1. INTRODUCTION AND OVERVIEW

1.1. 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 results from the scenario development component of this product; the review of scenario methods is the subject of a separate report. The guidelines for the development of these scenarios are set forth in the *Final Prospectus for Synthesis and Assessment Product 2.1* ("the Prospectus"; CCSP 2005).

This report discusses the overall design of scenarios (this chapter), describes the key features of the participating models (Chapter 2), presents the new scenarios that have been prepared and reports the main results comparatively (Chapters 3 and 4), and reflects in conclusion on emerging insights from these new scenarios, the uses and limitations of these scenarios, and avenues for further research (Chapter 5). Scenario details are available in a separate data archive.[1]

As set forth in the Prospectus, the primary purpose of these scenarios is to serve as one of many inputs to decision-making for climate change. Consistent with the Prospectus and the nature of the climate change issue, these scenarios were developed using long-term, century-scale, models of the global energy-agriculture-land-use-economy systems coupled to models of global atmospheric compositions and radiation. The intended audience includes decision-makers and analysts who might benefit from enhanced understanding of the potential implications of stabilizing greenhouse gas concentrations at various levels. For example, technology planners such as those at the Climate Change Technology Program (CCTP) need to take account of the possible energy systems

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[1] This data archive will be made available upon completion of the final draft of this report.

implications of stabilization levels. The Prospectus for this product highlighted three areas in particular in which the scenarios might provide valuable insights:

1. Emissions Trajectories: What emissions trajectories over time are consistent with meeting the four stabilization levels, and what are the key factors that shape them?

2. Energy Systems: What energy system characteristics are consistent with each of the four alternative stabilization levels, and how do they differ from one another?

3. Economic Implications: What are the possible economic consequences of meeting the four alternative stabilization levels?

The scenarios may also serve as a point of departure for further CCSP and other analyses, such as exploring the implications for future climate or examining the costs and feasibility of mitigation and adaptation options. Finally, this effort will enhance the capabilities for future scenario analysis that might be conducted by the CCSP or related U.S. government offices such as the CCTP.

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. And they lack the level of detail that may be desired for local or regional decision-making, such as state or city planning or the decision-making of individual firms or members of the public.

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 teams. First, each team 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 teams, so they provide three separate visions of how the future might unfold across the globe over the 21st century without additional climate policies.[2]

Each team then produced four additional stabilization scenarios, which are departures from each team's reference case. The Prospectus specified that stabilization levels, common across the teams, 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, which is a measure of the direct heat-trapping by these six GHG's relative to preindustrial levels.

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[2] Although there are many reasons to expect that the three reference scenarios would be different, it is worth noting that the modeling teams 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.

Although stabilization is defined in terms of radiative forcing, the Prospectus also directed that stabilization levels be chosen to provide results easily compared with those from previous scenario exercises based only on CO_2 concentrations. Radiative forcing 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 ppmv, 550 ppmv, 650 ppmv, and 750 ppmv. Based on this requirement, the four stabilization levels were chosen as 3.4 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 pre-industrial levels for this suite of gases stood at roughly 2.2 W/m^2 in 2000. Details of these stabilization assumptions are elaborated in Section 4.

The production of emissions scenarios consistent with these stabilization goals required analysis beyond 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 project human activity and the emissions 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 exercise undertaken here uses models that represent both the anthropogenic sources (the global energy-industrial-agricultural economy) and the Earth system processes (ocean, atmosphere, 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's system as it is affected by human activity. These might include, for example, detailed studies of sub-components of the energy sector, regional projections of climate change using three-dimensional general circulation models and further downscaling techniques, and assessment of the implications for economic activity and natural ecosystems of climate change under various stabilization goals.

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 study design with a focus on the characteristics of the stabilization cases 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 and the associated data archive.

1.2. 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 for periods ranging from days to millennia, trapping heat while they are there. 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 from what it otherwise would be. These naturally occurring GHGs, plus clouds and the effect of 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 (31°C).

GHGs are not the only influences on the Earth's radiative balance. Other gases like 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 density 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 the melting land and sea ice or the potential release of GHGs such as methane from warming soils.

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)[3] and PFCs. Some of these substances remain in the atmosphere on the order of decades (CH_4, most HFCs), others for the order of 100 years (CO_2, N_2O) and some for thousands of years (PFCs, 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 and so their effects have a regional pattern as well as global consequences. These substances include aerosols such as black carbon and

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[3] 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.

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 gases themselves is problematic because there is no simple way to add them together in their natural units such as tons or parts per million by volume. Thus, a meaningful metric is needed in order 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 Arctic 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 direct heat-trapping (or, in case of cooling aerosols, light-reflecting) impact of a change in the concentration of such substances. It is constructed to represent the change in the net balance of the Earth with the sun (energy in *vs*. energy out) where the units are watts per square meter (W/m^2) of the Earth's shell. Generally referred to as radiative "forcing" (see Box 1.1), a positive value means a warming influence. This measure is widely used to compare the climate effects of different substances, although calculation of the net forcing of a group of gases, where there may be chemical interaction among them or saturation of the infrared spectrum, requires specialized models of atmospheric chemistry and radiation.

--- 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 these so-called greenhouse gases (GHGs) increase, the warming effect is augmented. The National Research Council (2005) defines direct radiative forcing as an effect on the climate system that directly affects the radiative budget of the Earth's climate which may result from a change in concentration of radiatively active gases, a change in solar radiation reaching the Earth, or changes in surface albedo. The increase is called radiative "forcing" and is typically measured in watts per square meter (W/m^2). Increases in radiative forcing influence global temperature by indirect effects and feedback from a variety of processes, most of which are subject to considerable uncertainty. Together, they affect, for example, the level of water vapor, the most important of the GHGs.

--- END BOX 1.1 ---

Figure 1.1 shows estimates of how increases in GHGs and aerosols and other changes have influenced radiative forcing since 1850. The main GHGs together have had the biggest effect, and CO_2 is the largest of these. 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 their concentrations, 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.

Figure 1.1: Estimated Influences of Atmospheric Gases on Radiative Forcing, 1850-present

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

--- BOX 1.2: ATMOSPHERIC LIFETIMES OF GREENHOUSE GASES ---

The atmospheric lifetime concept is more appropriate for CH_4, N_2O, HCFCs, 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 atmosphere as calcium carbonate; also, over long geological periods, carbon from vegetation is stored in fossil fuels, which is a permanent removal process as long as they are not burned to produce energy.

Although the lifetime concept is not strictly appropriate for CO_2 (see Box 2.2 in Chapter 2), for comparison purposes a CO_2 emission can be thought of as having a lifetime of about 120 years. (That is about two-thirds of a ton of CO_2 added to the atmosphere would no longer be there after 120 years, though some fraction would remain there for hundreds of 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. Hydrogenated halocarbons, such as HCFCs and 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.

--- END BOX 1.2 ---

An important difference between GHGs and most of the other substances in Figure 1.1 is their long lifetime. In contrast to GHGs, aerosols remain in the atmosphere only for a few days to a couple of weeks. Once an aerosol emission source is reduced, the effect on radiative forcing occurs 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.

1.3. Study Design

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

1.3.1. Model Selection

The Prospectus sets forth the types of analysis-model capabilities that would be required to carry out the desired stabilization analyses. 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 general circulation models (GCMs), such as the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM) and the Geophysical Fluid Dynamics Laboratory (GFDL) climate model
3. Be capable of simulating the radiative forcing from these GHGs
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 carbon capture and storage 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 teams 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 exercise: (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 MiniCAM Model of the Joint Global Change Research Institute, which is a partnership between the Pacific

Northwest National Laboratory and the University of Maryland; and (3) the Model for Evaluating the Regional and Global Effects [of greenhouse gas reduction policies] (MERGE), developed jointly at Stanford University and the Electric Power Research Institute.

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. Results of each have appeared widely in peer-reviewed publications. The features of the models are described in Chapter 2 with references to the 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). However, 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."

1.3.2. Development of Reference Scenarios

As required by the Prospectus, each participating modeling team first produced a "reference" scenario that assumes no policies specifically intended to address climate change beyond the implementation of any existing policies to their end of their commitment periods. The Kyoto Protocol and the policy of the United States to reduce greenhouse gas emissions intensity by 18% by 2012 are both existing policies. 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, this was not a serious problem given the focus of the current exercise.) As directed by the Prospectus, after 2012, all climate policies are assumed to expire and are assumed not to be renewed or replaced. It should be emphasized that this is not a prediction but a scenario designed to provide a clearly defined case to serve as a basis for illuminating the implications of alternative stabilization goals. As will be discussed in the following section, the paths toward stabilization are implemented to start after 2012. The reference scenarios and assumptions underlying them are discussed in more detail in Chapter 3.

The reference scenarios serve several purposes. First, they provide insight into how the world might evolve without additional efforts to constrain greenhouse gas 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 form of 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 is not predetermined but results from the combination of assumptions made.

Second, the reference scenarios serve as points of departure against which the changes required for stabilization may be compared, and the underlying assumptions also 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, fossil-fuel technologies will become cheaper over time, and low- or zero-carbon alternatives remain expensive, the scenario will show consumers having little reason to conserve, adopting more efficient energy-equipment, or switching to non-fossil sources. In 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 teams develop their reference scenarios independently, applying “plausible” and “meaningful” assumptions for key drivers.[4] 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 is unlikely to span the full range of possibilities.

1.3.3. Development of the Stabilization Scenarios

Although the model teams were required to independently develop their modeling assumptions, the Prospectus required 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 exercise 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. (Thus, the stabilization levels specified in the Prospectus explicitly omit the aerosol effects shown in Figure 1.1, which may be influenced by the measures taken to achieve the stabilization goal.) Table 1.1 shows the change in concentration levels for these gases from 1750 to the present and the estimated increase in radiative forcing. These are the data from Figure 1.1 in tabular form, with one important difference. Not shown in the table is the forcing from chlorofluorocarbons (CFCs) that have been historically significant. CFCs are already being phased out under the Montreal Protocol because of their stratospheric ozone-depleting properties, and so they are not expected to be a significant source of additional increased forcing in the future. In fact, the HFCs, which do not contribute to stratospheric ozone depletion, were developed as substitutes for the CFCs, but are of

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[4] See footnote 2.

concern because of their radiative properties. Table 1.2 shows the specific radiative forcing targets chosen.

Table 1.1. Greenhouse Gas Concentrations and Forcing

Table 1.2. Radiative Forcing Stabilization Levels (W/m^2) and Approximate CO_2 Concentrations (ppmv)

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 then (3) adding an initial estimate of the increases 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, however, and takes a different approach to representation of the tradeoffs among them, so it was not possible to for the teams to achieve the target levels exactly. Nevertheless the results are close enough that these new scenarios can be compared to previous work that has examined CO_2 targets ranging from 450 to 750 ppmv.

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 where the marginal costs of emission controls are equalized across countries and regions. The implications of this assumption, known as " where" flexibility, is that emissions will be reduced where it is cheapest to do so regardless of their geographical location. The potential impact of this assumption on the costs of emissions abatement will be discussed 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 would have little credibility over such time-frames. The Prospectus, therefore, instructed that the participating modeling teams 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.

1.4. 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: i.e, 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, like a car or a house, might plausibly construct a scenario in which changes in employment forces them to move. Scenarios developed for 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.

--- 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, USDOE 1985). Previous emissions scenarios have evolved from simple projections doubling CO_2 emissions in the atmosphere 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, 1992, 1996). The IPCC *Special Report on Emissions Scenarios* (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 story lines 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 and integrated assessment models. 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. Results are often published in the peer-reviewed literature. A recent study, EMF 21, focused on multi-gas stabilization scenarios (Weyant and de la Chesnaye 2005). The scenario exercise reported here adheres closely to the scenario protocol established in EMF 21.

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Models assist in creating scenarios by showing how assumptions about key drivers, such as economic and population growth or policy options, 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 resource available; 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-projections that users can build on, adding more detailed assumptions about variables and decisions of interest to them.

Possible users of emissions scenarios include climate modelers and the science community; those involved in national public policy formulation; managers of Federal research programs; individual firms, farms, and members of the public; as well as state and local government officials who face decisions that might be affected by climate change and mitigation measures. A single scenario exercise cannot hope to provide the details needed by all potential users or 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 the ongoing and iterative international 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 teams use assumptions that they believe to be “plausible” and “meaningful”. Formal uncertainty analysis has much to offer and could be a useful additional follow-on or complementary exercise. Here, however, the range of outcomes from the different modeling teams help to illustrate, if incompletely, the range of possibilities.

The scenarios developed here take the best information available now and assess what that may mean for the future. Any such exercise, however, will necessarily be incomplete and will not foresee all possible future developments. The best planning must, of course, prepare to change course later.

1.5. 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 reference scenario results. Chapter 4 provides greater detail on the design of the stabilization scenarios and presents their results. Chapter 5 provides concluding observations, including possible avenues for additional research.

The chapters seek to show how the models differ and, to the degree possible, relate where these differences matter and how they shape the results. The models have their own respective strengths and each offers its own reasonable representation of the world. The authors have been at pains to distill general conclusions common to the scenarios generated by the three modeling teams, while recognizing that other plausible representations could well lead to quite different results. The major results are presented primarily in the figures. Associated with the report is a database with the quantitative results 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.[5]

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[5] This data archive and associated appendix will be made available upon completion of the final draft of this report.

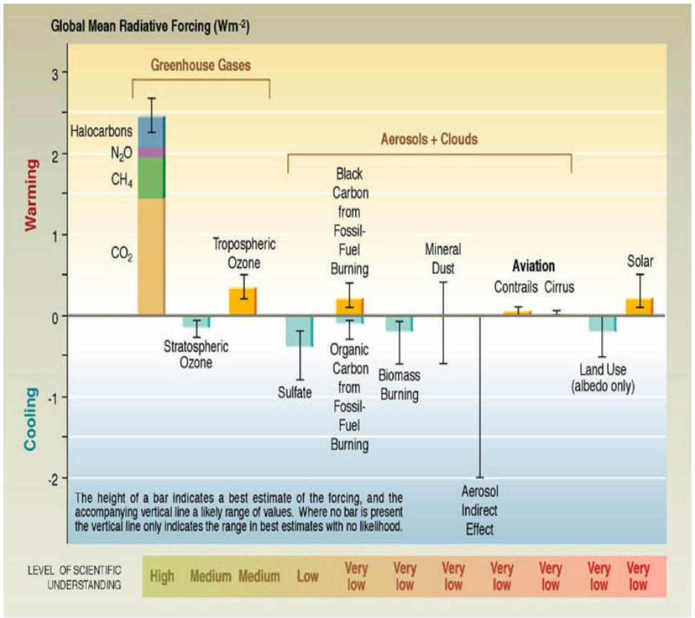
Table 1.1. Greenhouse Gas Concentrations and Forcing

	Preindustrial Concentration (1750)	Current Concentration (2000)	Increased Forcing W/m^2 (1750-2000)
CO_2	280 ppmv	369 ppmv	1.52
CH_4	700 ppbv	1760 ppbv	0.517
N_2O	270 ppbv	316 ppbv	0.153
HFCs	0	NA	0.005
PFCs	0	NA	0.014
SF_6	0	4 ppt	0.0025

Table 1.2. Radiative Forcing Stabilization Levels (W/m^2) and Approximate CO_2 Concentrations (ppmv)

	(1) From Preindustrial (1750)	(2) From Current (2000)	(3) Approximate CO_2 Level (2100)	(4) Increase in CO_2 from Preindustrial	(5) Increase in CO_2 from Current
Level 1	3.4	1.2	450	172	81
Level 2	4.7	2.5	550	272	181
Level 3	5.8	3.5	650	372	281
Level 4	6.7	4.5	750	472	381

Figure 1.1. Estimated Influences of Atmospheric Gases on Radiative Forcing, 1850-present



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.