Climate Projections from Well-Mixed Greenhouse Gas Stabilization Emission Scenarios

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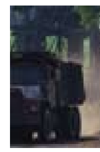
QUESTIONS AND ANSWERS

This chapter focuses on climate projections for the long-lived greenhouse gas stabilization emissions scenarios for the time period 2000 to 2100 that were produced under the U.S. Climate Change Science Program by an earlier Synthesis and Assessment Product, 2.1a (Clarke *et al.*, 2007). Those scenarios[1] are called "stabilization emissions scenarios" because they are constrained so that the atmospheric concentrations of the long-lived greenhouse gases level off, or stabilize, at predetermined levels by the end of the twenty-first century. Our overall goal in this Chapter is to assess these "stabilization emissions scenarios" and the climates they would project for the twenty-first century in the context of the most recent Intergovernmental Panel on Climate Change Report, the Fourth Assessment Report of Working Group I (IPCC, 2007a). The major conclusions are summarized below as the answers to the first four questions in our Prospectus, and then receive more detailed attention in the remainder of the Chapter:



Q1. Do the stabilization emissions scenarios produced by Synthesis and Assessment Product (SAP) 2.1a differ significantly from those used in the Fourth Assessment Report of the IPCC?

A1. While different in concept and method of derivation (stabilization *vs.* "storyline"—see Box 1.2 for details) the long-lived greenhouse gas stabilization emissions scenarios outlined in Synthesis and Assessment Product 2.1a fall among the principal storyline emissions scenarios studied in the Fourth Assessment Report of the IPCC. While each individual stabilization emissions scenario differs somewhat from the individual IPCC scenarios, they are generally encompassed by the IPCC envelope of estimated future emissions.

Q2. If the Synthesis and Assessment Product 2.1a emissions scenarios do fall within the envelope of emissions scenarios previously considered by the IPCC, can the existing IPCC climate simulations be used to estimate 50 to 100 year climate responses for the SAP 2.1a carbon dioxide emissions scenarios?

A2. Given the close agreement between the ranges of emissions scenarios, time evolution of global concentrations and associated radiative forcings[2], and global mean temperature responses in the two assessments, we conclude that the key global and regional climate features noted in the IPCC reports can indeed be used to estimate the 50 to 100 year climate responses for the SAP 2.1a scenarios.

[1] Scenarios are representations of the future development of emissions of a substance based on a coherent and internally consistent set of assumptions about the driving forces (such as population, socioeconomic development, technological change) and their key relationships.

[2] Radiative forcing is a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate, such as atmospheric composition or surface reflectivity, are altered. When radiative forcing is positive, the energy of the Earth-atmosphere system will ultimately increase, leading to a warming of the system. In contrast, for a negative radiative forcing, the energy will ultimately decrease, leading to a cooling of the system. For technical details, see Box 3.2.

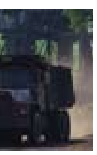
Q3. What would be the changes to the climate system under the scenarios being put forward by SAP 2.1a?

A3. The key climate changes resulting from the "stabilization emissions scenarios" should be quite similar to the key findings from Chapters 10 (Meehl *et al.*, 2007) and 11 (Christensen *et al.*, 2007) of the Fourth Assessment Report of the IPCC, which are listed in Box 2.1 in Section 2.7 and discussed in more detail in Appendix A. The simulations by the simple climate model used in this Chapter, as well as the comprehensive climate model[3] simulations in Chapter 10 of the Fourth Assessment Report of the IPCC all find increases in global-average surface air temperature throughout the twenty-first century; with the warming increasing roughly proportional to the increasing concentrations of long-lived greenhouse gases.

Q4. For the next 50 to 100 years, can the climate projections using the emissions scenarios from SAP 2.1a be distinguished from one another or from the scenarios recently studied by the IPCC?

A4. For the first 30 years there is little difference in the predicted global-average climate among either the principal IPCC scenarios or the SAP 2.1a stabilization emissions scenarios for the long-lived greenhouse gases. For the second half of the twenty-first century, global mean and certain robust regional properties predicted for the different IPCC emission scenarios and applicable to the SAP 2.1a scenarios are distinguishable from each other in magnitude (the greater the concentration of long-lived greenhouse gases, the greater the magnitude) though not in their qualitative features.

[3] A comprehensive climate model is a numerical representation of the climate based on the physical, chemical, and biological properties of its components and their interactions and feedback processes, which account for many of its known properties. Coupled Atmosphere-Ocean (-sea ice) General Circulation Models (AOGCMs) provide the current state-of-the-art representation of the physical climate system.



2.1 INTRODUCTION

Chapter 2 is focused on climate projections for the four long-lived greenhouse gas scenarios developed by an earlier report, Synthesis and Assessment Product 2.1a (SAP 2.1a) (Clarke *et al.*, 2007). Our work in this chapter involves two different types of models:

1. Three integrated assessment models[4] that were used in Synthesis and Assessment Product 2.1a to produce stabilization emissions scenarios for long-lived greenhouse gases;
2. A simplified global climate model, Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC)[5] that was used to simulate global levels of carbon dioxide, global-average radiative forcings for a variety of radiatively active[6] gases and particles, global-average surface temperature increases and global-average sea-level rise (due only to thermal expansion of water, not melting ice caps) for the four stabilization emissions scenarios.

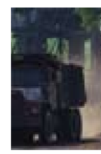
The second section, 2.2, introduces the stabilization emissions scenarios and the models that were used to generate them in Synthesis and Assessment Product 2.1a. The stabilization levels were defined in terms of the combined radiative forcing for carbon dioxide (CO_2) and the other long-lived greenhouse gases that are potentially controlled under the Kyoto Protocol (methane, nitrous oxide, a suite of halocarbons, and sulfur hexafluoride [SF_6]). These radiative forcing levels were chosen to be more or less equivalent to 450, 550, 650, and 750 parts per million (ppm) of carbon dioxide, and attainment was required within 100 to 200 years. For reference, preindustrial levels were approximately 280 ppm, and current levels of carbon dioxide are around 380 ppm.

Each integrated assessment model produced its own reference scenario, which is considered a "business as usual" or no-climate-policy scenario, as well as four stabilization emissions scenarios for long-lived greenhouse gas emissions that required a range of policy choices. The scenarios generated by each integrated assessment model were internally consistent, and each modeling group made independent choices in determining both their reference emissions, and their multi-gas policies required to achieve the specified stabilization levels. "All of the groups developed pathways to stabilization targets designed around economic principles. However, each group used somewhat different approaches to stabilization emissions scenario construction".

The third section, 2.3, introduces the simplified global climate model, MAGICC, which is used to generate the projections of carbon dioxide concentrations, radiative forcings due to the long-lived greenhouse gases, and global surface temperature increases for the four stabilization emissions scenarios introduced in the previous section 2.2. While the three integrated assessment models used in Synthesis and Assessment Product 2.1a each treated the cycling of carbon dioxide between the land, ocean and atmosphere in their own ways, in this study we use the carbon cycling treatment employed by MAGICC for all of the stabilization emissions scenarios. This provides a level playing field for all of the scenarios (see Wigley *et al.*, 2008 for a detailed discussion of this issue). We find that there is little difference between the two approaches.

MAGICC has four atmosphere boxes, one each over land and sea in each hemisphere, and two ocean boxes, one for each hemisphere. It consists of two highly simplified components: a climate component that has been adjusted to produce a global-average temperature change when the carbon dioxide concentration is doubled that is similar to the comprehensive climate models used in the IPCC Fourth As-

Preindustrial levels of carbon dioxide were approximately 280 parts per million, and current levels are around 380 parts per million. The stabilization emissions scenarios used here were constructed to be more or less equivalent to 450, 550, 650, and 750 parts per million of carbon dioxide.

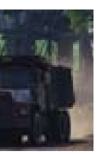


[4] Integrated assessment models are a framework of models, currently quite simplified, from the physical, biological, economic, and social sciences that interact among themselves in a consistent manner and can evaluate the status and the consequences of environmental change and the policy responses to it.

[5] MAGICC is a two-component numerical model consisting of a highly simplified representation of a climate model coupled with an equally simplified representation of the atmospheric composition of radiatively active gases and particles. This model is adjusted, based on the results of more complex climate models, to make representative predictions of global mean surface temperature and sea-level rise.

[6] "Radiatively active" indicates the ability of a substance to either absorb or emit sunlight or infrared radiation, thus changing the temperature of the atmosphere.

sessment Report, and a greenhouse gas and particle component that has also been adjusted to reproduce the global-average surface temperature and sea-level rise simulated by the same set of complex climate models for the various storyline emissions scenarios analyzed in the Fourth Assessment Report of the IPCC. A more detailed description of MAGICC is provided for the technical audience in Appendix B.



Projected warming in the twenty-first century shows scenario-independent geographical patterns similar to those observed over the past several decades.

The fourth section, 2.4, shows that the concentrations of carbon dioxide projected by MAGICC for the twelve stabilization emissions scenarios (three models, four stabilization levels each) from Synthesis and Assessment Product 2.1a fall among earlier projections of carbon dioxide concentrations for the three primary storyline emissions scenarios employed in the Fourth Assessment Report of the IPCC (IPCC, 2007a). Next, it is shown that the 12 time series of radiative forcings for the long-lived greenhouse gases potentially regulated by the Kyoto Protocol, again calculated by MAGICC, fall among the time series of radiative forcings for the twenty-first century previously calculated for the same gases with the three time series of principal storyline emissions scenarios used in the IPCC Fourth Assessment Report.

The fifth section, 2.5, deals with the contribution of the short-lived pollutants (ozone, elemental and organic carbon particles and sulfate particles) to radiative forcing calculations by MAGICC for the stabilization emissions scenarios. While short-lived pollutants were not explicitly included in determining the stabilization emissions scenarios for the long-lived greenhouse gases, two of the three integrated assessment models did produce emissions scenarios for the short-lived pollutants that were consistent with the energy and policy decisions required for stabilization of the long-lived greenhouse gas concentrations. To assign a full radiative forcing to the scenarios calculated for the third model, an intermediate IPCC emissions scenario for the short-lived pollutants was added to its stabilization emissions scenario for long-lived gases. Again we find that the total radiative forcing (short-lived and long-lived radiatively active gases and particles) calculated by MAGICC for the 12 stabilization emissions scenarios fall among the total radiative forcings calculated by MAGICC for the principal storyline emissions scenarios employed in the Fourth Assessment Report of the IPCC.

The sixth section, 2.6, compares two sets of global-average surface temperature time series: an average of those calculated by a broad collection of comprehensive global climate models for the three principal IPCC emissions scenarios and reported in Chapter 10 of the IPCC's Fourth Assessment Report (Meehl *et al.*, 2007), and those calculated by MAGICC for the 12 SAP 2.1a stabilization emissions scenarios and reported here. As was found for the carbon dioxide concentration and radiative forcing time series discussed previously, the global-average surface temperatures calculated for the 12 stabilization emissions scenarios by MAGICC are generally contained within those calculated for the three IPCC scenarios by comprehensive global climate models. The exceptions are for the lower bound stabilization emissions scenario that would require carbon dioxide not to exceed 450 ppm by year 2100 (remember that current levels of carbon dioxide already exceed 380 ppm). The global-average surface temperatures tend to fall below those for the lowest IPCC scenario, particularly in the second half of the twenty-first century.

The seventh and final section, 2.7, addresses the primary objective of Chapter 2, *"Climate Projections for SAP 2.1a Scenarios."* While the stabilization emissions scenarios used in this report were derived in a fundamentally different manner from the storyline emissions scenarios used in the IPCC Fourth Assessment Report, they are generally contained within the storyline emissions scenarios and show a similar evolution with time. Moreover, the same is true for the resulting radiative forcings and global-average surface temperatures that are calculated with a simple global climate model. Drawing on the conclusion from the latest IPCC Summary for Policy Makers (IPCC, 2007b) that "Projected warming in the twenty-first century shows scenario-independent geographical patterns similar to those observed over the past several decades," we conclude that the robust conclusions arrived at in the latest IPCC report apply equally well to the climate responses expected for the four stabilization emissions scenarios provided by Synthesis and Assessment Product 2.1a.

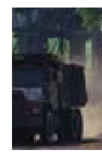
2.2 WELL-MIXED GREENHOUSE GAS EMISSIONS SCENARIOS FROM SAP 2.1A

The three integrated assessment models used in SAP 2.1a were EPPA (Paltsev *et al.*, 2005), MiniCAM (Kim *et al.*, 2006) and MERGE (Richels *et al.*, 2007). These models have different levels of complexity in their modeling of socioeconomic, energy, industry, transport, and land-use systems. With respect to emissions, EPPA and MiniCAM are similarly comprehensive, and produce output for emissions of the following: all the major greenhouse gases (carbon dioxide [CO_2], methane [CH_4], nitrous oxide [N_2O], and a suite of halocarbons and sulfur hexafluoride [SF_6]); sulfur dioxide (SO_2), black carbon (BC) and organic carbon (OC) particles and their precursors; and the reactive gases carbon monoxide (CO), nitrogen oxides (NOx) and volatile organic compounds (VOCs), which are important determinants of tropospheric ozone change. MERGE produces emissions output for the major greenhouse gases and idealized short-lived and long-lived halocarbons (characterized by HFC-134a and SF_6), but not for any other short-lived radiatively active gases and particles and their precursors.

The stabilization levels were defined in terms of the combined radiative forcing for CO_2 and for the other gases that are potentially controlled under the Kyoto Protocol (CH_4, N_2O, halocarbons, and SF_6). *All of the groups developed pathways to stabilization targets designed around economic principles. However, each group used somewhat different approaches to stabilization emission scenario construction.* (Reilly *et al.*, 1999; Manne and Richels, 2001; Sarofim *et al.*, 2005).

Consistent time series for the emissions of short-lived radiatively active gases and particles, carbon (both elemental and organic) and the precursors of sulfate particles and tropospheric ozone, were produced by the integrated assessment models to varying degrees, but the resulting radiative forcings were not part of the scenario definitions, nor were they considered as contributing to the radiative forcing targets. The stabilization levels for radiative forcing were constructed by determining the CO_2-only forcing associated with concentrations of 450, 550, 650, and 750 ppm and then adding additional radiative forcing to account for the other Kyoto Gases (0.8, 1.0, 1.2 and 1.4 W per m^2 respectively). The four stabilization levels are referred to as Level 1, Level 2, Level 3, and Level 4, where Level 1 requires the largest reduction in radiative forcing and is associated with CO_2 stabilization at roughly 450 ppm.

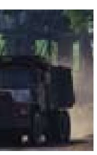
The robust conclusions arrived at in the latest IPCC report apply equally well to the climate responses expected for the four stabilization emission scenarios used here.



As SAP 2.1a (Clarke *et al.*, 2007) notes, "The three models display essentially the same relationship between greenhouse gas concentrations and radiative forcing, so the three reference scenarios also all exhibit higher radiative forcing, growing from roughly 2.2 W per m^2 above preindustrial in 2000 for the Kyoto Gases to between 6.4 W per m^2 and 8.6 W per m^2 in 2100". These differences arise primarily from differences in the assumptions underlying the reference scenarios, which lead to different reference emissions across the models.

The three models incorporate carbon cycles of different complexity, ranging from MERGE's neutral biosphere assumption to EPPA's coarse 3-D ocean. MiniCAM uses MAGICC to represent its carbon cycle. However, SAP 2.1a notes that the concentration of gases that reside in the atmosphere for long periods of time—decades to millennia—is more closely related to cumulative emissions than to annual emissions. In particular, this is true for CO_2, the gas responsible for the largest contribution to radiative forcing. This relationship can be seen for CO_2 in Figure 3.21 in SAP 2.1a (Clarke *et al.*, 2007), where cumulative emissions over the period

2000 to 2100, from the three reference scenarios and the 12 stabilization emission scenarios, are plotted against the CO_2 concentration in the year 2100. The plots for all three models lie on essentially the same line, indicating that despite considerable differences in representation of the processes that govern CO_2 uptake, the aggregate response to increased emissions is very similar. This basic linear relationship also holds for other long-lived gases, such as N_2O, SF_6, and the halocarbons."



The remainder of this chapter starts with the emissions scenarios generated by the three integrated assessment models in SAP 2.1a and examines their atmospheric composition, radiative forcing, and global-mean temperature. In the SAP 2.1a results, differences arise due to inter-model differences in the emissions for any given scenario, and differences between the models in their gas-cycle and climate components. Here we eliminate the second factor by using a single coupled gas-cycle/climate model to assess the scenarios—the MAGICC model as used in the IPCC Third Assessment Report (Cubasch and Meehl, 2001; Wigley and Raper, 2001). Many of the results given here have also been produced by the integrated assessment models, and some are described in SAP 2.1a. Using a single gas-cycle/climate model allows us to isolate differences arising from emissions scenario differences. Moreover, the MAGICC model was used previously to generate the carbon dioxide concentrations, Kyoto Gas[7] radiative forcing, and total radiative forcing associated with the IPCC scenarios B1, A1B, and A2 (described in Appendix A) that we compare with the current MAGICC calculations for the SAP 2.1a scenarios (Wigley *et al.*, 2008).

2.3 SIMPLIFIED GLOBAL CLIMATE MODEL (MAGICC)

MAGICC is a coupled gas-cycle/climate model that was used in the Third Assessment Report (Cubasch and Meehl, 2001; Wigley and Raper, 2001). A critical assessment focused on its skill in predicting global average sea-level rise is found in Chapter 10, Appendix 1 of the Working Group I contribution to the Fourth Assessment Report of the IPCC (Meehl *et al*. 2007).

The climate component is an energy-balance model with a one-dimensional, upwelling-diffusion ocean. For further details of models of this type, see Hoffert *et al.* (1980) and Harvey *et al.* (1997). In MAGICC, the globe is divided into land and ocean "boxes" in both hemispheres in order to account for different thermal inertias and climate sensitivities over land and ocean, and hemispheric and land/ocean differences in forcing for short-lived gases and particles such as tropospheric ozone and sulfate particles.

The climate model is coupled interactively with a series of gas-cycle models for CO_2, CH_4, N_2O, a suite of halocarbons, and SF_6. The carbon cycle model includes both CO_2 fertilization and temperature feedbacks, with model parameters tuned to give results consistent with the other carbon cycle models used in the Third Assessment Report (Kheshgi and Jain, 2003) and the Bern model (Joos *et al.*, 2001). For sulfate particles, both direct and indirect forcings are included using forcing/emissions relationships developed in Wigley (1989, 1991), with central estimates for 1990 forcing values.

The standard inputs to MAGICC are emissions of the various radiatively important gases and various climate model parameters. These parameters were tuned so that MAGICC was able to emulate results from a range of complex global climate models called Atmosphere-Ocean General Circulation Models (AOGCMs) in the Third Assessment Report (see Cubasch and Meehl, 2001). We use a value of 2.6°C equilibrium global-mean warming for a CO_2

[7] "Kyoto Gases" refers to those long-lived greenhouse gases covered by the Kyoto Protocol (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride).

doubling, the median of values for the above set of AOGCMs (see Appendix B for additional details).

2.4 LONG-LIVED GREENHOUSE GAS CONCENTRATIONS AND RADIATIVE FORCINGS

Figure 2.1 compares the concentrations of the primary greenhouse gas, CO_2, calculated by MAGICC for the 12 SAP 2.1a stabilization emission scenarios with earlier calculations of CO_2 concentrations for B1, A1B and A2, the principal storyline emission scenarios reported in Appendix II of the IPCC's Third Assessment Report (IPCC, 2001). For the first 20 years there is little difference among the 12 SAP 2.1a scenarios due to the long CO_2 lifetime, although the extreme Level 1 (L1) scenarios start to separate noticeably by 2030. By year 2100, CO_2 concentrations for the MiniCAM and EPPA Level 1 scenarios have converged on values close to 450 ppm. For MERGE, the 2100 value is lower. CO_2 concentrations for Levels 2 through 4 (L2 through L4) start to spread in the second half of the twenty-first century, but remain approximately bound between B1 and A1B all the way to 2100. EPPA now has the lowest CO_2 for Levels 2 through 4. The CO_2 levels for the lower bound Level 1 scenario, which requires immediate reductions in CO_2 emissions followed by ever increasing reductions (see SAP 2.1a for details), remain substantially below those for B1.

Next, Figure 2.2 considers where the radiative forcing due to increasing Kyoto greenhouse gases in the 12 SAP 2.1a stabilization emission scenarios, again calculated by MAGICC, are plotted with the Kyoto Gas radiative forcing values taken from Appendix II in the Third Assessment Report (IPCC, 2001) for the B1, A1B, and A2 storyline emission scenarios. The evolution of the 12 radiative forcing time series over the twenty-first century is very similar to that of CO_2, in Figure 2.1, which should not be surprising. However, there are some differences. The EPPA values undershoot the stabilization target for Levels 2 through 4 because they are on a trajectory where radiative forcing stabilizes some time after 2100, although emissions were calculated only to 2100 (Clarke *et al.*, 2007). For the Level 2, 3 and 4 stabilization cases, it is not possible to stabilize as early as 2100 (Wigley *et al.*, 1996). As we saw for carbon dioxide, the Kyoto Gas radiative forcing time series for stabilization Levels 2 through 4 are contained within the radiative forcings calculated for the IPCC scenarios, A1B and B1.

It should be noted that in general the three integrated assessment models hit their radiative forcing targets when they employ their own carbon cycle and atmosphere models. Thus, failure to hit these same radiative forcing targets when all three long-lived gases are run in MAGICC would seem to reflect the underlying uncertainties in the carbon cycles of the three integrated assessment models, which are known to be substantial.

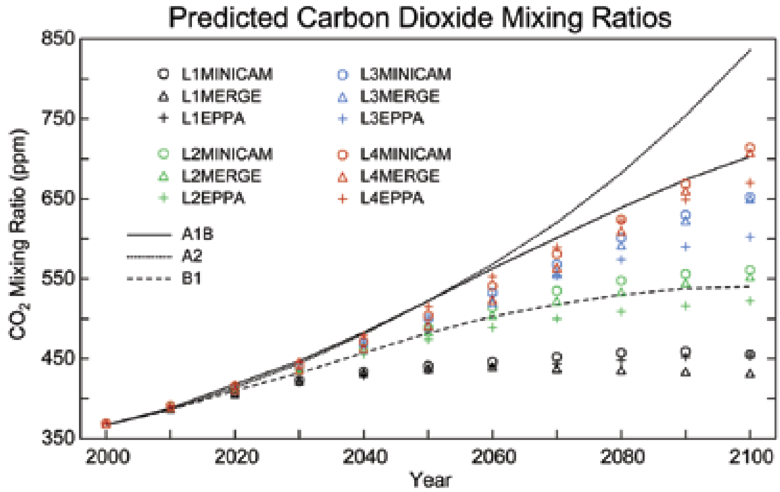
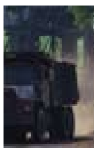


Figure 2.1 CO_2 concentrations (ppm) calculated by MAGICC for the 12 SAP 2.1a stabilization emission scenarios (Clarke *et al.*, 2007) plotted with calculations of CO_2 concentrations for the principal scenarios (B1, A1B and A2) reported in Appendix II of the Third Assessment Report (IPCC, 2001b).



For the first 20 years, there is little difference among the 12 Synthesized Assessment Product 2.1a scenarios, due to the long CO_2 lifetime.

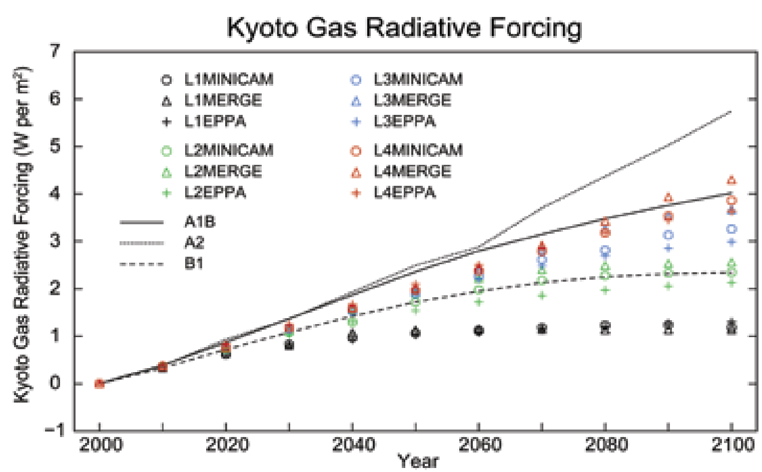
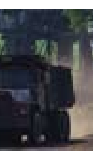


Figure 2.2 Kyoto Gas radiative forcing (W per m^2) for the SAP 2.1a scenarios (Clarke *et al.*, 2007), calculated by MAGICC, plotted with the Kyoto Gas Radiative Forcing values taken from Appendix II in the Third Assessment Report (IPCC, 2001) for the B1, A1B, and A2 SRES scenarios.

2.5 SHORT-LIVED GASES AND PARTICLES AND TOTAL RADIATIVE FORCING

The differences between the radiative forcing time evolution for the Kyoto Gases in Figure 2.2 and for all radiatively active gases and particles in Figure 2.3 are the result of differences among treatments of short-lived gases and particles.



While EPPA and MiniCAM produce emissions of sulfur dioxide (SO_2), elemental or black carbon and organic carbon particles and their precursors, and the key precursors of tropospheric ozone (CO, NOx and VOCs) as part of their model's climate projections, MERGE does not. To complete the MERGE scenarios, all four of its stabilization levels use the IPCC's B2 scenario of emissions for sulfur dioxide (Nakićenović and Swart, 2000) and assume that ozone precursor emissions remain constant. For all of the models, rather than use emissions for the elemental and organic particles, it is assumed that the elemental and organic particle radiative forcings track the sulfur dioxide emissions in each integrated assessment model's four stabilization emission scenarios. Therefore, while carbon dioxide emissions tend to track the IPCC scenarios, the emissions of short-lived gases and particles may be different, with the exception of sulfur dioxide emissions in MERGE.

Figure 2.3 compares the total radiative forcing calculated by MAGICC for the 12 SAP 2.1a scenarios, *i.e.*, the sum of Kyoto Gas forcings (Figure 2.2) plus forcings due to particles, tropospheric ozone, halocarbons controlled under the Montreal Protocol, and stratospheric ozone (Wigley *et al.*, 2008 and supplementary material referenced therein) with the total radiative forcing calculated by MAGICC for the B1, A1B, and A2 scenarios used in the IPCC Fourth Assessment Report (IPCC, 2007a). Again, just as for CO_2 and Kyoto Gas radiative forcing, the 12 total radiative forcing time series do not begin to separate noticeably before 2030.

Because of the assumptions made about the short-lived gases and particles, the MERGE Kyoto Gas and total forcings differ least. MiniCAM shows the largest differences with total forcings now significantly exceeding the stabilization targets for all four levels, primarily due to sharp decreases in sulfur dioxide emissions, which produce significant increases in total radiative forcing by 2100 (approximately 1 W per m^2). In the EPPA stabilization emission scenarios the changes in sulfur dioxide emissions are small, and most of the short-lived forcing comes from increased nitrogen oxide emissions that drive increases in tropospheric ozone and its positive radiative forcing (Wigley *et al.*, 2008). Remember that in SAP 2.1a, the stabilization targets were met using only the long-lived greenhouse gases.

The spread of stabilization forcings is significantly less for the Kyoto Gas forcings (which were used to define the stabilization targets) than for total forcing. Again the Level 1 total radiative forcings are generally below those of the B1 scenario, while the other Levels are bounded by B1 and A1B. However, in this case the Level 2 through 4 scenarios appear to track the B1 total radiative forcing out to 2060 to 2070 before the Level 3 and 4 scenarios start moving up to A1B. The differences between the radiative forcing time evolution for the Kyoto Gases in Figure 2.2 and for all radiatively active gases and particles in Figure 2.3 are the result of differences among treatments of short-lived gases and particles. The changes in global average surface temperatures that are driven by the total radiative forcing in Figure 2.3 are examined in the next section. We will continue to explore the potential impact of short-lived gases and particles on future global warming in considerable detail in Chapter 3.

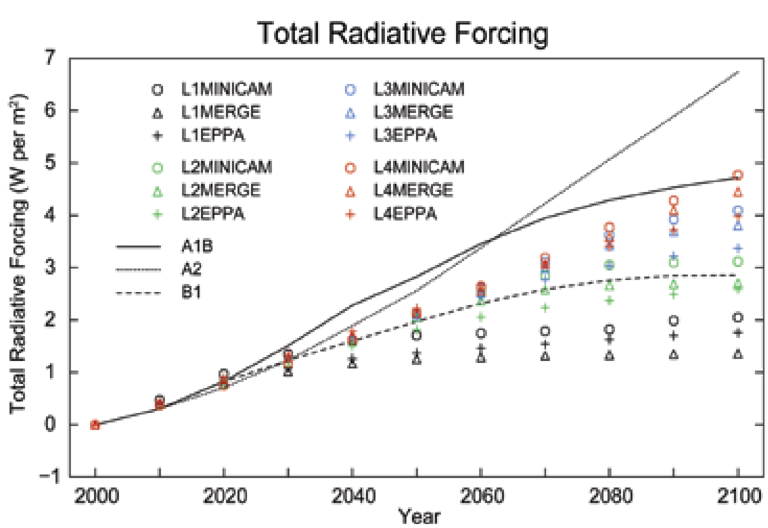


Figure 2.3 Total radiative forcing (W per m^2) calculated by MAGICC for the 12 SAP 2.1a scenarios (Clarke *et al.*, 2007) plotted with the total calculated by MAGICC for the B1, A1B, and A2 scenarios (IPCC, 2001).

2.6 SURFACE TEMPERATURE: MAGICC AND IPCC COMPARISONS

Figure 2.4 compares multi-model global-mean surface temperature changes reported in Chapter 10 of the IPCC's Fourth Assessment Report for the standard storyline emission scenarios, B1, A1B and A2, with global-mean surface temperature changes calculated by MAGICC for the 12 SAP 2.1a stabilization emission scenarios (Clarke *et al.*, 2007). As we might expect, the general behavior is quite similar to that observed for total radiative forcing. All scenarios are close through 2020. Levels 2 through 4 stay in close agreement out to around 2050. The Level 1 scenarios are lower than B1, except for MiniCAM, where there is enhanced warming out to 2050 due to the rapid reduction in SO_2 emissions (Wigley, 1991). The other three levels follow B1 closely out to 2050 and then remain between B1 and A1B out to 2100.

For Level 1 and Level 2 temperatures, the rate of increase has begun to slow appreciably by 2100, which suggests that global-mean temperature could be stabilized if the emissions scenarios produced by the three integrated assessment models for these two stabilization cases (corresponding to 450 and 550 ppm CO_2, but also including the assumed or modeled levels of short-lived gases and particles) were followed. This in turn depends on the economic and technological feasibility of the Level 1 and 2 scenarios for both the long-lived greenhouse gases and the short-lived gases and particles. However, the temperatures for the less extreme Level 3 and 4 stabilization emission scenarios (corresponding to 650 and 750 ppm CO_2) are still growing, particularly Level 4 MiniCAM. It should also be noted that their upper bound, the A1B model-mean surface temperature, is also still growing at 2100. The global mean surface temperature projections for the 12 SAP 2.1a stabilization emission scenarios are well bounded by the comprehensive climate model simulations for the A1B scenario reported in Chapter 10 of the IPCC Fourth Assessment Report.

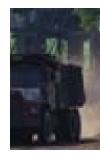
Table 2.1 displays the radiative forcings and temperature changes for the year 2100 for the 12 stabilization emissions scenarios from SAP 2.1a and for the three storyline emissions scenarios (A1B, A2 and B1) taken from the IPCC Fourth Assessment Report (IPCC, 2007a). These values were compiled from Figures 2.1 through 2.4.

2.7 CLIMATE PROJECTIONS FOR SAP 2.1A SCENARIOS

The 2.1a stabilization emissions scenarios (Clarke *et al.*, 2007) are derived in a fundamentally different manner from the development of the storyline emissions scenarios used in Fourth Assessment Report of the IPCC (IPCC, 2007a). However, we have shown in Section 2.4 that the 12 (three integrated assessment models, four stabilization emissions scenarios each) stabilization emissions scenarios reported in SAP 2.1a are contained within the range of the three principal storyline emissions scenarios used in the IPCC Assessment Report and show a similar evolution with time. The Kyoto Gases and total radiative forcings for those 12 emissions scenarios are generally constrained within the three principal scenarios used to make the climate projections discussed in Chapter 10 of the IPCC Fourth Assessment Report (Meehl *et al.*, 2007).

Section 2.6 shows that the global surface temperatures predicted for the SAP 2.1a scenarios over the twenty-first century by a simple coupled gas-cycle/climate model, MAGICC, fall within the range of the multi-model mean temperatures

Three integrated assessment models produced four stabilization emission scenarios each in Synthesized Assessment Product 2.1a. These 12 scenarios are generally contained within the range of the three principal storyline emission scenarios used in the IPCC Fourth Assessment Report and show a similar evolution with time.



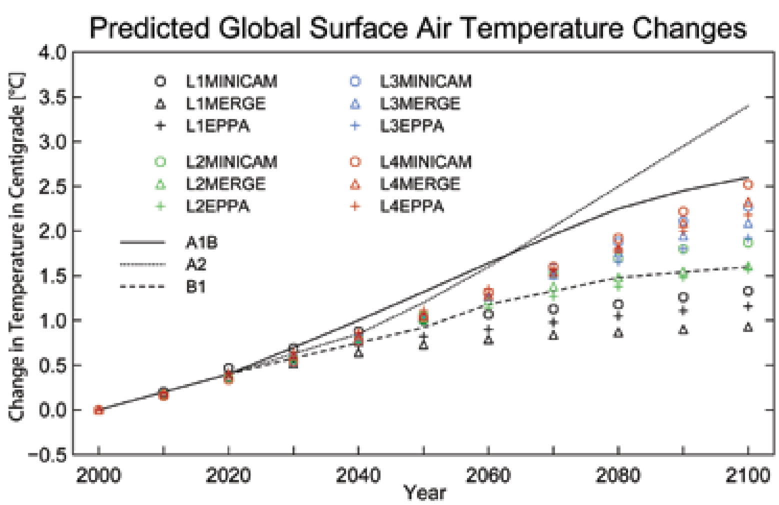


Figure 2.4 Multi-Atmosphere-Ocean General Circulation Model global-mean surface temperature changes (°C) reported in Chapter 10 of IPCC Fourth Assessment Report (Meehl *et al.*, 2007) for the standard storyline emissions scenarios B1, A1B, and A2 plotted with global-mean surface temperatures calculated by MAGICC for the 12 SAP 2.1a stabilization emissions scenarios (Clarke *et al.*, 2007).

We conclude that the robust conclusions arrived at in Chapter 10 of the Fourth Assessment Report regarding the predicted climate response to the three scenarios studied in the most detail in that report apply equally well to the climate responses expected for the four long-lived greenhouse gas stabilization emission scenarios provided by SAP 2.1a.

calculated with state-of-the-art comprehensive climate models for the three principal IPCC scenarios and reported in Chapter 10 (Meehl *et al*., 2007). In fact, the global average surface temperatures for Levels 2 through 4 scenarios all track the values reported by the IPCC for B1 out to 2050. The primary exceptions are all of the Level 1 scenarios beyond year 2050 which are significantly below B1. We also draw on the conclusion in the Summary for Policy Makers in the IPCC Fourth Assessment Report (IPCC, 2007b): "Projected warming in the twenty-first century shows scenario-independent geographical patterns similar to those observed over the past several decades." Figure 10.8 in Chapter 10 of the Fourth Assessment Report (Meehl *et al.*, 2007) also clearly shows that the geographical pattern of the robust climate features are preserved across scenarios employed in the IPCC projections for the twenty-first century climate, while the magnitude of the warming increases with the magnitude of the radiative forcing and with increases in the concentration of the long-lived greenhouse gases.

We conclude that the robust conclusions arrived at in Chapter 10 of the Fourth Assessment Report (Meehl *et al*., 2007) regarding the predicted climate response to the three scenarios studied in the most detail in that Report, (B1, A1, and A1B) apply equally well to the climate responses expected for the four long-lived greenhouse gas stabilization emission scenarios (three realizations of each) provided by SAP 2.1a (Clarke *et al*., 2007). These robust conclusions are highlighted in Box 2.1 below and further discussed in Appendix A.

At this time, we also introduce in Box 2.2 our general approach to treating uncertainty in this document. Since much of this report deals with ranges of projections of radiative forcing and surface temperature rather than explicit predictions, we do not generally assign uncertainty values. We do quote the IPCC explicit uncertainty values in Box 2.1. Later in Chapter 3 we present Box 3.3 that addresses the determination of statistical significance and our use of it in a more technical manner.

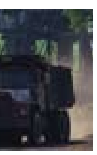


Table 2.1 Year 2100 values from Figures 2.1, 2.2, 2.3, and 2.4.

Scenario	CO2 (ppm) (Figure 2.1)	Kyoto Gases Radiative Forcing (W per m²) (Figure 2.2)	Total (W per m²) (Figure 2.3)	Temperature Change (degrees C) (Figure 2.4)
A2	836	5.75	6.74	3.40
A1B	703	4.02	4.72	2.60
B1	540	2.34	2.86	1.60
L1 MiniCAM	454	1.17	2.04	1.32
L1 Merge	432	1.14	1.36	0.93
L1 EPPA	453	1.28	1.75	1.16
L2 MiniCAM	559	2.33	3.10	1.83
L2 Merge	553	2.56	2.71	1.61
L2 EPPA	551	2.12	2.58	1.56
L3 MiniCAM	651	3.23	4.09	2.27
L3 Merge	650	3.67	3.81	2.09
L3 EPPA	601	2.98	3.36	1.92
L4 MiniCAM	712	3.83	4.73	2.50
L4 Merge	708	4.30	4.45	2.33
L4 EPPA	668	3.63	3.97	2.18

BOX 2.1: Robust conclusions for global climate from Chapter 10 of the Fourth Assessment Report (Meehl *et al.*, 2007):

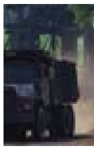
- Surface Air Temperatures show their greatest increases over land (roughly twice the global average temperature increase), over wintertime high northern latitudes, and over the summertime United States and southern Europe, and show less warming over the southern oceans and North Atlantic. These patterns are similar across the B1, A1B, and A2 scenarios with increasing magnitude with increasing radiative forcing.
- It is very likely that heat waves will be more intense, more frequent, and longer lasting in a future warmer climate.
- By 2100, global-mean sea level is projected across the 3 SRES scenarios to rise by 0.28m to 0.37m for the three multi-model averages with an overall 5-95 percent range of 0.19 to 0.50 m. Thermal expansion contributes 60-70 percent of the central estimate for all scenarios. There is, however, a large uncertainty in the contribution from ice sheet melt, which is poorly represented in current models.
- Globally averaged mean atmospheric water vapor content, evaporation rate, and precipitation rate are projected to increase. While, in general, wet areas get wetter and dry areas get dryer, the geographical patterns of precipitation change during the twenty-first century are not as consistent across the complex climate model simulations and across scenarios as they are for surface temperature.
- Multi-model projections based on SRES scenarios give reductions in ocean pH of between 0.14 and 0.35 units over the twenty-first century, adding to the present decrease of 0.1 units from preindustrial times.
- There is no consistent change in El Niño-Southern Oscillation (ENSO) for those complex climate models that are able to reproduce ENSO-like processes.
- Those models with a realistic Atlantic Meridional Overturning Circulation (MOC) predict that it is very likely that the MOC will slow by 2100, but will not shut down.
- The Fourth Assessment Report Summary for Policymakers finds it "Likely that intense hurricanes and typhoons will increase through the twenty-first century".

There are also important robust conclusions for North America from Chapter 11 of the Fourth Assessment Report (Christensen *et al.*, 2007):

- "All of North America is very likely to warm during this century, and the annual mean warming is likely to exceed the global-mean warming in most areas."
- "Annual-mean precipitation is very likely to increase in Canada and the U. S. Northeast, and likely to decrease in the U.S. Southwest".
- "Snow season length and snow depth are very likely to decrease in most of North America, except in the northernmost part of Canada where maximum snow depth is likely to increase".

NOTE: The terms "very likely" and "likely" have specific statistical meanings defined by the IPCC.

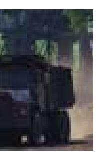
Very likely	greater than 90 percent chance of occurring
Likely	greater than 67 percent chance of occurring



BOX 2.2: Uncertainty

In doing any assessment, it is helpful to precisely convey the degree of certainty of various findings and projections. There are numerous choices for categories of likelihood and appropriate wording to define these categories. In Chapter 2 of this report, since many of the findings of this Report are comparable to those discussed in the Fourth Assessment Report of the IPCC, we have chosen to be consistent with the IPCC lexicon of uncertainty:

Lexicon	Probability of Occurrence
Virtually certain	> 99 percent
Extremely likely	> 95 percent
Very Likely	> 90 percent
Likely	> 66 percent
More likely than not	> 50 percent
Unlikely	< 33 percent
Very unlikely	< 10 percent
Extremely unlikely	< 5 percent



Elsewhere in the report, we are projecting climate, based on model simulations that use, as a foundation, scenarios of short-lived gases and particles, which are themselves plausible, but highly uncertain. For this reason, we have largely avoided assigning uncertainty values. However, where they do occur, we have condensed the IPCC ranges of uncertainty to fewer categories because we are unable to be as precise as in the IPCC assessments, which consider primarily the long-lived greenhouse gases. This lexicon is also consistent with other CCSP reports, such as SAP 3.3 and SAP 4.1.

Figure Box 2.2 Language in this Synthesis and Assessment Product (Chapters 3 and 4) used to express the team's expert judgment of likelihood, when such a judgment is appropriate.