberate land modification, or anthropogenic emissions of greenhouse gases, aerosols, and their precursors. A climate feedback is an internal climate process that amplifies or dampens the climate response to an initial forcing. An example is the increase in atmospheric water vapor that is triggered by an initial warming due to rising carbon dioxide (CO_2) concentrations, which then acts to amplify the warming through the greenhouse properties of water vapor. . . .*
>
> *Climate forcing: An energy imbalance imposed on the climate system either externally or by human activities.*
>
> - ***Direct radiative forcing:*** *A climate forcing that directly affects the radiative budget of the Earth's climate system; for example, added carbon dioxide (CO_2) absorbs and emits infrared radiation. Direct radiative forcing may be due to a change in concentration of radiatively active gases, a change in solar radiation reaching the Earth, or changes in surface albedo. Radiative forcing is reported in the climate change scientific literature as a change in energy flux at the tropopause, calculated in units of watts per square meter (W/m^2); model calculations typically report values in which the stratosphere was allowed to adjust thermally to the forcing under an assumption of fixed stratospheric dynamics.*
> - ***Indirect radiative forcing:*** *A climate forcing that creates a radiative imbalance by first altering climate system components (e.g., precipitation efficiency of clouds), which then almost immediately lead to changes in radiative fluxes. Examples include the effect of solar variability on stratospheric ozone and the modification of cloud properties by aerosols.*
> - ***Nonradiative forcing:*** *A climate forcing that creates an energy imbalance that does not immediately involve radiation. An example is the increasing evapotranspiration flux resulting from agricultural irrigation.*

For purposes of this report, the radiative forcing stabilization levels are defined in terms of the direct radiative forcing caused by increases from preindustrial concentrations of CO_2, CH_4, N_2O, PFCs, HFCs, and SF_6. The indirect radiative effects are not included in calculating whether the radiative forcing stabilization level levels are met, nor are the direct radiative effects (positive or negative) of other substances such as ozone, CFCs, or aerosols, although emissions of these substances and their radiative and climatic effects are part of these integrated system models.

measure, is the persistence of their influence on the radiative balance – a characteristic discussed in Box 1.2. The W/m^2 measure of radiative forcing accounts for only the effect of a concentration in the atmosphere at a particular instant. The GHGs considered here have influences that may last from a decade or two (e.g., the influence of CH_4) to millennia, as noted earlier.

An important difference between GHGs and most of the other substances in Figure 1.1 is their long lifetimes. In contrast to GHGs,

BOX 1.2 Atmospheric Lifetimes of Greenhouse Gases

The atmospheric lifetime concept is more appropriate for CH_4, N_2O, HFCs, PFCs, and SF_6 than it is for CO_2. These non-CO_2 gases are destroyed via chemical processes after some time in the atmosphere. In contrast, CO_2 is constantly cycled between pools in the atmosphere, the surface layer of the ocean, and vegetation, so it is (for the most part) not destroyed. Very slow processes lead to some removal of carbon from oceans, vegetation, and the atmosphere as calcium carbonate. Also, over long geological periods, carbon from vegetation is stored as fossil fuels, which is a permanent removal process as long as the fossil fuels are not burned to produce energy.

Although the lifetime concept is not strictly appropriate for CO_2 (see Box 2.2 in Chapter 2), the molecules in a kilogram of emissions can be thought of as residing in the atmosphere, exercising their radiative effect, for around 100 years. This approximation allows a rough comparison with the other gases: CH_4 at 12 years, N_2O at 114 years, and SF_6 at 3200 years. HFCs are a family of gases with varying lifetimes from less than a year to over 200 years; those predominantly in use now have lifetimes mostly in the range of 10 to 50 years. Similarly, the PFCs have various lifetimes, ranging from 2,600 to 50,000 years.

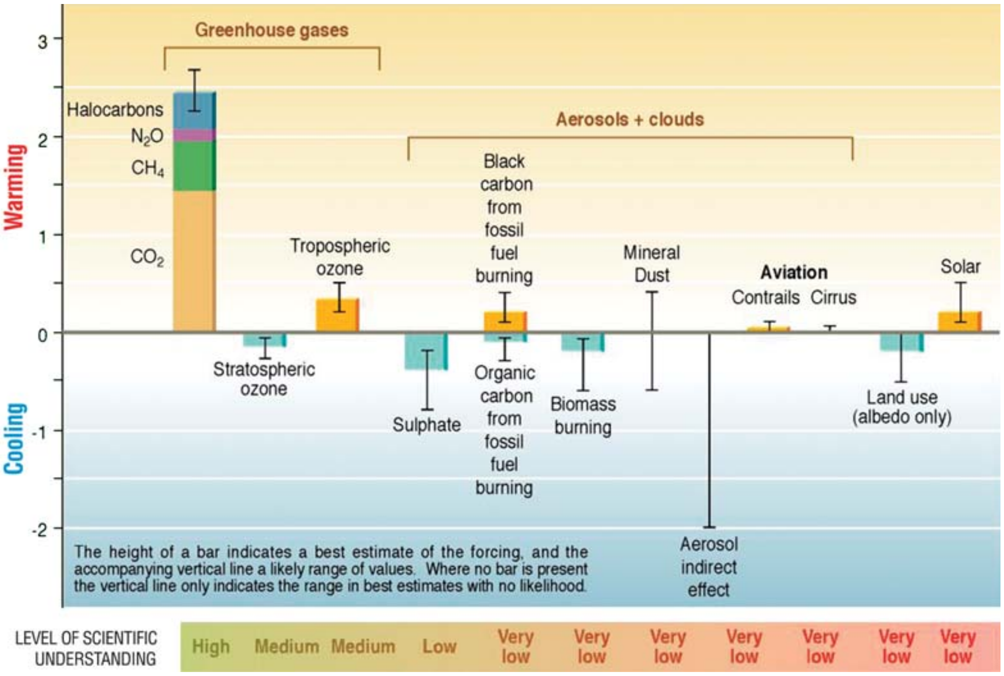
The lifetimes are not constant, as they depend to some degree on other Earth system processes. The lifetime of CH_4 is the most affected by the levels of other pollutants in the atmosphere.

aerosols remain in the atmosphere only for a few days to a couple of weeks. Once an aerosol emission source is eliminated, its effect on radiative forcing disappears very quickly. Tropospheric ozone lasts for a few months. Moreover, relatively short-lived substances are not well mixed in the atmosphere. Levels are very high near emissions sources and much lower in other parts of the world, so their climate effect has a different spatial pattern than that of long-lived substances. The regional differences and much shorter lifetimes of non-GHG substances make comparisons among them more difficult than among GHGs. The radiative effects of these substances also subject to more uncertainty, as shown in Figure 1.1.

RESEARCH DESIGN

The broad elements of the research design for these scenarios are set forth in the Prospectus, including (1) selection of models, (2) guidance to the modeling groups for development of a reference scenario, and (3) guidance for the development of stabilization scenarios.

Figure 1.1. Estimated Influences of Atmospheric Gases on Radiative Forcing, 1750-Present. Source: IPCC 2001



The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates with no likelihood.

Model Selection

The Prospectus set forth the model capabilities required to develop the desired stabilization scenarios. As stated in the Prospectus, participating models must:

1. Be global in scale
2. Be capable of producing global emissions totals for, at a minimum, CO_2, N_2O, CH_4, HFCs, PFCs, and SF_6 that may serve as inputs to global GCMs, such as the National Center for Atmospheric Research (NCAR) Community Climate System Model and the Geophysical Fluid Dynamics Laboratory climate model
3. Be capable of simulating the radiative forcing from CO_2, N_2O, CH_4, HFCs, PFCs, and SF_6
4. Represent multiple regions
5. Have technological resolution capable of distinguishing among major sources of primary energy (e.g., renewable energy, nuclear energy, biomass, oil, coal, and natural gas) as well as between fossil fuel technologies with and without CO_2 capture and storage (CCS) systems
6. Be economics based and capable of simulating macroeconomic cost implications of stabilization
7. Look forward to the end of the century or beyond.

In addition, the Prospectus required that the modeling groups have a track record of publications in professional, refereed journals, specifically in the use of their models for the analysis of long-term GHG emission scenarios.

Selection by these criteria led to the three models used in this research: (1) The Integrated Global Systems Model (IGSM) of the Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change; (2) the Model for Evaluating the Regional and Global Effects of GHG reduction policies (MERGE), developed jointly at Stanford University and the Electric Power Research Institute; and (3) the MiniCAM Model of the Joint Global Change Research Institute, which is a partnership between the Pacific Northwest National Laboratory and the University of Maryland.

Each of these models has been used extensively for climate change analysis. The roots of each extend back more than a decade, during which time features and details have been added. Analyses using each have appeared widely in peer-reviewed publications. The features of the models are described in Chapter 2 with references to publications and reports that provide complete documentation.

These models fall into a class that has come to be known as Integrated Assessment Models (IAMs). There are many ways to define IAMs and to characterize the motivations for developing them (IPCC 1996). A particularly appropriate definition of their primary purposes, provided by Parson and Fisher-Vanden (1997), is "evaluating potential responses to climate change, structuring knowledge and characterizing uncertainty, contributing to broad comparative risk assessments, and contributing to scientific research."

Development of Reference Scenarios

As required by the Prospectus, each participating modeling group first produced a reference scenario that assumes no policies specifically intended to address climate change beyond implementation of any existing policies to the end of their commitment periods, including the Kyoto Protocol and the policy of the U.S. to reduce greenhouse gas emissions intensity by 18% by 2012. For purposes of the reference scenario (and for each of the stabilization scenarios), it was assumed that these policies are successfully implemented through 2012 and their goals are achieved. (This assumption could only be approximated within the models because their time steps did not coincide exactly with the period from 2002 to 2012. However, such approximation is a minor consideration as slight differences in emissions for a few years have little impact on long term concentrations.) As directed by the Prospectus, after 2012 these existing climate policies expire and are not renewed or replaced. This is not a prediction or a best-judgment forecast, but a scenario designed to provide a clearly defined point of departure for illuminating the implications of alternative stabilization goals. The paths toward stabilization are implemented to start after 2012 as discussed further in the following section. The reference scenarios and assumptions underlying them are detailed in Chapter 3.

The reference scenarios serve two main purposes. First, they provide insight into how the world might evolve without additional efforts to constrain GHG emissions, given various assumptions about principal drivers of the economy, energy use, and emissions. These assumptions include those concerning population increase, land and labor productivity growth, technological options, and resource endowments. These forces govern the supply and demand for energy, industrial goods, and agricultural products – the production and consumption activities that lead to GHG emissions. The reference scenarios are a thought experiment in that they assume that even as emissions increase and climate changes nothing is done to reduce emissions. The specific levels of GHG emissions and concentrations are not predetermined but result from the combination of assumptions made.

Second, the reference scenarios serve as points of departure for analysis of the changes brought about by stabilization of radiative forcing, and the underlying assumptions have a large bearing on the characteristics of the stabilization scenarios. For example, all other things being equal, the lower the economic growth and the higher the availability and competitiveness of low-carbon energy technologies in the reference scenario, the lower will be the GHG emissions and the easier it will be to reach stabilization. On the other hand, if a reference scenario assumes that fossil fuels are abundant, and fossil fuel technologies will become cheaper over time while low- or zero-carbon alternatives remain expensive, the scenario will show consumers having little reason to conserve, adopt more efficient energy equipment, or switch to non-fossil sources. Under such a reference scenario, emissions will grow rapidly, and stronger economic incentives will be required to achieve stabilization.

Finally, the Prospectus specified that the modeling groups develop their reference scenarios independently[3], applying *meaningful* and *plausible* assumptions for key drivers. Similarities and differences among the reference scenarios are useful in illustrating the uncertainty inherent in long-run treatment of the climate challenge. At the same time, with only three participating models, the range of scenario assumptions produced does not span the full range of possibilities.

Development of the Stabilization Scenarios

Although the model groups were required to independently develop their modeling assumptions, the Prospectus specified that a common set of four stabilization targets be used across the participating models. Also, whereas much of the literature on atmospheric stabilization focuses on concentrations of CO_2 only, an important objective of this research was to expand the range of coverage to include other GHGs. Thus, the Prospectus required that the stabilization levels be defined in terms of the combined effects of CO_2, N_2O, CH_4, HFCs, PFCs, and SF_6. This suite of GHGs forms the basis for the U.S. GHG-intensity-reduction policy, announced by the President on February 14, 2002; it is the same set subject to control under the Kyoto Protocol. These gases are included in the left-most bar of Figure 1.1. The stabilization targets specified in the Prospectus explicitly omit the aerosol, ozone, land surface, and other effects shown in Figure 1.1, which may be influenced by measures taken to achieve the stabilization goal. Table 1.1 shows the change in concentration levels for these gases from 1750 to 2000. The left-most bar in Figure 1.1 shows radiative forcing of roughly 2.4 W/m^2 compared with a sum of 2.1 W/m^2 in Table 1.1. The difference exists because Figure 1.1 includes roughly 0.3 W/m^2 of forcing from chlorofluorocarbons (CFCs) not in Table 1.1. CFCs, important in the historical data, are already being phased out under the Montreal Protocol because of their stratospheric ozone-depleting properties, so they are not expected to be a significant source of additional increased forcing in the future. The HFCs, which do not contribute to stratospheric ozone depletion, were developed as substitutes

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[3] See footnote 1.

Table 1.1. Greenhouse Gas Concentrations and Forcing. Concentrations of GHGs have increased since 1750 (preindustrial), altering the radiative energy budget of the Earth's climate system.

	Preindustrial Concentration (1750)	Current Concentration (1998)	Contribution to Radiative Forcing, (W/m^2, 1750 to 1998)
CO_2	278 ppmv	365 ppmv	1.46
CH_4	700 ppbv	1745 ppbv	0.48
N_2O	270 ppbv	314 ppbv	0.15
HFCs, PFCs, SF_6	0	various	≈ 0.02
Total	—	—	≈ 2.1

Source: IPCC 2001.

for the CFCs, but are of concern because of their radiative properties. Table 1.2 shows the specific radiative forcing targets chosen.

As noted earlier, the Prospectus instructed that the stabilization levels be constructed so that the CO_2 concentrations resulting from stabilization of total radiative forcing, after accounting for radiative forcing from the non-CO_2 GHGs, would be roughly 450 ppmv, 550 ppmv, 650 ppmv, and 750 ppmv. This correspondence was achieved by (1) calculating the increased radiative forcing from CO_2 at each of these concentrations, (2) adding to that amount the radiative forcing from the non-CO_2 gases from 1750 to present, and (3) adding an estimate of the change in radiative forcing from the non-CO_2 GHGs under each of the stabilization levels. Each of the models represents the emissions and abatement opportunities of the non-CO_2 gases somewhat differently and takes a different approach to representation of the tradeoffs among them, so an exact correspondence between overall radiative forcing and CO_2 levels that would fit all three models was not possible.

The Prospectus also specified that, beyond the implementation of any existing policies, the stabilization scenarios should be based on universal participation by the world's nations. This guidance was implemented by assuming a climate regime with simultaneous global participation in emissions mitigation and in which the marginal costs of emission controls are equalized across countries and regions. Under this assumption, known as *where* flexibility, emissions will be reduced where it is cheapest to do so regardless of their geographical location. One important implication of this assumption is that the stabilization scenarios produce estimates of stabilization costs that are systematically lower than what might be expected in a world in which some major countries remain out of an emissions mitigation regime for an extended period of time, some economies use more costly regulatory mechanisms, or emissions mitigation regimes within nations are incomplete either in terms of GHG or sectoral coverage. On the other hand, possible ancillary benefits, tax interaction effects, or effects of carbon policies on technical change were not considered, which in

Table 1.2. Radiative Forcing Stabilization Levels (W/m^2) and Approximate CO_2 Concentrations (ppmv). The radiative forcing levels were constructed so that the CO_2 concentrations resulting from stabilization of total radiative forcing, after accounting for radiative forcing from the non-CO_2 GHGs, would be roughly 450 ppmv, 550 ppmv, 650 ppmv, and 750 ppmv.

	Total Radiative Forcing from GHGs (W/m^2)	Approximate Contribution to Radiative Forcing from non-CO_2 GHGs (W/m^2)	Approximate Contribution to Radiative Forcing from CO_2 (W/m^2)	Corresponding CO_2 Concentration (ppmv)
Level 1	3.4	0.8	2.6	450
Level 2	4.7	1.0	3.7	550
Level 3	5.8	1.3	4.5	650
Level 4	6.7	1.4	5.3	750
Year 1998	≈ 2.1	0.65	1.46	365
Preindustrial (1750)	—	—	—	278

some cases can lower costs. These issues are discussed in more detail in Chapter 4.

In addition, the Prospectus required that stabilization be defined as long term. Because of the inertia in the Earth system, largely attributable to the ocean, perturbations to the climate and atmosphere have effects for thousands of years. Economic models have little credibility over such timeframes. The Prospectus, therefore, instructed that the participating modeling groups report scenario information only up through 2100. Each group then had to address how to relate the level in 2100 to the long-term goal. The chosen approaches were generally similar, but with some differences in implementation. This and other details of the stabilization scenario design are addressed more completely in Chapter 4.

INTERPRETING SCENARIOS: USES, LIMITS, AND UNCERTAINTY

Emissions scenarios have proven to be useful aids to understanding climate change, and there is a long history of their use (see Box 1.3). Scenarios are descriptions of future conditions, often constructed by asking *what if* questions, such as what if events were to unfold in a particular way? Informal scenario analysis is part of almost all decision making. For example, families making decisions about big purchases, such as a car or a house, might plausibly construct a scenario in which changes in employment forces them to move. Scenarios addressing major public-policy questions perform the same purpose, helping decision makers and the public to understand the consequences of actions today in the light of plausible future developments.

Models assist in creating scenarios by showing how assumptions about key drivers, such as economic and population growth or policy op-

BOX 1.3 Emissions Scenarios and Climate Change

Emissions scenarios that describe future economic growth and energy use have been important tools for understanding the long-term consequences of climate change. They were used in assessments by the U.S. National Academy of Sciences in 1983 and by the Department of Energy in 1985 (NAS 1983, US DOE 1985). Previous emissions scenarios have evolved from simple projections that extrapolated a 1% per year increase in CO_2 emissions to scenarios that incorporate assumptions about population, economic growth, energy supply, and controls on GHG emissions and CFCs (Leggett et al. 1992, Pepper et al. 1992). They played an important role in the reports of the Intergovernmental Panel on Climate Change (IPCC 1991, IPCC 1992, IPCC 1996). The IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000) was the most recent major effort undertaken by the IPCC to expand and update earlier scenarios. This set of scenarios was based on storylines of alternative futures, updated with regard to the variables used in previous scenarios and with additional detail on technological change and land use.

The Energy Modeling Forum (EMF) has been an important venue for intercomparison of emissions scenarios and IAMs. The EMF, managed at Stanford University, includes participants from academic, government, and other modeling groups from around the world. It has served this role for the energy-modeling community since the 1970s. Individual EMF studies run over a course of about two years, with scenarios designed by the participants to provide insight into the behavior of the participating models. Scenarios are often published in the peer-reviewed literature. A recent study, EMF 21, focused on multi-gas stabilization scenarios (de la Chesnaye and Weyant 2006).

tions, lead to particular levels of GHG emissions. Model-based scenario analysis is designed to provide quantitative estimates of multiple outcomes and to assure consistency among them that is difficult to achieve without a formal structure. Thus, a main benefit of such model simulation of scenarios is that they ensure basic accounting identities: the quantity demanded of fuel is equal to the quantity supplied, imports in one region are balanced by exports from other regions, cumulative fuel used does not exceed estimates of the available resources, and expenditures for goods and services do not exceed income. The approach complements other ways of thinking about the future, ranging from formal uncertainty analysis to narratives. Also, such model analyses offer a set of macro-scenarios that users can build on, adding more detailed assumptions about variables and decisions of interest to them.

The possible users of these scenarios are many and diverse, and a single scenario research product cannot hope to provide the details needed by all potential users or to address their specific questions. Thus, these scenarios are an initial set offered to potential user communities. If successful, they will generate further questions and the demand for more detailed analysis, some of which might be satisfied by further scenario development from models like those used here, but more often demanding detail that can only be provided with other modeling and analysis techniques. As such, this effort is one step in an ongoing and iterative process of producing and refining climate-related scenarios and scenario tools.

Although the required long-term perspective demands scenarios that stretch into the distant future, any such scenarios carry with them considerable uncertainty. Inevitably, the future will hold surprises. Scientific advances will be made, new technologies will be developed, and the direction of the economy will change, making it necessary to reassess the issues examined here. The Prospectus called for development of a limited number of scenarios, without a formal treatment of likelihood or uncertainty, requiring as noted earlier, only that the modeling groups use assumptions that they believe to be *meaningful* and *plausible*. Formal uncertainty analysis has much to offer and could be a useful additional follow-on or complementary research task. Here, however, the range of outcomes from the different modeling groups help to illustrate, if incompletely, the range of possibilities.

The scenarios developed here take the best information available now and assess what it may mean for the future. Any such research, however, will necessarily be incomplete and will not foresee all possible future developments. The best planning must prepare for changes in course later as new information becomes available.

REPORT OUTLINE

Chapter 2 of this report provides an overview of the three models used in development of the scenarios. Chapter 3 describes the assumptions about key drivers in each of the models and reports the reference scenarios. Chapter 4 provides greater detail on the design of the stabilization scenarios and then presents these scenarios. Chapter 5 provides concluding observations, including possible avenues for additional research.

The chapters seek to show how the models and the assumptions used by the modeling groups to develop the scenarios differ and, to the degree possible, to relate where these differences matter and how they shape the scenarios. The models have their own respective areas of focus, and each offers its own reasonable representation of the world. The authors have distilled general conclusions common to the scenarios generated by the three modeling groups, while recognizing that other plausible representations could well lead to quite different scenarios. The scenarios are presented primarily in the figures. Associated with the report is a database with quantitative information available for those who wish to further analyze and use these scenarios. A description of the database, directions for use, and its location can be found in the appendix.