Chapter 2 Climate Projections From Well-Mixed Greenhouse Gas Stabilization Scenarios

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KEY FINDINGS

This chapter focuses on climate projections for the long-lived greenhouse gas stabilization scenarios for the time period 2000–2100 that were produced under the U.S. Climate Change Science Program by an earlier Synthesis and Assessment Product, 2.1a. Those scenarios[27] are called "stabilization scenarios" because they are constrained so that the atmospheric concentrations of the long-lived greenhouse gases level off, or stabilize, at pre-determined levels by the end of the 21st century. Our overall goal in this Chapter is to assess these "stabilization scenarios" and the climates they would project for the 21st century in the context of the most recent Intergovernmental Panel on Climate Change (IPCC) report (4th Assessment Report, Working Group 1). 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:

[27] 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, socio-economic development, technological change) and their key relationships.

- **Do the stabilization1 emission scenarios produced by Synthesis and Assessment Product (SAP) 2.1a differ significantly from those used in the 4th Assessment Report of the IPCC?**

While different in concept and method of derivation (stabilization vs. "storyline" – see Box in Preface for detail) the long-lived greenhouse gas stabilization scenarios outlined in Synthesis and Assessment Product 2.1 fall among the principle storyline emission scenarios studied in the 4th Assessment Report of the IPCC. While each individual stabilization scenario differs somewhat from the individual IPCC scenarios, they are encompassed by the IPCC envelope of estimated future emissions.

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

Given the close agreement between the ranges of emission scenarios, time evolution of global concentrations and associated radiative forcings[28], 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 - 100 year climate responses for the CCSP 2.1 scenarios.

[28] 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

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

The key climate changes resulting from the "stabilization scenarios" should be quite similar to the key findings from Chapters 10 and 11 of the 4th Assessment Report of the IPCC, which are listed in the Box in Section 2.7 and discussed in more detail in Appendix 2.1. The simulations by the simple climate model used in this Chapter, as well as the comprehensive climate model[29] simulations in Chapter 10 of the 4th Assessment Report of the IPCC all find increases in global-average surface air temperature throughout the 21st century; with the warming increasing roughly proportional to the increasing concentrations of long-lived greenhouse gases.

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

For the first 30 years there is little difference in the predicted global-average climate among either the principal IPCC scenarios or the SAP 2.1 stabilization scenarios for the long-lived greenhouse gases. For the second half of the 21st century, global mean and certain robust regional properties predicted for the different IPCC 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.

[29] Comprehensive climate model is a numerical representation of the climate based on the physical, chemical, and biological properties of its components, 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). Our work in this chapter involves two different types of models:

1) Three integrated assessment models[30] that were used in Synthesis and Assessment Product 2.1a to produce stabilization scenarios for long-lived greenhouse gases;

2) A simplified global climate model, Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC)[31] that was used to simulate global levels of carbon dioxide, global-average radiative forcings for a variety of radiatively active[32] species, 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 scenarios.

The second section, 2.2, introduces the stabilization 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

[30] 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.
[31] 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 species. 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.
[32] Radiatively active indicates the ability of a substance to either absorb or emit sunlight or infrared radiation, thus changing the temperature of the atmosphere.

Protocol (methane, nitrous oxide, a suite of halocarbons, and sulfur hexafluoride (SF_6). These 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 – 200 years. For reference, pre-industrial levels of carbon dioxide were approximately 280 ppm, and are currently around 380 ppm of carbon dioxide.

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 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 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 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 emission scenarios. This provides a level playing field for all of the scenarios (see Wigley *et al.*, 2007b 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 complex climate models used in the latest IPCC 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 emission scenarios analyzed in the 4th Assessment Report of the IPCC. A more detailed description of MAGICC is provided for the technical audience in Appendix 2.2.

In the fourth section, 2.4, we show that the concentrations of carbon dioxide projected by MAGICC for the twelve stabilization emission 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 scenarios employed in the 4th Assessment Report of the IPCC. We next show that the radiative forcings for the long-lived greenhouse gases potentially regulated by the Kyoto Protocol, again calculated by MAGICC, fall among the radiative forcings time series for the 21st century previously

calculated with the same gases for the three principle storyline emission scenarios used in the 4th IPCC report.

In the fifth section, 2.5, we deal 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 scenarios. While short-lived pollutants were not explicitly included in determining the stabilization scenarios for the long-lived greenhouse gases, two of the three integrated assessment models did produce emission 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 by the third model, an intermediate IPCC emission scenario was used for the short-lived pollutants. Again we find that the total radiative forcing (short-lived and long-lived radiatively active species) calculated by MAGICC for the 12 stabilization scenarios fall among the total radiative forcings calculated by MAGICC for the principle storyline emission scenarios employed in the 4th Assessment Report of the IPCC.

In the sixth section, 2.6, we compare two sets of global-average surface temperature time series: an average of those calculated by a broad collection of complex global climate models for the three principle IPCC scenarios and reported in Chapter 10 of the IPCC's 4th Assessment Report, and those calculated by MAGICC for the twelve SAP 2.1a stabilization scenarios and reported here. As we found for the carbon dioxide concentration and radiative forcing time series discussed previously, the global-average

surface temperatures calculated for the twelve stabilization scenarios by MAGICC are generally contained within those calculated for the three IPCC scenarios by complex global climate models. The exceptions are for the most extreme stabilization 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 for this extreme stabilization scenario tend to fall below those for the lowest IPCC scenario, particularly in the 2nd half of the 21st century.

In the seventh and final section, 2.7, we address the primary objective of Chapter 2, *"Climate Projections for SAP 2.1a Emissions Scenarios of Greenhouse Gases."* While the stabilization scenarios were derived in a fundamentally different manner from the storyline scenarios used in the most recent IPCC report, they are generally contained within the storyline 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 report that "Projected warming in the 21st century shows scenario-independent geographical patterns", 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 scenarios provided by Synthesis and Assessment Product 2.1a.

2.2 Well-Mixed Greenhouse Gas Emission 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) aerosols 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 (carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)) and idealized short-lived and long-lived halocarbons (characterized by HFC134a and SF_6), but not for any other short-lived radiative species 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 scenario construction."* (see, *e.g.*, Reilly *et al.*, 1999; Manne and Richels, 2001; Sarofim *et al.*, 2005).

Consistent time series for the emissions of short-lived radiative species, carbon (both elemental and organic) and the precursors of sulfate aerosols 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/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.

As SAP 2.1a 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 Wm^{-2} above preindustrial in 2000 for the Kyoto gases to between 6.4 Wm^{-2} and 8.6 Wm^{-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, "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, where cumulative emissions

over the period 2000 to 2100, from the three reference scenarios and the twelve stabilization 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."

In this Chapter we start with the emission scenarios generated by the three integrated assessment models in SAP 2.1a and examine their atmospheric composition, radiative forcing and global-mean temperature. In the raw 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 provides a level playing field that isolates differences arising from emissions scenario differences. Moreover, the MAGICC model was used previously to generate the carbon dioxide concentrations, Kyoto Gas 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.*, 2007b).

2.3 Simplified Global Climate Model (MAGICC)

MAGICC is a coupled gas-cycle/climate model that was used in the Third Assessment (Cubasch and Meehl, 2001; Wigley and Raper, 2001).

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 species such as sulfate aerosols and tropospheric ozone.

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 aerosols, 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 2.6C equilibrium global-mean warming for a CO_2 doubling, the median of values for the above set of AOGCMs. (see Appendix 2.2 for additional details).

2.4 Long-Lived Greenhouse Gas Concentrations and Radiative Forcings

In Figure 2.1 we compare the concentrations of the primary greenhouse gas, CO_2, calculated by MAGICC for the 12 SAP 2.1a stabilization scenarios with earlier calculations of CO_2 concentrations for B1, A1B and A2, the principle storyline 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 scenario starts 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 2-4 start to spread in the second half of the 21st century but remain approximately bound between B1 and A1B all the way to 2100. EPPA now has the lowest CO_2 for Levels 2-4. The CO_2 levels for the extreme 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.

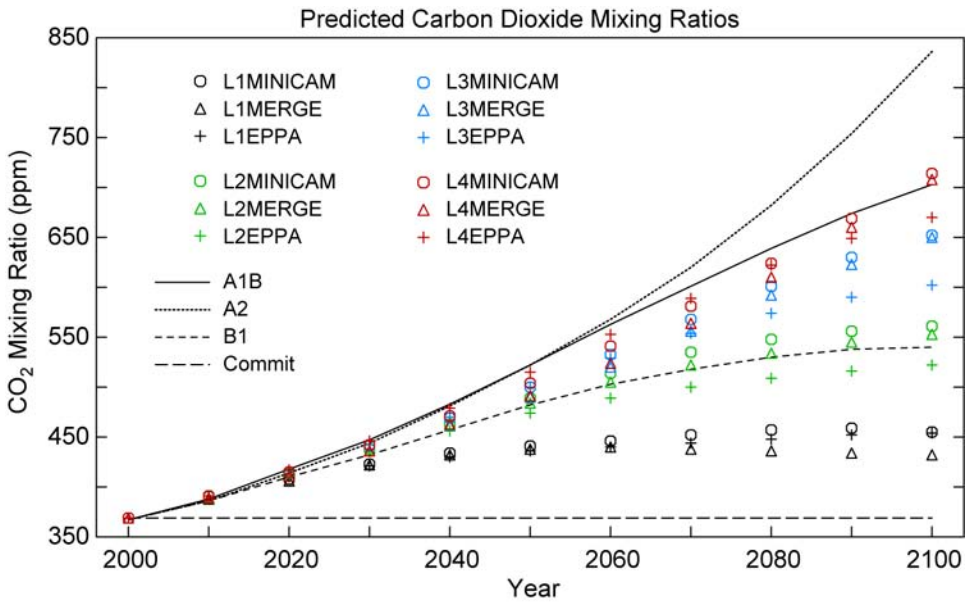

Figure 2.1 CO_2 concentrations (ppm) calculated by MAGICC for the 12 SAP 2.1a stabilization scenarios plotted with calculations of CO_2 concentrations for the principle scenarios (B1, A1B and A2) reported in Appendix II of the TAR (IPCC, 2001).

We next consider Figure 2.2, where the radiative forcing due to increasing Kyoto greenhouse gases in the 12 SAP 2.1a stabilization scenarios, again calculated by MAGICC, are plotted with the Kyoto gas radiative forcing values taken from Appendix II in the Third Assessment (IPCC, 2001) for the B1, A1B, and A2 storyline scenarios. The evolution of the 12 radiative forcing time series over the 21st 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 2-4 because they are on a trajectory where radiative forcing stabilizes some time after 2100, although emissions were calculated only to 2100 (SAP 2.1a, 2007). For the Level 2, 3 and 4 stabilization cases. it is not possible to stabilize as early as 2100 (c.f. Wigley *et al.*, 1996). As we saw for carbon dioxide, the Kyoto gas radiative forcing time series for stabilization levels 2-4 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 employed their own carbon cycle and atmosphere models in SAP 2.1a. 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 uncertainty in the three integrated assessment models' carbon cycles, which is known to be substantial.

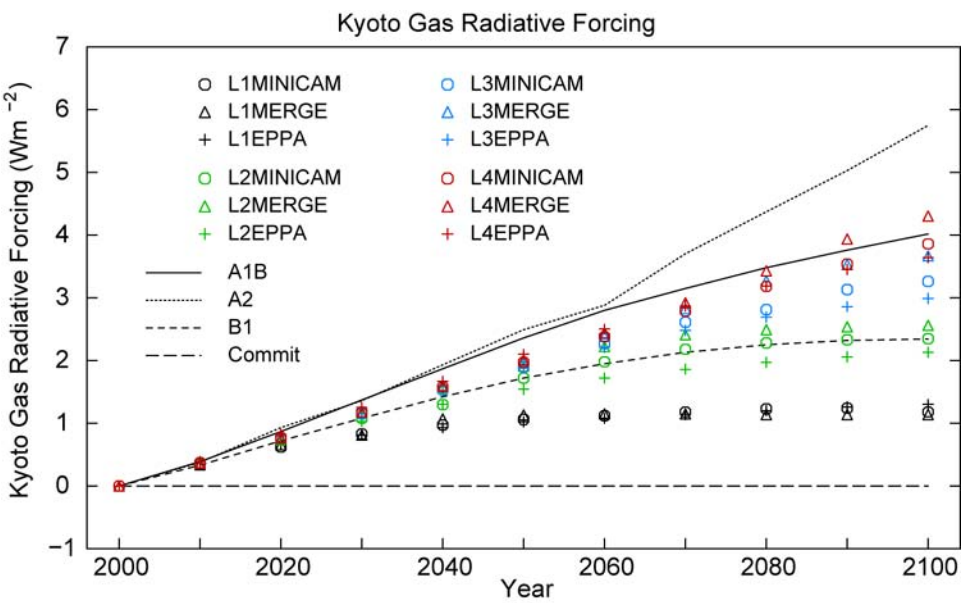

Figure 2.2 Kyoto Gas Radiative Forcing (W/m2) for the SAP 2.1a scenarios, calculated by MAGICC, plotted with the Kyoto Gas Radiative Forcing values taken from Appendix II in the TAR (IPCC, 2001) for the B1, A1B, and A2 SRES scenarios.

2.5 Short-Lived Species and Total Radiative Forcing

While EPPA and MiniCAM produce emissions of sulfur dioxide (SO_2), elemental or black carbon and organic carbon aerosols[33] and their precursors, and the key precursors

[33] Very small airborne solid or liquid particles, that reside in the atmosphere for at least several hours with the smallest remaining airborne for days.

of tropospheric ozone [CO), NOx and VOCs] as part of their 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 aerosols, it is assumed that the elemental and organic aerosol radiative forcings track the sulfur dioxide emissions in each integrated assessment model's 4 stabilization scenarios. Therefore, while carbon dioxide emissions tend to track the IPCC scenarios, the emissions of short-lived species may be different, with the exception of sulfur dioxide emissions in MERGE.

In Figure 2.3 we compare the Total radiative forcing calculated by MAGICC for the 12 SAP 2.1a scenarios, *i.e.*, the sum of Kyoto-gas forcings (Fig. 2.2) plus forcings due to aerosols, tropospheric ozone, halocarbons controlled under the Montreal Protocol, and stratospheric ozone (Wigley *et al.*, 2007b and supplementary material referenced therein) with the Total radiative forcing calculated by MAGICC for the B1, A1B, and A2 scenarios used in the latest IPCC report. 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 species, 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 4 Levels, primarily due to sharp decreases in sulfur dioxide emissions, which produce significant increases in

Total radiative forcing by 2100 (~1 Wm^{-2}). In the EPPA stabilization scenarios the changes in sulfur dioxide emissions are small, and most of the non-Kyoto forcing comes from increased nitrogen oxide emissions that drive increases in tropospheric ozone and its positive radiative forcing (Wigley *et al.*, 2007b). Remember that in SAP 2.1, the stabilization targets were met using only the long-lived greenhouse gases.

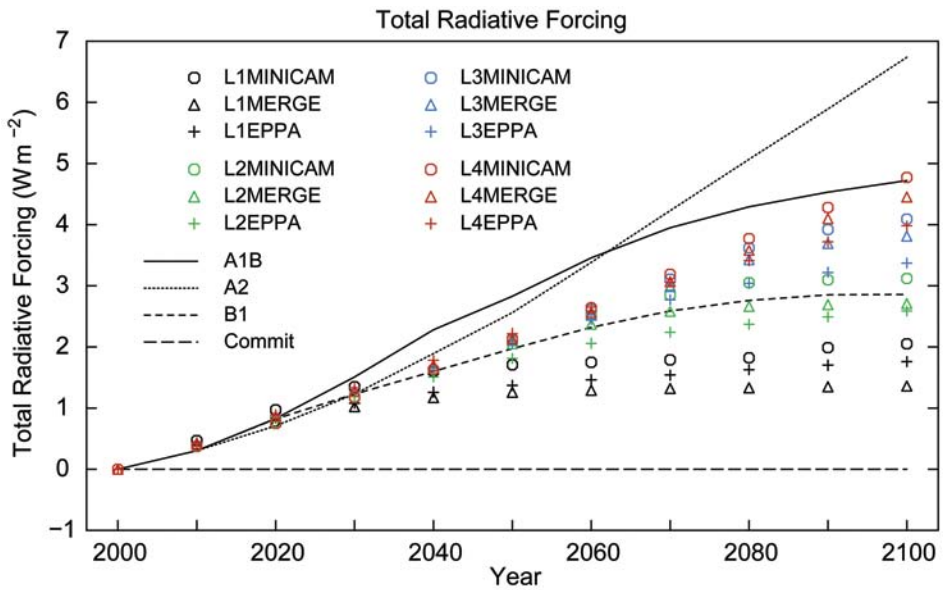

Figure 2.3 Total Radiative Forcing (W/m2) calculated by MAGICC for the 12 SAP 2.1a scenarios plotted with the Total calculated by MAGICC for the B1, A1B, and A2 scenarios (IPCC, 2001).

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 2-4 scenarios appear to track the B1 Total radiative forcing out to 2060 - 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 radiative species in Figure 2.3 are

the result of differences among treatments of short-lived species. 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 species on future global warming in considerable detail in Chapter 3.

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 4th Assessment Report for the standard storyline scenarios, B1, A1B and A2, with global-mean surface temperature changes calculated by MAGICC for the twelve SAP 2.1a stabilization scenarios. As we might expect, the general behavior is quite similar to that observed for Total radiative forcing. All scenarios are close through 2020. Levels 2-4 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 (c.f., 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 most extreme stabilization cases (corresponding to 450 and 550 ppm CO_2 but also including the assumed or modeled levels of short-lived species) 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 species. However, the

temperatures for the less extreme Level 3 and 4 stabilization 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 twelve SAP 2.1a stabilization scenarios are well bounded by the complex climate model simulations for the A1B scenario reported in Chapter 10 of the latest IPCC assessment.

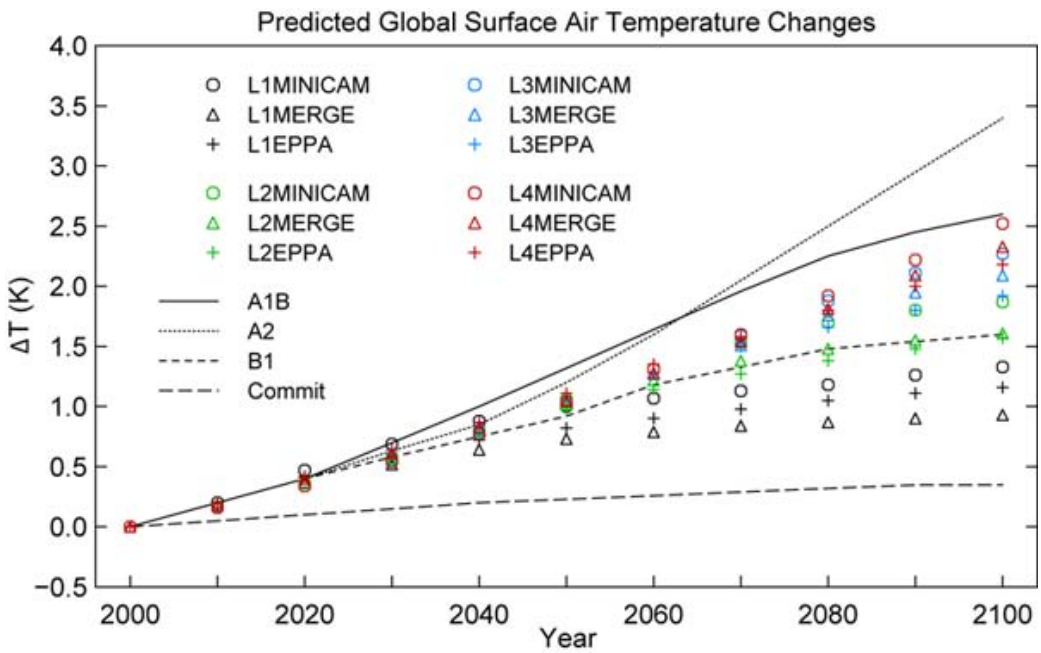

Figure 2.4 Multi-AOGCM global-mean surface temperature (deg C) changes reported in Chapter 10 of AR4 (IPCC, 2007a) for the standard scenarios B1, A1B, and A2 plotted with global-mean surface temperature changes calculated by MAGICC for the twelve SAP 2.1a stabilization scenarios.

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

Scenario	CO2 (ppm)	Kyoto gases (W/m^2)	Total (W/m^2)	Temperature (deg C)
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

2.7 Climate Projections for SAP 2.1a Scenarios

The 2.1a stabilization emission scenarios are derived in a fundamentally different manner from the development of the storyline emission scenarios used in 4th Assessment Report of the IPCC (IPCC, 2007a). However, we show in Section 2.4 that the twelve (three integrated assessment models, four stabilization scenarios each) stabilization scenarios reported in SAP 2.1a are contained within the principal emission scenarios used in the latest IPCC assessment and show a similar evolution with time. We also show that the Kyoto gases and Total radiative forcings for those 12 emission scenarios are generally constrained within the three principle scenarios used to make the climate projections discussed in Chapter 10 of the report (IPCC, 2007a).

In Section 2.6, we show that the global surface temperatures predicted for the 2.1a scenarios over the 21st century by a simple coupled gas-cycle/climate model, MAGICC, fall within the range of the multi-model mean temperatures calculated with state-of-the-art complex climate models for the three principle IPCC scenarios and reported in Chapter 10 (IPCC, 2007a). In fact, the global average surface temperatures for Levels 2-4 scenarios all track the values reported by the IPCC for B1 out to 2050. The primary exceptions are all of the L1 scenarios beyond year 2050 which are significantly below B1. We also draw on the conclusion in the Summary for Policy Makers in the latest report (IPCC, 2007a): "Projected warming in the 21st century shows scenario-independent geographical patterns similar to those observed over the past 50 years." Figure 10.8 in Chapter 10 of the 4th Assessment Report also clearly shows that the geographical pattern of the robust climate features are preserved across scenarios, 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 4th Assessment Report (IPCC, 2007a) regarding the predicted climate response to the three scenarios studied in 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 scenarios (three realizations of each) provided by SAP 2.1a. These robust conclusions are highlighted in Box 2.1 below and summarized in Appendix 2.1.

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 will present a more technical Box 3.3 that addresses the determination of statistical significance and our use of it.

Box 2.1: **Robust conclusions for global climate from Chapter 10 of the 4th Assessment Report (IPCC, 2007a):**

- 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 US 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 37m for the three multi-model averages with an overall 5-95% range of 0.19 to 0.50 m. Thermal expansion contributes 60-70% 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 21st 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 21st century, adding to the present decrease of 0.1 units from pre-industrial 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 AR4 Summary for Policymakers finds it "**Likely** that intense hurricanes and typhoons will increase through the 21st century".

There are also important robust conclusions for North America from Chapter 11 of the 4th Assessment Report (IPCC, 2007b):

- "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 northeast USA, and **likely** to decrease in the southwest USA."
- "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% chance of occurring
Likely	greater than 67% chance of occurring

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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:

Virtually certain	> 99% probability of occurrence
Extremely likely	>95%
Very likely	*> 90%*
Likely	> 66%
More likely than not	> 50%
Unlikely	< 33%
Very unlikely	< 10%
Extremely unlikely	< 5%

Elsewhere in the report, we are projecting climate, based on model simulations that use, as a foundation, scenarios of short-lived gases and particulates, 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 P.1 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.

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Appendix 2.1 IPCC 4th Assessment Climate Projections

These robust conclusions, which we believe also apply to the climate projections from the SAP 2.1a scenarios, are taken primarily from the Executive Summary of Chapter 10 of the IPCC's 4th Assessment Report (IPCC, 2007a) as well as some details extracted from the body of Chapter 10, and are summarized below.

A.2.1.1 Mean Temperature

All AOGCMs In Chapter 10 of the AR4 (IPCC, 2007a) project increases in global mean surface air temperature (SAT) throughout the 21st century, with the warming proportional to the associated radiative forcing. There is close agreement among globally averaged SAT multi-model mean warming for the early 21st century for the three SRES (B1, A1B and A2) scenarios as well as for SAP 2.1a Level 2-4 scenarios out to 2050. The warming rate over the next few decades in Chapter 10 (IPCC, 2007a) is affected little by different scenario assumptions or different model sensitivities, and is similar to that observed for the past few decades. By mid-century (2046 – 2065), the choice of SRES scenario becomes more important and they start to separate, though the range among the collection of AOGCMs is comparable. By the end of the 21st century, the SATs generated by MAGICC using the 12 SAP 2.1 scenarios as well as the full spread of all of the AOGCMs for the A2, B1 and Committed projections have completely separated, though A1B still has some overlap with A2 and B1.

In general, geographical patterns of projected SAT warming show greatest temperature increases over land (roughly twice the global average temperature increase) and at high northern latitudes, and show less warming over the southern oceans and North Atlantic, consistent with observations during the latter part of the 20th century. These patterns are similar across the B1, A1B, and A2 scenarios (see Figure 10.8 in Chapter 10 of the AR4; IPCC, 2007a) only increasing in magnitude with increasing radiative forcing. Results for the stabilization scenarios similar to those studied here should show the same pattern similarities at least out to 2100 (see, *e.g.*, Dai *et al.* 2001a, b). It should be noted that, in none of the cases considered here, has the climate stabilized by 2100 – for the higher stabilization levels this may take centuries. Temperature change patterns may differ as one approaches closer to a stable climate.

A.2.1.2 Temperature Extremes

It is very likely that heat waves will be more intense, more frequent and longer lasting in a future warmer climate. Cold episodes are projected to decrease significantly in a future warmer climate. Almost everywhere, daily minimum temperatures are projected to increase faster than daily maximum temperatures, leading to a decrease in diurnal temperature range. Decreases in frost days are projected to occur almost everywhere in the mid and high latitudes, with a comparable increase in growing season length (IPCC, 2007a).

A.2.1.3 Mean Precipitation

Globally averaged mean atmospheric water vapor, evaporation and precipitation are projected to increase. By 2100, precipitation generally increases in the areas of regional tropical precipitation maxima (such as the monsoon regimes) and over the tropical Pacific in particular, with general decreases in the subtropics, and increases at high latitudes as a consequence of a general intensification of the global hydrological cycle. The geographical patterns of precipitation change during the 21st century are not as consistent across AOGCMs and across scenarios as they are for surface temperature (IPCC, 2007a).

A.2.1.4 Precipitation Extremes and Droughts

Intensity of precipitation events is projected to increase, particularly in tropical and high latitude areas that experience increases in mean precipitation. There is a tendency for drying of the mid-continental areas during summer, indicating a greater risk of droughts in those regions. Precipitation extremes increase more than the mean in most tropical and mid- and high latitude areas (IPCC, 2007a).

A.2.1.5 Snow and Ice

As the climate warms, snow cover and sea ice extent decrease; glaciers and ice caps lose mass owing to dominance of summer melting over winter precipitation increases. There is a projected reduction of sea ice in the 21st century both in the Arctic and Antarctic with a large range of model responses. Widespread increases in thaw depth over much of the permafrost regions are projected to occur in response to warming over the next century (IPCC, 2007a).

Note: All of the AR4 predictions for precipitations, snow cover and sea and land ice are less certain and more variable across the suite of AOGCMs than they are for both the global average and the more robust geographic patterns of temperature.

A.2.1.6 Carbon Cycle

Under the SRES illustrative emissions scenarios, for central carbon-cycle model parameters, CO_2 concentrations are projected to increase from its present value of about 380 ppm to 540–970 ppm by 2100. The SAP 2.1a Reference scenarios give 2100 concentrations of 740–850 ppm. There is unanimous agreement amongst the simplified climate-carbon cycle models that future climate change would reduce the efficiency of the Earth system (land and ocean) to absorb anthropogenic carbon dioxide. The higher the stabilization scenario warming, the larger is the impact on the carbon cycle. Both MAGICC and two of the three integrated assessment models used in SAP 2.1a contain simplified carbon cycle models comparable to those in Chapter 10 of the AR4 (IPCC, 2007a).

A.2.1.7 Ocean Acidification

Increasing atmospheric CO_2 concentrations lead directly to increasing acidification of the surface ocean. Multi-model projections based on SRES scenarios give reductions in pH of between 0.14 and 0.35 units over the 21st century, adding to the present decrease of 0.1 units from pre-industrial times. Southern Ocean surface waters are projected to exhibit undersaturation with regard to $CaCO_3$ for CO_2 atmospheric concentrations higher

than 600 ppm. Low latitude regions and the deep ocean will be affected as well. While ocean acidification would lead to dissolution of shallow-water carbonate sediments and could affect marine calcifying organisms, the net effect on the biological cycling of carbon in the oceans is not well understood (IPCC, 2007a).

A.2.1.8 Sea Level

"Sea level is projected to rise between the present (1980-1999) and the end of this century (2090-2099) under the SRES B1 scenario by 0.28 m for the multi-mode average (range 0.19 to 0.37 m), under A1B by 0.35 m (0.23 to 0.47 m), under A2 by 0.37 m (0.25 to 0.50 m) and under A1FI by 0.43 m (0.28 to 0.58 m). These are central estimates with 5-95% intervals based on AOGCM results, not including uncertainty in carbon-cycle feedbacks. In all scenarios, the average rate of rise during the 21st century very likely exceeds the 1961–2003 average rate (1.8 ± 0.5 mm yr^{-1}). During 2090 – 2099 under A1B, the central estimate of the rate of rise is 3.8 mm yr^{-1}. For an average model, the scenario spread in sea level rise is only 0.02 m by the middle of the century, and by the end of the century it is 0.15 m."(IPCC, 2007a) The projections of sea-level rise for the 12 SAP 2.1 scenarios by MAGICC are within the range reported by AR4 (Wigley *et al.*, 2007b).

"Thermal expansion is the largest component, contributing 60-70% of the central estimate in these projections for all scenarios. Glaciers, ice caps and the Greenland ice sheet are also projected to contribute positively to sea level. GCMs indicate that the Antarctic ice sheet will receive increased snowfall without experiencing substantial

surface melting, thus gaining mass and contributing negatively to sea level. Further accelerations in ice flow of the kind recently observed in some Greenland outlet glaciers and West Antarctic ice streams could substantially increase the contribution from the ice sheets. Current understanding of these effects is limited, so quantitative projections cannot be made with confidence" (IPCC, 2007a).

A.2.1.9 Ocean Circulation

a. There is no consistent change in the ENSO for those AOGCMs with a quasi-realistic base state.

b. Among those models with a realistic Atlantic Meridional Overturning Circulation (MOC),), while it is very likely that the MOC will slow by 2100, there is little agreement among models for the magnitude of the slow-down. Models agree that the MOC will not shut down completely (IPCC, 2007a).

A.2.1.10 Monsoons

Current AOGCMs predict that, in a warmer climate, there will be an increase in precipitation in both the Asian monsoon (along with an increase in interannual variability) and the southern part of the west African monsoon with some decrease in the Sahel in northern summer, as well as an increase in the Australian monsoon in southern summer. The monsoonal precipitation in Mexico and Central America is projected to decrease in association with increasing precipitation over the eastern equatorial Pacific. However, the uncertain role of aerosols complicates the projections of monsoon precipitation, particularly in the Asian monsoon (IPCC, 2007a).

A.2.1.11 Tropical Cyclones (Hurricanes and Typhoons)

The Summary for Policymakers finds it **likely** that intense hurricanes and typhoons will increase through the 21st century as it warms. Results from embedded high-resolution models and global models, ranging in grid spacing from 1 degree to 9 km, generally project increased peak wind intensities and notably, where analyzed, increased near-storm precipitation in future tropical cyclones (IPCC, 2007a). However, these questions of changes in frequency and intensity under global warming continue to be the subject of very active research.

A.2.1.12 Midlatitude Storms

Model projections show fewer midlatitude storms averaged over each hemisphere, associated with the poleward shift of the storm tracks that is particularly notable in the Southern Hemisphere, with lower central pressures for these poleward-shifted storms. The increased wind speeds result in more extreme wave heights in those regions (IPCC, 2007a).

A.2.1.13 Radiative Forcing

"The radiative forcings by long-lived greenhouse gases computed with the radiative transfer codes in twenty of the AOGCMs used in the AR4 have been compared against results from benchmark line-by-line (LBL) models. The mean AOGCM forcing over the period 1860 to 2000 agrees with the mean LBL value to within 0.1 W m^{-2} at the tropopause. However, there is a range of 25% in longwave forcing due to doubling CO_2

from its concentration in 1860 across the ensemble of AOGCM codes. There is a 47% relative range in longwave forcing at 2100 contributed by all greenhouse gases in the A1B scenario across the ensemble of AOGCM simulations. These results imply that the ranges in climate sensitivity and climate response from models discussed in this chapter may be due in part to differences in the formulation and treatment of radiative processes among the AOGCMs."(IPCC, 2007a)

A.2.1.14 Climate Change Commitment (Temperature and Sea Level)

"Results from the AOGCM multi-model climate change commitment experiments (concentrations stabilized for 100 years at year 2000 for 20th century commitment, and at 2100 values for B1 and A1B commitment) indicate that if greenhouse gases were stabilized, then a further warming of 0.5°C would occur."(IPCC, 2007a)

"If concentrations were stabilized at A1B levels in 2100, sea level rise due to thermal expansion in the 22nd century would be similar to in the 21st, and would amount to 0.3–0.8 m above present by 2300. The ranges of thermal expansion overlap substantially for stabilization at different levels, since model uncertainty is dominant; A1B is given here because most model results are available for that scenario. Thermal expansion would continue over many centuries at a gradually decreasing rate, reaching an eventual level of 0.2–0.6 m per degree of global warming relative to present."(IPCC, 2007a)

Appendix 2.2 MAGICC Model Description

MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) is a coupled gas-cycle/climate model. Various versions of MAGICC have been used in all IPCC assessments. The version used here is the one that was used in the IPCC Third Assessment Report (TAR; Cubasch and Meehl, 2001; Wigley and Raper, 2001).

The climate component is an energy-balance model with a one-dimensional, upwelling-diffusion ocean (a "UDEBM"). 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 species such as sulfate aerosols and tropospheric ozone.

In order to allow inputs as emissions, the climate model is coupled interactively to a series of gas-cycle models for CO2, CH4, N2O, a suite of halocarbons and SF6. Details of the carbon cycle model are given in Wigley (1991, 1993, 2000). The carbon cycle model includes both CO2 fertilization and temperature feedbacks, with model parameters tuned to give results consistent with the other two carbon cycle models used in the TAR; viz. ISAM (Kheshgi and Jain, 2003) and the Bern model (Joos *et al.*, 2001) over a wide range of emissions scenarios. Details are given in Wigley *et al.* (2007). The other gas cycle models are those used in the TAR (Prather and Ehhalt, 2001; Wigley *et al.*, 2002). Radiative forcings for the various gases are as used in the TAR. For sulfate aerosols, both

direct and indirect forcings are included using forcing/emissions relationships developed in Wigley (1989, 1991), with central estimates for 1990 forcing values. Sea level rise estimates use thermal expansion values calculated directly from the climate model. Ice-melt and other contributions are derived using formulae given in the TAR (Church and Gregory, 2001), except for the glacier and small ice-cap contribution which employs an improved formulation that can be applied beyond 2100 (Wigley and Raper, 2005).

The standard inputs to MAGICC are emissions of the various radiatively important gases and various climate model parameters. For the TAR, these parameters were tuned so that MAGICC was able to emulate results from a range of AOGCMs (see Cubasch and Meehl. 2001; Raper *et al.*, 2001). For the present calculations, a central set of parameters has been used. The most important of these is the climate sensitivity, where we have used a value of 2.6C equilibrium global-mean warming for a CO2 doubling, the median of values for AOGCMs used in the TAR.

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