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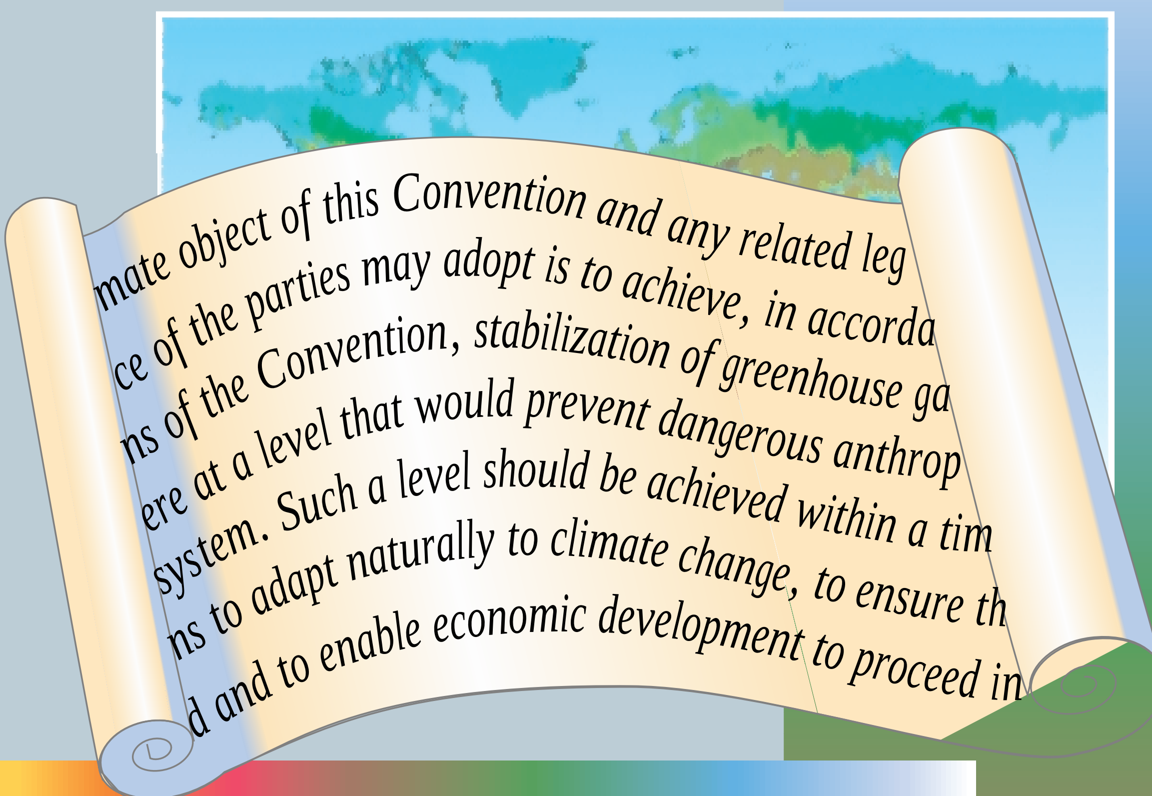

STABILIZATION OF ATMOSPHERIC GREENHOUSE GASES: PHYSICAL, BIOLOGICAL AND SOCIO-ECONOMIC IMPLICATIONS

IPCC Technical Paper III

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Stabilization of Atmospheric Greenhouse Gases: Physical, Biological and Socio-economic Implications

Edited by

John T. Houghton **L. Gylvan Meira Filho** **David J. Griggs** **Kathy Maskell**

This is a Technical Paper of the Intergovernmental Panel on Climate Change prepared in response to a request from the United Nations Framework Convention on Climate Change. The material herein has undergone expert and government review, but has not been considered by the Panel for possible acceptance or approval.

February 1997

This paper was prepared under the auspices of IPCC Working Group I, which is co-chaired by Sir John T. Houghton of the United Kingdom and Dr L. Gylvan Meira Filho of Brazil.

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Preface

This Intergovernmental Panel on Climate Change (IPCC) Technical Paper on "Stabilization of Atmospheric Greenhouse Gases: Physical, Biological and Socio-economic Implications" is the third paper in the IPCC Technical Paper series and was produced in response to a request made by the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UN/FCCC).

Technical Papers are initiated either at the request of the bodies of the COP, and agreed by the IPCC Bureau, or as decided by the IPCC. They are based on the material already in IPCC Assessment Reports and Special Reports and are written by Lead Authors chosen for the purpose. They undergo a simultaneous expert and government review, during which comments on this Paper were received from 93 reviewers from 27 countries, followed by a final government review. The Bureau of the IPCC acts in the capacity of an editorial board to ensure that review comments have been adequately addressed by the Lead Authors in the finalization of the Technical Paper.

The Bureau met in its Twelfth Session (Geneva, 3-5 February 1997) and considered the major comments received during the final government review. In the light of its observations and requests, the Lead Authors finalized the Technical Paper. The Bureau was satisfied that the agreed Procedures had been followed and authorized the release of the Paper to the SBSTA and thereafter publicly.

We owe a large debt of gratitude to the Lead Authors who gave of their time very generously and who completed the Paper at short notice and according to schedule. We thank the Co-chairmen of Working Group I of the IPCC, John Houghton and Gylvan Meira Filho who oversaw the effort, the staff of the United Kingdom Meteorological Office graphics studio who prepared the figures for publication, Christy Tidd who assisted the convening Lead Author in the preparation of the paper and particularly David Griggs, Kathy Maskell and Anne Murrill from the IPCC Working Group I Technical Support Unit, for their insistence on adhering to quality and timeliness.

B. Bolin
Chairman of the IPCC

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Secretary of the IPCC

Stabilization of Atmospheric Greenhouse Gases: Physical, Biological and Socio-economic Implications

This paper was prepared under the auspices of IPCC Working Group I.

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SUMMARY

Introduction

An understanding of the constraints on the stabilization of greenhouse gas concentrations is fundamental to policy formulation with regard to the goals of the United Nations Framework Convention on Climate Change and its implementation. This Technical Paper provides:

(*a*) A tutorial on the stabilization of greenhouse gases, the estimation of radiative forcing[1], and the concept of "equivalent carbon dioxide (CO_2)" (the concentration of CO_2 that leads to global mean radiative forcing consistent with projected increases in all gases when a suite of gases is being considered);

(*b*) A basic set of CO_2 stabilization profiles leading, via two types of pathway, to stabilization between 350 and 750 ppmv, with a single profile stabilizing at 1 000 ppmv (Figure 1);

(*c*) The deduced emissions for the aforementioned concentration stabilization profiles;

(*d*) A consideration of the stabilization of radiative forcing agents other than CO_2;

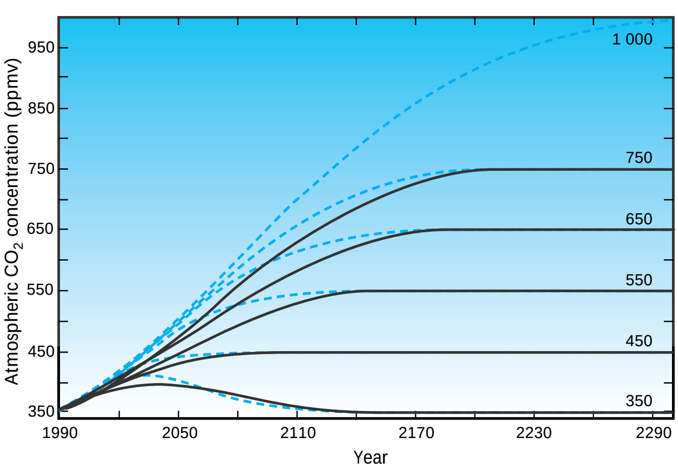

Figure 1. Profiles of CO_2 leading to stabilization at concentrations from 350 to 1 000 ppmv. For comparison, the pre-industrial concentration was close to 280 ppmv and the current concentration is approximately 360 ppmv. For stabilization at concentrations from 350 to 750 ppmv, two different routes to stabilization are shown: the S profiles (from IPCC94) and the WRE profiles (from Wigley, *et al.*, 1996) which allow CO_2 emissions to follow IS92a until the year 2000 or later (depending on the stabilization level). A single profile is defined for 1 000 ppmv. These two sets of profiles are merely examples from a range of possible routes to stabilization that could be defined.

(*e*) Global mean temperature and sea level changes for the CO_2 profiles using a range of emissions assumptions for methane (CH_4), nitrous oxide (N_2O) and sulphur dioxide (SO_2), and different values of the climate sensitivity and ice-melt model parameter values in order to characterize uncertainties;

(*f*) A discussion of the potential environmental consequences of the derived changes in temperature and sea level;

(*g*) A discussion of the factors that influence mitigation costs; and

(*h*) A review of the methodology for integrating climate and sea level change effects and mitigation costs to produce a more complete view of the consequences of changing atmospheric composition.

Fundamentals

Of the greenhouse gases, this paper focuses on CO_2 because it has had, and is projected to have, the largest effect on radiative forcing. The effects of other greenhouse gases are also considered and a series of assumptions are made about their potential future emissions.

In addition, the effects of aerosols, which act to cool the planet, are considered. Tropospheric aerosols (microscopic airborne particles) resulting from the combustion of fossil fuels, biomass burning, and other anthropogenic sources have led to a negative forcing that is highly uncertain. Because aerosols have short lifetimes in the atmosphere, their distribution and hence immediate radiative effects are very regional in character.

Some implications associated with stabilizing greenhouse gases

Among the range of CO_2 stabilization cases studied, accumulated anthropogenic emissions from 1991 to 2100 fall between 630 and 1410 GtC, for stabilization levels between 450 and 1 000 ppmv. For comparison, the corresponding accumulated emissions for the IPCC IS92 emissions scenarios range from 770 to 2190 GtC.

Calculations of CO_2 emissions consistent with a range of stabilization levels and pathways are presented using models and input data available and generally accepted at the time of the IPCC Second Assessment Report. Ecosystem and oceanic feedbacks may reduce terrestrial and oceanic carbon storage to levels somewhat below those assumed in the simplified global carbon cycle models used here and in the Second Assessment Report. Uncertainties resulting from the omission of potentially critical oceanic and biospheric processes during climate change could have a significant effect on the conclusions regarding emissions associated with stabilization.

[1] For a definition of radiative forcing, see Appendix 2.

Subject to uncertainties concerning the "climate sensitivity", future anthropogenic climate change is determined by the sum of all positive and negative radiative forcings arising from all anthropogenic greenhouse gases and aerosols, and not by the level of CO_2 alone. The forcing scenarios considered here use the sum of the radiative forcings of all the trace gases (CO_2, CH_4, ozone (O_3), etc.) and aerosols. The total forcing may be treated as if it came from an "equivalent" concentration of CO_2. Therefore, the "equivalent CO_2" concentration is the concentration of CO_2 that would cause the same amount of global mean radiative forcing as the given mixture of CO_2, other greenhouse gases, and aerosols.

The difference between the equivalent CO_2 level and the true CO_2 level depends on the levels at which the concentrations of other radiatively active gases and aerosols are stabilized.

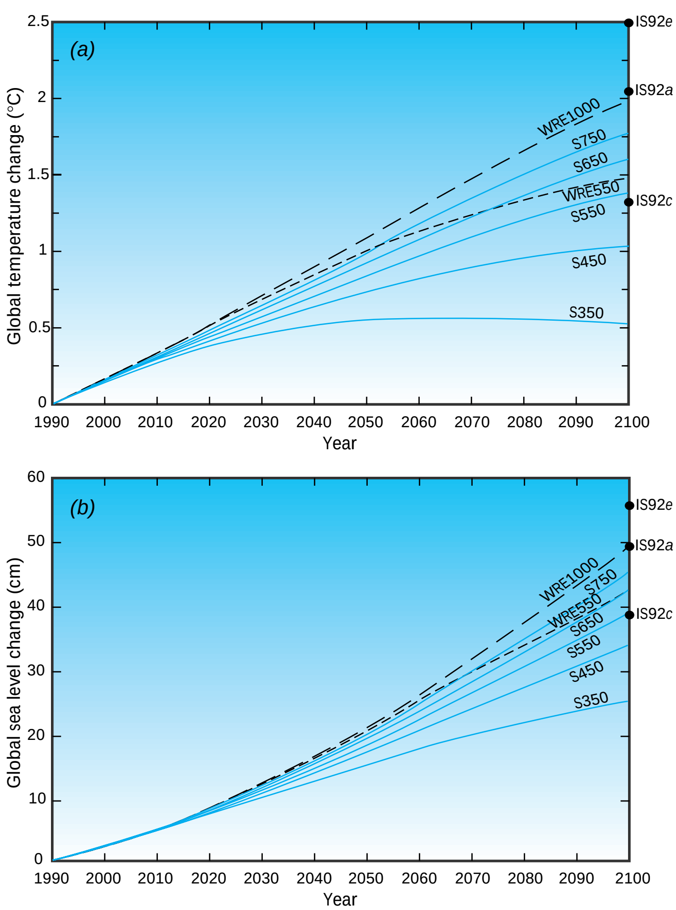

Figure 2. (*a*) Projected global mean temperature when the concentration of CO_2 is stabilized following the S profiles and the WRE550 and 1 000 profiles. CH_4, N_2O and SO_2 emissions are assumed to remain constant at their 1990 levels and halocarbons follow an emissions scenario consistent with compliance with the Montreal Protocol. The climate sensitivity is assumed to be the mid-range value of 2.5˚C. For comparison, results for the IS92*a*, *c* and *e* emissions scenarios are shown for the year 2100. The values are shown relative to 1990; to obtain the anthropogenic change from pre-industrial times, a further 0.3 - 0.7˚C should be added; (*b*) As for (*a*), but for global sea level change using central ice-melt parameters.

Because the effects of greenhouse gases are additive, stabilization of CO_2 concentrations at any level above about 500 ppmv is likely to result in atmospheric changes equivalent to at least a doubling of the pre-industrial CO_2 level.

Temperature and sea level projections depend on the assumed climate sensitivity, the target and pathway chosen for CO_2 concentration stabilization, and the assumed scenarios for other greenhouse gases and aerosol forcing. For the mid-range climate sensitivity of 2.5°C, global mean temperature increases from 1990 for reference stabilization cases, in which the emissions of non-CO_2 gases and SO_2 are assumed to remain constant at their 1990 levels, range from 0.5 to 2.0˚C by the year 2100 (Figure 2). For increases from pre-industrial times, 0.3 to 0.7˚C should be added. Rates of temperature change over the next fifty years range from 0.1 to 0.2˚C/decade. Projections of sea level rise from 1990 to 2100 range from 25 to 49 cm (Figure 2), for mid-range climate sensitivity and ice-melt parameter values. Temperature and sea level projections are sensitive to assumptions about other gases and aerosols.

This paper is presented in terms of the temperature and sea level changes that might result from different greenhouse gas stabilization levels. However, it would be possible, given further work, to deduce the greenhouse gas stabilization levels required to meet specific policy objectives in terms of temperature or sea level change targets, which are more readily related to climate change impacts.

Impacts of climate change

A great deal is known about the potential sensitivity and vulnerability of particular systems and sectors; both substantial risks and potential benefits can be identified. Currently, however, our ability to integrate this information into an assessment of impacts associated with different stabilization levels or emissions trajectories is relatively limited.

While the regional patterns of future climate change are poorly known, it is clear that the altered patterns of radiative forcing associated with anthropogenic emissions will alter regional climates noticeably, and will have different effects on climate conditions in different regions. These local and regional changes include changes in the lengths of growing seasons, the availability of water, and the incidence of disturbance regimes (extreme high temperature events, floods, droughts, fires and pest outbreaks), which, in turn, will have important impacts on the structure and function of both natural and human-made environments. Systems and activities that are particularly sensitive to climate change and related changes in sea level include: forests; mountain, aquatic and coastal ecosystems; hydrology and water resource management (including the cryosphere); food and fibre production; human infrastructure and human health.

Impacts are not a linear function of the magnitude and rate of climate change. For some species (and hence systems), thresholds of change in temperature, precipitation or other factors may exist, which, once exceeded, may lead to discontinuous changes in viability, structure or function. The aggregation of impacts to produce a global assessment is not currently possible because of uncertainties regarding regional climate changes and regional responses, the difficulty of valuing impacts on natural systems and human health, and issues related to both interregional and intergenerational equity.

The ultimate concentration of greenhouse gases reached in the atmosphere, as well as the speed at which concentrations increase, is likely to influence impacts, because a slower rate of climate change will allow more time for systems to adapt. However, knowledge is not currently sufficient to identify clear threshold rates and magnitudes of change.

Mitigation costs of stabilizing CO_2 concentrations

Factors that affect CO_2 mitigation costs include:

(*a*) Future emissions in the absence of policy intervention ("baselines");

(*b*) The concentration target and route to stabilization, which determine the carbon budget available for emissions;

(*c*) The behaviour of the natural carbon cycle, which influences the emissions carbon budget available for any chosen concentration target and pathway;

(*d*) The cost differential between fossil fuels and carbon-free alternatives and between different fossil fuels;

(*e*) Technological progress and the rate of adoption of technologies that emit less carbon per unit of energy produced;

(*f*) Transitional costs associated with capital stock turnover, which increase if carried out prematurely;

(*g*) The degree of international cooperation, which determines the extent to which low cost mitigation options in different parts of the world are implemented; and

(*h*) Assumptions about the discount rate used to compare costs at different points in time.

The costs of reducing emissions depend on the emissions "baseline", i.e., how emissions are projected to grow in the absence of policy intervention. The higher the baseline, the more carbon must be removed to meet a particular stabilization target, thus the greater the need for intervention. The costs of emissions reductions are also sensitive to the concentration stabilization target. As a first approximation, a stabilization target defines an amount of carbon that can be emitted between now and the date at which the target is to be achieved (the "carbon budget"). The size of the "carbon budget" is an important determinant of mitigation costs. Lower stabilization targets require smaller carbon budgets, which require a greater degree of intervention.

The cost of stabilizing CO_2 concentrations also depends on the cost of fossil fuels relative to carbon-free alternatives. The cost of meeting a stabilization target generally increases with the cost difference between fossil fuels and carbon-free alternatives. A large cost differential implies that consumers must increase their expenditures on energy significantly to reduce emissions by replacing fossil fuels with carbon-free alternatives. The cost difference between unconventional fossil fuels and carbon-free alternatives is likely to be smaller than the difference between conventional oil and gas and carbon-free alternatives. If oil and gas still contribute significantly to the energy mix at the time when global CO_2 emissions must be reduced consistent with a given stabilization target, transition costs will be higher than if oil and gas compose a small part of energy use. While the cost premium for carbon-free alternatives is likely to be smaller for higher stabilization levels, we cannot predict how this cost differential will change over time. Since, in addition, total energy demand is larger for higher stabilization levels, the net effect on the transition costs for different stabilization levels is not clear.

A given concentration target may be achieved through more than one emission pathway. Emissions in the near-term may be balanced against emissions in the long-term. For a given stabilization level, there is a "budget" of allowable accumulated carbon emissions and the choice of pathway to stabilization may be viewed as a problem of how to best (i.e., with the greatest economic efficiency and least damaging impacts) allocate this carbon budget over time. The differences in the emissions path for the same stabilization level are important because costs differ among pathways. Higher early emissions decrease the options to adjust emissions later on.

Energy-related capital stock is typically long-lived and premature retirement is apt to be costly. To avoid premature retirement, mitigation efforts can be spread more evenly over time and space. The cost of any stabilization target can be reduced by focusing on new investments and replacements at the end of the economic life of plant and equipment (i.e., at the point of capital stock turnover), which is a continuous processes.

The cost of a stabilization path also depends on how technology affects the cost of abating emissions at a point in time and over time. In general, the cost of an emission pathway increases with the amount of emissions that must be abated at any point in time. The technological changes needed to lower the cost of abating emissions will require a mix of measures. Greatly increased government research and development, removal of market barriers to technology development and dissemination, explicit market supports, tax incentives and appropriate emission constraints will probably act together to stimulate the technology needed to lower the costs of stabilizing atmospheric CO_2 concentration.

With regard to mitigation costs, a positive discount rate lowers the present value of the costs incurred. This is because it places a lower weight on investments made in the future. Indeed, the further in the future an economic burden (here, emission reductions) lies, the lower the present value of costs. In a wider context, discounting reduces the weight placed on future environmental impacts relative to the benefits of current energy use. Its use makes serious challenges, such as rapid switching of energy systems in the future, seem easy in terms of present dollars and may affect consideration of intergenerational equity.

Integrating information on impacts and mitigation costs

This report provides a framework for integrating information on the costs, benefits and impacts of climate change. Concentration stabilization profiles that follow "business-as-usual" emissions for periods of a few to several decades should not be construed as a suggestion that no action is required for those periods. In fact, studies suggest that even in those cases of business-as-usual emissions for some period of time, actions must be taken during that time to cause emissions to decline subsequently. The strategies for developing portfolios of actions leading to immediate or eventual reductions below business-as-usual are discussed below.

Numerous policy measures are available to facilitate adaptation to climate change, to reduce emissions of greenhouse gases, and to create technologies that will reduce emissions in the future. If expressed in terms of CO_2 equivalent or total radiative forcing, a given stabilization level can be met through various combinations of reductions in the emissions of different gases and by enhancing sinks of greenhouse gases. Governments must decide both the amount of resources to devote to this issue and the mix of measures they believe will be most effective. IPCC WGIII (1996)[2] states that significant "no-regrets"[3] measures are available. Because no-regrets policies currently are beneficial, the issues facing governments are how to implement the full range of no-regrets measures and whether, and if so, when and how far to proceed beyond purely no-regrets options. The risk of aggregate net impacts due to climate change, consideration of risk aversion, and the application of the precautionary principle provide rationales for action beyond no-regrets.

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[2] Hereafter referred to as SAR WGIII.

[3] "No regrets" measures are those whose benefits, such as reduced energy costs and reduced emissions of local/regional pollutants, equal or exceed their cost to society, excluding the benefits of climate change mitigation.

1. INTRODUCTION

1.1 Aims

Based on material in the IPCC Second Assessment Report (IPCC WGI, WGII and WGIII, 1996[4]), this Technical Paper expands and clarifies the scientific and technical issues relevant to interpreting the objective of the United Nations Framework Convention on Climate Change (UN/FCCC) as stated in Article 2 (United Nations, 1992):

> "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

Article 2 requires stabilization of greenhouse gas concentrations. Here we emphasize CO_2, but we also consider several other gases to illustrate the uncertainties associated with a more general multi-gas stabilization objective and to highlight what can be said with some confidence.

The clear historical relationship between CO_2 emissions and changing atmospheric concentrations, as well as our considerable knowledge of the carbon cycle, implies that continued fossil fuel, cement production, and land-use related emissions of CO_2 at historical, present, or higher rates in the future will increase atmospheric concentrations of this greenhouse gas. Understanding how CO_2 concentrations change in the future requires quantification of the relationship between CO_2 emissions and atmospheric concentration using models of the carbon cycle.

This paper draws on information presented in SAR WGI, WGII and WGIII. We first review the results of a range of standardized calculations (presented in the 1994 IPCC Report[5] and SAR WGI) used to analyse the relationships between emissions and concentrations for several levels of atmospheric CO_2 stabilization, including two pathways to reach each level. We then consider the effects of other greenhouse gases and sulphate aerosol (from SO_2 emissions), and estimate the temperature and sea level changes associated with the various stabilization levels studied. Finally, we review briefly the potential positive and negative impacts associated with the projected temperature and sea level changes, and discuss the mitigation costs associated with stabilizing greenhouse gases.

[4] Hereafter referred to as SAR WGI, SAR WGII and SAR WGIII.
[5] IPCC, 1995, hereafter referred to as IPCC94.

The temperature change and sea level rise projections are calculated using the simplified models used in SAR WGI, models that have been calibrated against more complex models. These more complex models are not used for the analyses presented here because they are too expensive and time consuming to run for the large number of cases studied here, and because their global mean results may be adequately represented using simpler models (see IPCC Technical Paper: *An Introduction to Simple Climate Models used in the IPCC Second Assessment Report* (IPCC TP SCM, 1997)).

A range of alternative concentration profiles were employed in SAR WGI to assess the potential climatic consequences of: (*a*) stabilizing CO_2 concentrations via a range of pathways; (*b*) plausible future emissions scenarios for trace gases other than CO_2; and (*c*) several levels of future SO_2 emissions (leading to different levels of aerosol). In the context of Article 2, it is important to investigate a range of emissions profiles of greenhouse gases that might stabilize atmospheric concentrations so that different possibilities and impacts can be considered. In addition, evaluating several profiles avoids making any judgement about the rates or magnitudes of climate change that would qualify as "dangerous interference". Because an understanding of the constraints on the stabilization of greenhouse gases is fundamental to policy formulation with regard to the goals of the UN/FCCC and its implementation, this Technical Paper provides both a tutorial and an expanded evaluation of the stabilization calculations presented in IPCC94 and SAR WGI and WGIII.

The Technical Paper will specifically:

(*a*) Present a tutorial on stabilization of greenhouse gases, the estimation of radiative forcing, and the concept of "equivalent CO_2" (the concentration of CO_2 that leads to global mean radiative forcing consistent with projected increases in all gases when a suite of gases is being considered);

(*b*) Present a basic set of CO_2 stabilization profiles leading, via two types of pathway, to stabilization between 350 and 750 ppmv, with a single profile stabilizing at 1 000 ppmv;

(*c*) Present the deduced emissions for the aforementioned concentration stabilization profiles;

(*d*) Consider stabilization of radiative forcing agents other than CO_2;

(*e*) Compute (using a simplified climate model) global mean temperature and sea level changes for the CO_2 profiles using a range of emissions assumptions for CH_4, N_2O and SO_2, and different values of the climate sensitivity and ice-melt model parameter values in order to characterise uncertainties (see IPCC TP SCM, 1997 for a discussion of simple climate models);

(*f*) Discuss the potential environmental consequences of the derived changes in temperature and sea level;

(*g*) Discuss the factors that influence mitigation costs; and

(*h*) Review the methodology for integrating climate and sea level change effects and mitigation costs to produce a more complete view of the consequences of changing atmospheric composition.

1.2 Key Points

1.2.1 Some Fundamentals Regarding Greenhouse Gases and Tropospheric Aerosols (see SAR WGI for more details)

Of the greenhouse gases, this paper focuses on CO_2 because it has had, and is projected to have, the largest effect on radiative forcing (in 1990, 1.56 W m^{-2} for CO_2 versus 0.47 W m^{-2} for CH_4, 0.14 W m^{-2} for N_2O and 0.27 W m^{-2} for the halocarbons). For a discussion of the utility of radiative forcing in climate change studies see IPCC94 (Chapter 4) and IPCC TP SCM (1997). This paper also considers the effects that arise when a series of assumptions are made about potential future emissions of other greenhouse gases and SO_2, a primary aerosol precursor (aerosols may act to cool the planet).

Tropospheric aerosols (microscopic airborne particles) resulting from combustion of fossil fuels, biomass burning, and other anthropogenic sources have led to a highly uncertain estimate of direct forcing of -0.5 W m^{-2} (range: -0.25 to -1.0 W m^{-2}) over the past century as a global average. There is possibly also a negative indirect forcing – via modifications of clouds – that remains very difficult to quantify (SAR WGI: Chapter 2). Because aerosols have short lifetimes in the atmosphere, their distribution and hence immediate radiative effects are very regional in character. Locally, the aerosol forcing can be large enough to more than offset the positive forcing due to greenhouse gases. However, although the negative forcing is focused in particular regions and subcontinental areas, it has continental to hemispheric scale effects on climate because of couplings through atmospheric circulation.

1.2.2 Stabilization of CO_2 Concentrations (see SAR WGI for more details)

Among the range of stabilization cases studied, accumulated anthropogenic emissions from 1991 to 2100 fall between 630 and 1410 GtC, for stabilization levels between 450 and 1000 ppmv. For comparison, the corresponding accumulated emissions for the IPCC IS92 emissions scenarios range from 770 to 2190 GtC.

For each stabilization level from 350 to 750 ppmv, two pathways are considered: the "S" pathways, that depart immediately from IS92*a*, and the "WRE" pathways that follow IS92*a* initially. A single pathway that stabilizes at 1 000 ppmv is also considered. The WRE pathways imply higher emissions in the short-term, but an earlier and more rapid change from increasing to decreasing emissions, and lower emissions later.

Ecosystem and oceanic feedbacks may reduce terrestrial and oceanic carbon storage to levels somewhat below those assumed in the simplified global carbon cycle models used here and in the Second Assessment Report. Uncertainties resulting from the omission of potentially critical oceanic and biospheric processes during transient climate change could have a significant effect on the conclusions regarding emissions associated with stabilization.

1.2.3 Taking the Climatic Effects of Other Greenhouse Gases and Aerosols into Account: the Concept of Equivalent CO_2

Subject to uncertainties concerning the climate sensitivity (see below), future anthropogenic climate change is determined by the sum of all positive and negative forcings arising from all anthropogenic greenhouse gases and aerosols, not by the level of CO_2 alone. The forcing scenarios used in many of the model runs are the sum of the radiative forcings of all the trace gases (CO_2, CH_4, O_3, etc.) and aerosols. The total forcing may be treated as if it came from an "equivalent" concentration of CO_2. Therefore, the "equivalent CO_2" concentration is the concentration of CO_2 that would cause the same amount of global mean radiative forcing as the given mixture of CO_2, other greenhouse gases, and aerosols.

The difference between the equivalent CO_2 level and the true CO_2 level depends on the levels at which the concentrations of other radiatively active gases and aerosols are stabilized. The stabilization levels chosen for CH_4, N_2O and SO_2 can significantly affect equivalent CO_2. If the emissions of these gases were held constant at today's levels, equivalent CO_2 would stabilize at approximately 26 ppmv (S350) to 74 ppmv (WRE1000) ppmv above the level for CO_2 alone. Because the effects of greenhouse gases are additive, stabilization of CO_2 concentrations at any level above about 500 ppmv is likely to result in atmospheric changes equivalent to at least a doubling of the pre-industrial CO_2 level.

1.2.4 The Global Temperature and Sea Level Implications of Stabilizing Greenhouse Gases

This report considers two simple indices of climate change, global mean temperature and sea level rise. The change in global mean temperature is the main factor determining the rise in sea level; it is also a useful proxy for overall climate change. It is important to realize, however, that climate change will not occur uniformly over the globe; the changes in temperature and in other climate variables such as precipitation, cloudiness, and the frequency of extreme events, will vary greatly among regions. In order to evaluate the consequences of climate change, one must consider the spatial variability of all factors: climate forcing, climate response, and the vulnerability of regional human and natural resource systems. However, consideration of regional details is outside the scope of this paper.

The spatial patterns of some radiative forcing agents, especially aerosols, are very heterogeneous and so add further to the spatial variability of climate change. In this paper, aerosol forcing is presented in terms of global averages so that an impression can be gained of its likely overall magnitude, its effect on global average temperature, and its effect on sea level rise. The effect of aerosol forcing on the detail of climate change, however, is likely to be quite different from the effect of a forcing of similar magnitude, in terms of global average, due to greenhouse gases. In terms of regional climate change and impacts, therefore, the negative forcing or cooling from aerosol forcing must not be considered as a simple offset to that from greenhouse gases.

Temperature and sea level projections depend on the assumed climate sensitivity, the target and pathway chosen for CO_2 concentration stabilization, and the assumed scenarios for other greenhouse gases and aerosol forcing. The relative importance of these factors depends on the time interval over which they are compared. Out to the year 2050, CO_2 concentration pathway differences for any single stabilization target are as important as the choice of target; but on longer time-scales the choice of target is (necessarily) more important. Outweighing all of these factors, however, is the climate sensitivity, uncertainties in which dominate the uncertainties in all projections.

1.2.5 Impacts

A great deal is known about the potential sensitivity and vulnerability of particular systems and sectors, and both substantial risks and potential benefits can be identified. Currently however, our ability to integrate this information into an assessment of impacts associated with different stabilization levels or emissions trajectories is relatively limited.

While the regional patterns of future climate change are poorly known, it is clear that the altered patterns of radiative forcing associated with anthropogenic emissions will alter regional climates noticeably, and will have different effects on climate conditions in different regions. These local and regional changes will necessarily include changes in the lengths of growing seasons, the availability of water, and the incidence of disturbance regimes (extreme high temperature events, floods, droughts, fires, and pest outbreaks), which, in turn, will have important impacts on the structure and function of both natural and human-made environments. Systems and activities that are particularly sensitive to climate change and related changes in sea level include: forests; mountain, aquatic and coastal ecosystems; hydrology and water resource management (including the cryosphere); food and fibre production; human infrastructure and human health. Most existing impacts studies are analyses of what may result from the equilibrium climate changes associated with a doubled equivalent CO_2 level; few studies have considered responses over time to more realistic conditions involving increasing concentrations of greenhouse gases.

Impacts are not a linear function of the magnitude and rate of climate change. For some species (and hence systems), thresholds of change in temperature, precipitation, or other factors may exist, which, once exceeded, may lead to discontinuous changes in viability, structure, or function.

Aggregation of impacts to produce a global assessment is not currently possible because of our lack of knowledge of regional climate changes and regional responses, because of the difficulty of valuing impacts on natural systems and human health, and because of issues related to both interregional and intergenerational equity.

The ultimate concentration of greenhouse gases reached in the atmosphere, as well as the speed at which concentrations increase, is likely to influence impacts, because a slower rate of climate change will allow more time for systems to adapt. However, knowledge is not currently sufficient to identify clear threshold rates and magnitudes of change.

1.2.6 Mitigation Costs of Stabilizing CO_2 Concentrations

Factors that affect CO_2 mitigation costs include:

(*a*) Future emissions in the absence of policy intervention (“baselines”);

(*b*) The concentration target and route to stabilization, which determine the carbon budget available for emissions;

(*c*) The behaviour of the natural carbon cycle, which influences the emissions carbon budget available for any chosen concentration target and pathway;

(*d*) The cost differential between fossil fuels and carbon-free alternatives and between different fossil fuels;

(*e*) Technological progress and the rate of adoption of technologies that emit less carbon per unit of energy produced;

(*f*) Transitional costs associated with capital stock turnover, which increase if carried out prematurely;

(*g*) The degree of international cooperation, which determines the extent to which low cost mitigation options in different parts of the world are implemented; and

(*h*) Assumptions about the discount rate used to compare costs at different points in time.

1.2.7 Integrating Information on Impacts and Mitigation Costs

This reports provides a framework for integrating information on the costs, benefits and impacts of climate change. The points below must be prefaced with the critical observation that concentration stabilization profiles that follow "business-as-usual" emissions for periods of a few to several decades should not be construed as a suggestion that no action is required for those periods. In fact, studies suggest that even in those cases of business-as-usual emissions for some period of time, actions must be taken during that time to cause emissions to decline subsequently. The strategies for developing portfolios of actions leading to immediate or eventual reductions below business-as-usual are discussed below.

This paper is designed to demonstrate how information can be assembled on the costs, impacts and benefits of stabilizing atmospheric greenhouse gases. This analysis, which supports many decision making formats, has two "branches". The first branch, "impacts", assembles information beginning with assumed concentration changes, and then evaluates potential climate change, and its consequences. The second branch, "mitigation", assembles information on emissions and mitigation costs associated with achieving a range of stabilization pathways and levels. The two branches must be combined to produce an integrated assessment of climate change and stabilization (Figure 3).

If expressed in terms of CO_2 equivalent or total radiative forcing, a given stabilization level can be met through various combinations of reductions in the emissions of different gases and by enhancing sinks of greenhouse gases. Considering all such options, and selecting the least expensive ones while taking account of different sources and sinks, should lower the costs of mitigation. Approaching an optimum mix requires information about the concentration and climate implications of different emissions strategies, the mitigation costs and other characteristics of the different options, and decisions about the appropriate timescales and indices of impacts (climate and non-climate) to be used in comparing the different gases. Because of high uncertainty, as improved information becomes available, these mixes of options must be re-evaluated and modified in an evolving process.

In order to implement a portfolio of actions to address climate change, governments must decide both the amount of resources to devote to this issue and the mix of measures they believe will be most effective. Because no-regrets policies are currently beneficial, the issues facing governments are how to implement the full range of no-regrets measures and whether, and if so, when and how far to proceed beyond purely no-regrets options. The risk of aggregate net impacts due to climate change, consideration of risk aversion, and the application of the precautionary principle provide rationales for action beyond no-regrets (SAR WGIII).

Numerous policy measures are available to facilitate adaptation to climate change, to reduce emissions of greenhouse gases, and to create technologies that will reduce emissions in the future. These include immediate reductions in emissions to slow climate change; research and development on new supply and conservation technologies to reduce future abatement costs; continued research to reduce critical scientific uncertainties; and investments in actions to help human and natural systems adapt to climate change through mitigation of negative impacts and through advantages resulting from increasing CO_2 (e.g., increased water or nutrient use efficiency of some crops with elevated CO_2). The issue is not one of "either-or" but one of finding the right mix (i.e., portfolio) of options, taken together and sequentially. The mix at any point in time will vary and depend upon the concentration objective, which may itself be adjusted with advances in the scientific and economic knowledge base. The appropriate portfolio also varies among countries and depends upon energy markets, economic considerations, political structure, and societal receptiveness.

1.3 A "Road map" to this Report

1.3.1 Report Strategy

The organization of this report is illustrated in Figure 3. This organization is designed to assemble important information relevant to a wide variety of policy makers concerned with implementing the goal of the UN/FCCC. Information falls into two general categories needed to understand the costs and benefits associated with atmospheric stabilization. The first category (or "branch") assembles information about climate change, and its consequences, whereas the second category assembles information about emissions and mitigation costs. This approach organizes information from SAR WGI, WGII and WGIII relevant to the issue of greenhouse gas stabilization for use in a more integrated analysis.

The strategy chosen flows forward from SAR WGI, which considers a series of concentration profiles as a basis for deducing anthropogenic emissions consistent with the underlying

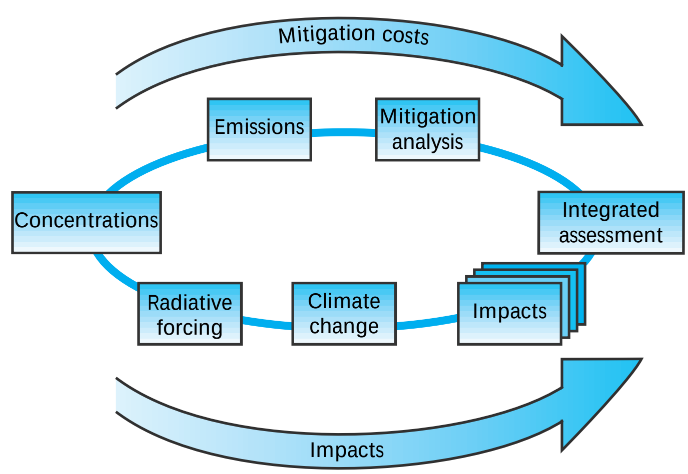

Figure 3. An overview of the structure and logic of this Technical Paper.

physics and biology of oceanic and terrestrial ecosystems, albeit simplified (see Section 2.2.1.3 on uncertainties). Beginning with concentration profiles, we calculate, using simplified climate models from SAR WGI (Section 6.3), the global mean temperature and sea level consequences of these CO_2 concentration profiles (covered in Section 2.3). We also carry out sensitivity analyses showing the effects of other gases and aerosols on these central CO_2 analyses. These global mean temperature and sea level changes provide a context for considering the consequences for natural resources, infrastructure, human health, and other sectors affected by the climate (covered in Section 3.1). This completes the "impacts branch" of the analysis (see Figure 3). Note that this analysis provides only a simplified global mean view of consequences. For a more appropriately detailed view, regional climate changes and system vulnerabilities must be considered (see SAR WGI: Chapter 6 and SAR WGII for discussions of regional climate change and vulnerabilities).

The "mitigation costs branch" of this analysis also begins with concentration profiles (see Figure 3). The concentration profiles are then used together with carbon cycle models (see SAR WGI: Section 2.1 and IPCC94: Section 1.5) to compute anthropogenic emissions (covered in Section 2.2.1). These deduced emissions can be used in economic models to estimate the "mitigation" costs of following the stabilization profile rather than a business-as-usual trajectory (covered in Section 3.2), given the appropriate assumptions. Mitigation costs can be computed for a wide range of stabilization profiles and with multiple economic models to provide a sense of the range of possible mitigation costs as a function of an eventual stabilization target and pathway. Note that all of these analyses consider the economic costs for mitigation associated with particular specified concentration profiles. They are thus not "optimal" trajectories nor do they represent policy recommendations. Rather, they are illustrative of the links from concentrations to emissions and thence to mitigation costs.

The two branches come together, conceptually, in the end in the section on integrating information on impacts and mitigation costs (Section 3.3). Neither branch provides a complete basis for decision making. This general type of problem supports a wide range of decision-making frameworks, which may integrate this information in a variety of ways (see SAR WGIII: Chapter 4).

1.3.2 Decision-making Frameworks

Although it is important to assemble information about the costs and benefits associated with atmospheric stabilization, assemblage is not the same as recommending a simple cost-benefit analysis. The cost-benefit paradigm is the most familiar decision related application of the economics of balancing costs and benefits, but it is not the only approach available. Other techniques include cost effectiveness analysis, multi-criteria analysis, and decision analysis (SAR WGIII, p.151). Decision-making frameworks must consider uncertainty in projected concentration changes, in consequent climate effects, and in consequences for human and natural systems. A wide range of paradigms for dealing with this uncertainty likewise exist, and are summarized in SAR WGIII.

The analysis of biophysical and economic uncertainties presented in this report is only a brief summary of issues. While a more detailed discussion can be found in SAR WGI, WGII, and WGIII, the full dimensions of uncertainty in the analysis linking concentrations to, ultimately, costs and consequences, remains an active area of investigation. Regardless of the method eventually employed in the decision-making process, information about the costs and benefits of emissions mitigation can be used to improve the quality of policy decisions.

The present document makes no attempt to judge the practical issues of implementing emissions mitigation strategies, nor does it consider the fairness and equity concerns that surround such deliberations. The global perspective employed here is for methodological and pedagogical convenience: it is not meant to imply that regional issues are less important — clearly, climate policy must be made within the context of a wide array of national and international policy considerations. Such matters add to the rich complexity of issues with which policy makers must grapple.

2. GEOPHYSICAL IMPLICATIONS ASSOCIATED WITH GREENHOUSE GAS STABILIZATION

2.1 General Principles of Stabilization: Stabilization of Carbon Dioxide and Other Gases

There has been confusion about the scientific aspects of stabilizing the atmospheric CO_2 concentration vis-à-vis the stabilization of the concentrations of other gases, particularly with regard to the concept of "lifetime". The processes that control the lifetimes of the key gases are reviewed in detail in SAR WGI (Chapter 2) and IPCC94, which provides vital background material for this brief review.

Most carbon reservoirs *exchange* CO_2 with the atmosphere: they both absorb (oceans) or assimilate (ecosystems), and release (oceans) or respire (ecosystems) CO_2. The critical point here is that anthropogenic carbon emitted into the atmosphere is not *destroyed* but *adds* to and is *redistributed* among the carbon reservoirs. These reservoirs exchange carbon between themselves on a wide range of time-scales determined by their respective turnover times. Turnover times range from years to decades (carbon turnover in living plants) to millennia (carbon turnover in the deep sea and in long-lived soil pools). These time-scales are generally much longer than the average time a particular CO_2 molecule spends in the atmosphere, which is only about four years. The large range of turnover times has another remarkable consequence: the relaxation of a perturbed atmospheric CO_2 concentration towards a new equilibrium cannot be described by a single time constant. Thus, attempts to characterize the removal of anthropogenic CO_2 from the atmosphere by a single time constant (e.g., 100 years) must be interpreted in a qualitative sense only. Quantitative evaluations based on a single lifetime are erroneous.

In contrast to CO_2, aerosols and non-CO_2 greenhouse gases such as the halocarbons, methane and N_2O are destroyed (e.g., by oxidation, photochemical decomposition, or, for aerosols, by deposition on the ground). The time such a molecule (or particle) spends on average in the atmosphere (i.e., its turnover time) is equal or roughly similar to the adjustment time.

Methane is emitted to the atmosphere from a range of sources (see SAR WGI) and is destroyed mainly through oxidation by the hydroxyl radical (OH) in the atmosphere and by soil micro-organisms. The adjustment time of a perturbation in atmospheric methane is controlled by its oxidation (to CO_2 and water vapour) rather than by exchange with other reservoirs, which could subsequently re-release methane back to the atmosphere. Methane's lifetime is complicated by feedbacks between methane and OH, such that increasing the methane concentration changes the methane removal rate by -0.17 to +0.35 per cent per 1 per cent increase in methane (SAR WGI: Section 2.2.3.1). Many other feedback processes in the CH_4—CO—O_3—OH—NO_x—UV system also influence the lifetime of methane. Methane can be stabilized on the time-scale of its atmospheric lifetime: decades or less.

Nitrous oxide has a long lifetime, 100 to 150 years. N_2O is removed from the troposphere (where it acts as a greenhouse gas) by exchange with the stratosphere where it is slowly destroyed by photochemical decomposition. Like methane, its lifetime is controlled by its destruction rate, and, like methane, it is destroyed rather than exchanged with other reservoirs of N_2O. Stabilization of the N_2O concentration requires reduction of sources, and such reductions would need to extend over lengthy periods to influence concentrations because of the ~120-year lifetime of this gas. On the other hand, atmospheric aerosol concentration adjusts within days to weeks to a change in emissions of aerosols and aerosol precursor gases.

2.2 Description of Concentration Profiles, Other Trace Gas Scenarios and Computation of Equivalent CO_2

2.2.1 Emission Consequences of Stabilization

2.2.1.1 Concentration Profiles Leading to Stabilization

In this Technical Paper, we evaluate the 11 illustrative CO_2 concentration profiles (stabilizing at 350 to 1 000 ppmv, referred to as the "S" and "WRE" profiles) as discussed in SAR WGI. These profiles prescribe paths of concentration with time, leading gradually to stabilization at the prescribed level (Figure 4). The WRE profiles prescribe larger increases in CO_2 concentration earlier in time when compared with the S profiles, but lead to the same stabilized levels (Wigley, *et al.*, 1996). The concentration profiles can also be used as input to compute a range of allowed emissions over time. Deduced emissions, in turn, can be used as inputs to economic models to compute the mitigation costs associated with reducing emissions to follow a specified concentration profile. It should be noted that this approach does not allow calculation of, or imply anything about, optimal paths of emissions.

2.2.1.2 Emissions Implications of Stabilization of CO_2 Concentrations

In this analysis, we again consider the S350–750 profiles and the WRE350–1000 profiles described in IPCC94 (Chapter 1) and SAR WGI (Section 2.1), but more completely than was possible in either of those documents. First, we present graphs showing CO_2 concentrations versus time (Figure 4) and the corresponding emissions versus time for all 11 profiles together with, for comparison, the IS92*a, c,* and *e* scenarios (Figure 5). Note that CO_2 emissions for the IS92*a* and *e* scenarios are higher in year 2050 than are emissions for

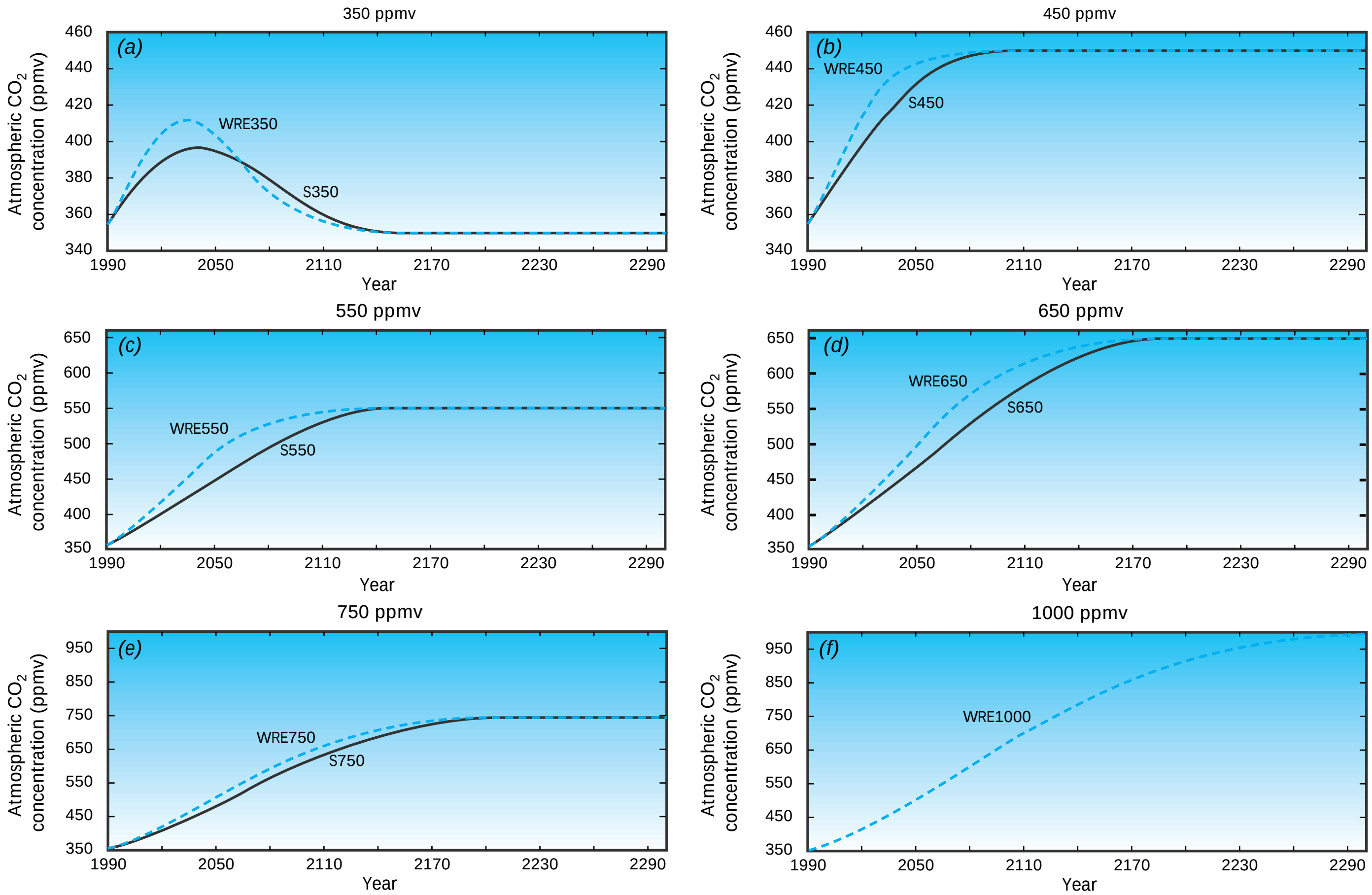

Figure 4. Profiles of CO_2 leading to stabilization at concentrations from 350 to 1000 ppmv. For comparison the pre-industrial concentration was close to 280 ppmv and the current concentration is approximately 360 ppmv. For stabilization at concentrations from 350 to 750 ppmv, two different routes to stabilization are shown: the S profiles (from IPCC94) and the WRE profiles (from Wigley, *et al.*, 1996) which allow CO_2 emissions to follow IS92a until 2000 or later (depending on the stabilization level). A single profile is defined for 1000 ppmv. These two sets of profiles are merely examples from a range of possible routes to stabilization that could be defined.

all the S and WRE profiles (except for WRE1000, which was constructed to follow IS92*a* concentrations to 2050). The IS92*c* scenario suggests emissions lower in 2050 than for S550, WRE550 and all higher levels of stabilization for either emissions pathway.

For further information concerning the assumptions made to derive these results, as well as inter-model differences, see Enting, *et al.*, (1994). For the given stabilization profiles, a period of increasing emissions is generally followed by a rapid decrease to a stabilized level. We note again that this pattern does not apply to the S350 and WRE350 profiles, and that they imply negative emissions for a period of time in these cases, because 350 ppmv is lower than the current atmospheric concentration. It can be seen from Figure 5 that the WRE profiles allow higher emissions initially, but imply a more rapid transition from increasing to decreasing emissions, and lower emissions later, before emissions for both the S and WRE profiles converge. We do not address here what an optimal emissions pathway is, but merely show the emissions consequences of prescribed pathways to concentration stabilization.

Figure 6 shows the cumulative CO_2 emissions over time for stabilization at 350, 450, 550, 750, and 1 000 ppmv, and the corresponding emissions associated with the IS92*a*, *c* and *e* scenarios. It shows clearly that by 2100, cumulative emissions associated with the IS92*a* and *e* scenarios are higher than those for all S and WRE profiles. As in Figure 5, it is clear in Figure 6 that the WRE profiles allow significantly higher emissions in the near-term future, but also that for later times the cumulative emissions in the WRE profiles are very similar to the total amount under the S profiles. This is because, for a given stabilization level, the long-term cumulative emissions are relatively insensitive to the pathway taken to stabilization.

The deduced emissions for a given concentration profile leading to stabilization define the “carbon budget” available for anthropogenic emissions from fossil fuel burning, cement manufacture, land-use conversion, and other activities. The larger the cumulative emissions (corresponding to higher stabilization levels) the larger the carbon budget available for anthropogenic activities (see Section 3.2). The size of the carbon budget is also sensitive, especially early on, to the choice of pathway (illustrated by differences between the S and WRE profiles in Figure 6).

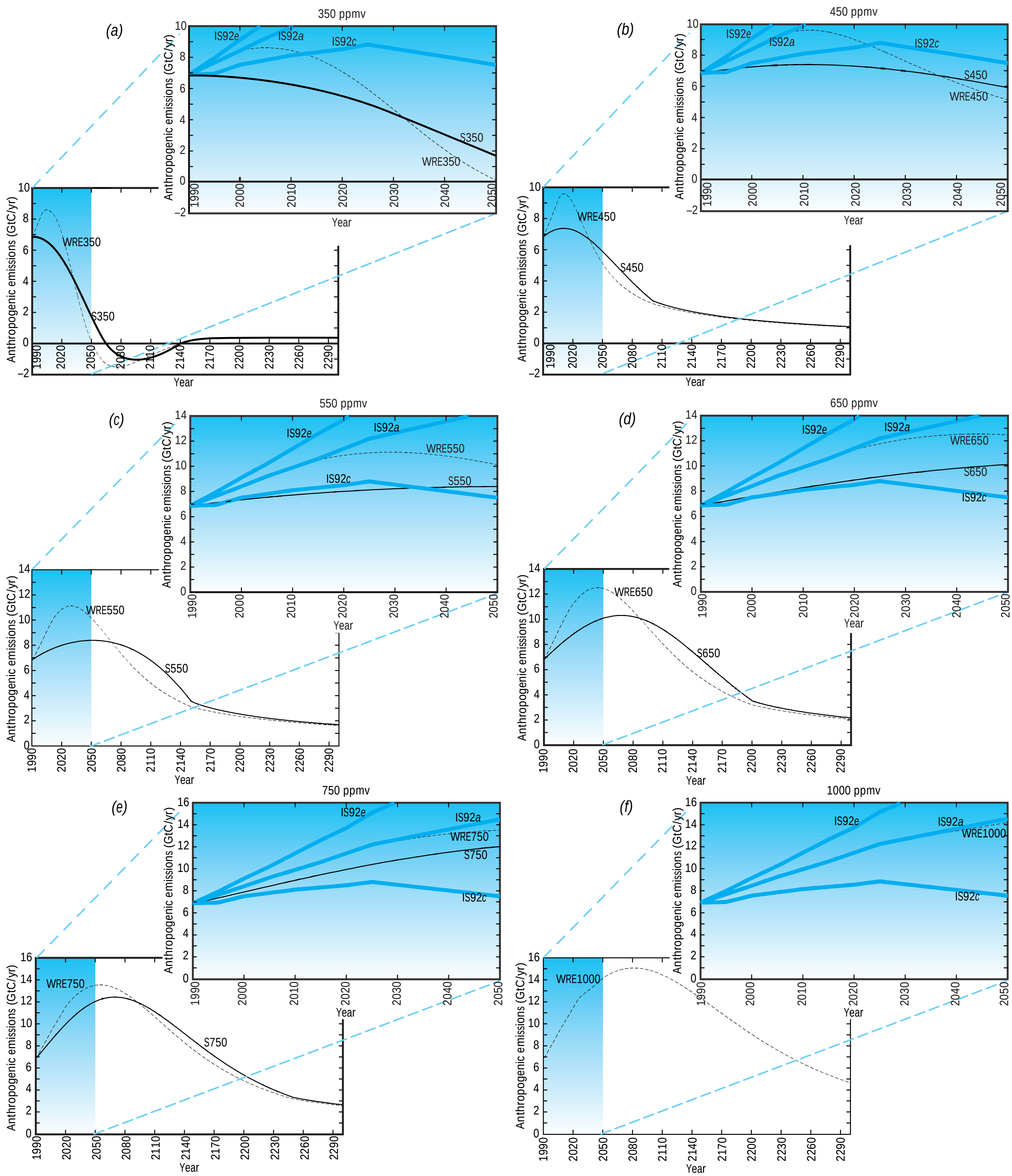

Figure 5. Implied anthropogenic (fossil fuel, cement and land-use) emissions of CO_2 from 1990 to 2300 that achieve stable CO_2 concentrations via the profiles shown in Figure 4 computed using the Bern carbon cycle model. The period from 1990 to 2050 is shown in more detail in the expanded panel with the CO_2 emissions from IS92*a*, *c* and *e* for comparison. The WRE results, which allow CO_2 emissions to follow IS92*a* initially, have higher maximum emissions than results for the S profiles, but have a more rapid and earlier transition from increasing to decreasing emissions. The analyses in IPCC94 and SAR WGI (Section 2.1) show that results from other models may differ from these results by ±15 per cent. Further uncertainty arises from inadequacies in our understanding, and exclusion from the carbon cycle models used in SAR WGI (Section 2.1), of critical biospheric processes and their responses to climate change (see Section 2.2.1.3).

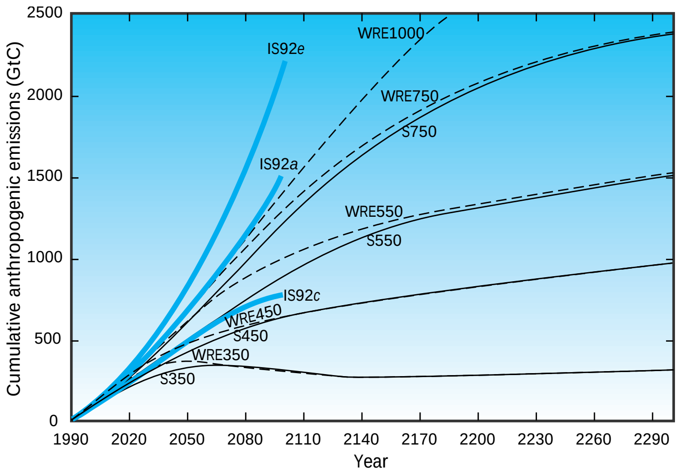

Figure 6. Anthropogenic CO_2 emissions accumulated over time from 1990. Initially, the cumulative emissions are lower for the S profiles than the WRE profiles, but as the emissions are accumulated over progressively longer periods the results for the two profiles converge for any given stabilization level. Note that the higher the eventual stabilization level, the greater the cumulative emissions (referred to as "the carbon budget" in the text) and the later the convergence of the two different profiles. These results were produced using the Bern carbon cycle model (see Section 2.3.3 and the caption of Figure 5 for a discussion of uncertainties).

2.2.1.3 *Critical Carbon Cycle Uncertainties*

For calculations of emissions consistent with a range of stabilization levels and pathways, SAR WGI (Section 2.1) used models and input data which were generally accepted at that time. In this Technical Paper, we review and synthesise material from the SAR and so rely on the models as presented in that document. However, work reviewed in SAR WGI (Section 2.1 and Chapters 9 and 10), suggested that the mechanisms not included in simplified global carbon cycle models could affect the results significantly. Uncertainties resulting from the omission of some potentially critical oceanic and biospheric processes, and their response during transient climate changes could have a significant effect on the conclusions regarding impacts.

The models of the carbon cycle used in SAR WGI, and relied on in this Technical Paper, include CO_2 fertilization of plant growth as the sole interaction between environmental conditions and terrestrial carbon. As discussed in SAR WGI (Section 2.1 and Chapter 9), this assumption is potentially flawed in several ways. First, ecosystem feedbacks may modulate the sensitivity of terrestrial carbon storages to levels somewhat below those assumed in the simplified global carbon cycle models used in SAR WGI. This uncertainty is explored in diagrams shown in SAR WGI (Section 2.1) and IPCC94 (Chapter 1). Second, the sensitivity to CO_2 may change via acclimation, again potentially weakening the effect over time. Other plant processes may act in the opposing direction and the balance in terms of carbon uptake is not known (SAR WGI: Chapter 9). Finally, additional processes may now and in the future affect terrestrial carbon storage. These include fertilization from nitrogen deposition; climate change (Dai and Fung, 1993); and land-use change (SAR WGI: Section 2.1 and Chapter 9). Some of these mechanisms, such as nitrogen deposition, may "saturate" in their effects and even cause forest die back in the future. Although sensitivity to these interactions has been explored (e.g., VEMAP, 1995), no consensus yet exists on how best to incorporate them into simplified models. Synthesising the results in SAR WGI (Section 2.1 and Chapter 9) and IPCC94 (Chapter 1), biospheric exchange could modify the cumulative emissions from fossil fuels during stabilization by ±100 GtC from the cases discussed. The impact of this on mitigation costs will be discussed in Section 3.2.

In addition, no climate feedback to ocean circulation and biogeochemistry or terrestrial ecosystems has been included in the carbon cycle model calculations of emissions from concentrations. There is theoretical (Townsend, *et al.*, 1992; IPCC94: Chapter 1) and observational evidence to support a significant sensitivity of biospheric CO_2 emissions to temperature (Keeling, *et al.*, 1995). However, any such temperature sensitivity probably varies geographically (IPCC94: Chapter 1) and its overall effects are thus sensitive to regional climate changes, rather than changes in the global mean (see Section 3.1). Warming and changes in precipitation could cause short-term effluxes of carbon from ecosystems (Smith and Shugart, 1993; Townsend, *et al.*, 1992; Schimel, *et al.*, 1994; Keeling, *et al.*, 1995; SAR WGI: Chapter 9) but could also cause long-term accumulation (VEMAP, 1995).

Climate feedbacks could significantly affect the oceanic carbon cycle as well. In IPCC94 (Chapter 1), a long-term range of uncertainty for future ocean uptake was estimated as -120 ppmv to +170 ppmv, based on assumptions regarding the role of biological processes in potential future oceans with two different steady state oceans. The impacts of changing ocean circulation during a climate transition (as in Manabe and Stouffer, 1994), however, have not yet been examined. The potential effects of ocean carbon cycle changes could noticeably modify the fossil fuel emissions consistent with stabilization, and future analyses should take account of these factors.

2.2.2 Stabilization of CH_4, N_2O and Other Gases

The potential global mean temperature and sea level consequences of the various CO_2 concentration stabilization profiles are described in Section 2.2.4. To make these calculations, assumptions are needed concerning how the emissions or concentrations of other gases may change in the future, because CO_2 is not the only anthropogenic climate forcing factor. Although Article 2 of the UN/FCCC has stabilization of greenhouse gas concentrations in general as its goal, it does not specify stabilization levels nor the pathways to stabilization. Furthermore, the UN/FCCC does not cover SO_2, a major aerosol precursor, nor other aerosols or aerosol precursors. Here, therefore, we consider a range of possibilities of how other trace gases may change in the future.

The greenhouse gases other than CO_2 that must be considered are those covered in SAR WGI: CH_4, N_2O, the halocarbons, and tropospheric ozone. Water vapour, also a greenhouse gas, enters into our analysis as a part of climate feedback (see IPCC TP SCM, 1997). Methane influences climate directly and also through its effects on atmospheric chemistry (generating tropospheric ozone) and as a result of its oxidation. Oxidation of methane affects tropospheric OH concentration and thereby influences the oxidizing capacity of the atmosphere, and, thus, the concentrations of other trace gases, and adds water vapour to the stratosphere. Halocarbon-induced ozone depletion in the lower stratosphere also has climatic consequences that must be accounted for (see SAR WGI: Section 2.4 and IPCC TP SCM, 1997). Finally, the emissions of SO_2 (which are oxidized to sulphate species) lead to the production of aerosol which acts to cool the climate by reflecting sunlight (SAR WGI). Sulphate particles may also act as condensation nuclei, thereby changing the radiative properties of some clouds.

Assessing the general implications of Article 2, involving the stabilization of all greenhouse gases (i.e., not just CO_2) is difficult because we lack clearly defined ranges for likely future emissions of methane, N_2O, SO_2 and other gases. Thus, one can construct a near-infinite number of factorial combinations for the various gases. We have attempted to choose some illustrative combinations to demonstrate the potential sensitivity of radiative forcing and climate responses to a range of combinations of gases and aerosols. We have not tried to "bound" the problem, as there is no agreement on the likely ranges of future methane and N_2O emissions, reflecting uncertainties in the biogeochemistry and in the sensitivity of emissions of these gases to climate. Nor is there agreement on future SO_2 emission ranges, which depend upon technology choices, economic activity, and the extent to which "clean air" policies become global.

The effects of sulphate aerosol are particularly difficult to evaluate in this regard. Aerosol effects have been important to date (see, e.g., SAR WGI: Chapter 8; Penner, *et al.*, 1994; Mitchell, *et al.*, 1995), and so must be included in any model calculations of future climate change, because the magnitude of these changes depends on the assumed history of past radiative forcing. For future climate change projections, aerosol related uncertainties are of considerable importance. These uncertainties arise for two reasons: through the uncertain relationship between SO_2 emissions and radiative forcing; and through uncertainties regarding future SO_2 emissions. These uncertainties are addressed here (see below) because they have been considered in the literature described in SAR WGI: Raper, *et al.*, (1996) address the former uncertainty (by assuming different values for the 1990 level of aerosol forcing), whereas Wigley, *et al.*, (1996) consider the latter (by evaluating future scenarios with increasing and constant SO_2 emissions).

Stabilization calculations in SAR WGI (Section 6.3) assume quite specific but arbitrary scenarios for these other gases (constant emissions for SO_2, constant concentrations for non-CO_2 greenhouse gases after 1990). In the climate calculations for the IS92 emissions scenarios, SAR WGI considers a wider range of possible future scenarios for aerosols and non-CO_2 greenhouse gases. In particular, for sulphate aerosol, SAR WGI considers both changing SO_2 emissions (as prescribed by the IS92 scenarios) and constant post-1990 SO_2 emissions.

The approach we take here is directed towards estimating both overall and individual gas sensitivities. It is based on data given by SAR WGI regarding future non-CO_2 greenhouse gas concentrations and the models used to derive these concentrations, and on the simplified climate model used in SAR WGI (Section 6.3), which (as we do here) uses individual gas forcing data as its primary input.

Some insight into the importance of non-CO_2 gases can be obtained by looking at the relative contributions of different gases to forcing under the IS92 scenarios (see Table 1). This shows that, under a range of "existing policies" scenarios, CO_2 is by far the dominant gas. Cumulatively, however, the effects of the non-CO_2 greenhouse gases may be quite appreciable: over 1990-2100 their contribution ranges from 0.7 W m^{-2} (IS92*c*) to 1.8 W m^{-2} (IS92*f*, not shown in Table 1). As percentages of the CO_2 forcing, non-CO_2 greenhouse gas forcing ranges from 28 per cent (IS92*e*) to 40 per cent (IS92*c*). This contribution is noticeably offset by negative aerosol forcing in IS92*a, b, e*, and *f*; but in IS92*c* and *d*, changes in aerosol forcing add to the forcing from other gases because SO_2 emissions in 2100 are less than in 1990. When aerosol and non-CO_2 greenhouse gas forcings are combined, their total over 1990–2100 in the IS92 scenarios ranges from 0.4 W m^{-2} (IS92*e*) to 1.0 W m^{-2} (IS92*c* and *f*). When expressed as percentages of CO_2 forcing, the values for non-CO_2 gases range from 9 per cent (IS92*e*) to 53 per cent (IS92*c*).

The figures given here are those used in SAR WGI (Section 6.3). For aerosol, SAR WGI (Section 6.3) uses only a central estimate for the relationship between SO_2 emissions and aerosol forcing (which has a total sulphate aerosol forcing contribution to 1990 of -1.1 W m^{-2}, compared to the total greenhouse gas contribution of 2.6 W m^{-2}). Changing the aerosol forcing would decrease or increase its relative importance; but this clearly would not affect the undoubted significance of non-CO_2 greenhouse gases.

It should be noted that aerosol forcing uncertainties are exacerbated by uncertainties in future SO_2 emissions, and by the uncertain influences of other aerosols (due to biomass burning, mineral dust, nitrates, etc.). With regard to future emissions, recent studies (IIASA/WEC, 1995) suggest that SO_2 emissions may be lower in the future than assumed in the IS92*a* and *e* scenarios. If so, the global offsetting effect in Table 1 may be overestimated, but SAR WGI accounts for this possibility by considering cases in which future SO_2 emissions are held constant at their 1990 level (see SAR WGI: Section 6.3). Future SO_2 emissions are the subject of some controversy, with strong arguments being presented for the likelihood of both increasing and decreasing emissions.

Scenario	*CO_2 (W m^{-2})*	*CH_4 (W m^{-2}) (%)*	*N_2O (W m^{-2}) (%)*	*Halocarbons (W m^{-2}) (%)*	*Low (mid) high SO_4 aerosol (W m^{-2}) (%)*
IS92*a*	4.35	0.78	0.37	0.28	-0.38 (-0.65) -0.93
		(18%)	(9%)	(6%)	9% (15%) 21%
IS92*c*	1.82	0.16	0.28	0.28	+0.13 (+0.24) +0.34
		(9%)	(15%)	(15%)	7% (13%) 19%
IS92*e*	6.22	1.02	0.42	0.28	-0.75 (-1.29) -1.82
		(16%)	(7%)	(4%)	12% (21%) 29%

Table 1. Relative contributions to total global radiative forcing change over 1990–2100 of different gases under the IS92*a*, *c* and *e* emissions scenarios. The forcing values here are those used in SAR WGI (Section 6.3). The low, mid and high sulphate aerosol forcing values are based on 1990 forcings of: direct aerosol forcing: -0.2, -0.3, -0.4 W m^{-2}; indirect aerosol forcing: -0.4, -0.8, -1.2 W m^{-2} (the full range of aerosol forcing uncertainty is larger than this; see SAR WGI, pp. 113-115). Only the mid-aerosol forcing values were used in SAR WGI (Section 6.3). Forcing values are given in W m^{-2}; non-CO_2 gas forcing values are also given as percentages of the CO_2 value. CH_4 forcing includes the related effects of tropospheric ozone and stratospheric water vapour changes. Halocarbon forcing includes the effects of stratospheric ozone changes.

2.2.3 Reference Stabilization Scenarios

Given the very large uncertainties in the roles of the non-CO_2 gases relative to CO_2 under an “existing policies” assumption, and given that no comprehensive studies have been carried out to examine their roles under the assumption of concentration stabilization, we can only consider them in a sensitivity study context. We, therefore, begin with a set of reference cases in which the emissions of CO_2 follow a range of stabilization pathways, the emissions of CH_4, N_2O and SO_2 are assumed to remain constant at their 1990 levels, and halocarbons follow the Montreal Protocol scenario used in the SAR WGI (Section 6.3) global mean temperature and sea level calculations.

For halocarbons in the reference scenarios we assume that the Montreal Protocol applies strictly (see SAR WGI: Chapters 2 and 6) so that there is only a single future scenario for these gases. Because the total forcing for these gases over 1990–2100 (accounting for the effects of stratospheric ozone changes) is relatively small (0.3 W m^{-2}), uncertainties due to incomplete compliance with the Protocol and/or future emissions of substitute (hydrofluorocarbon, HFC) or non-controlled gases may be even smaller. In the context of global climate change, therefore, and given that they are not addressed by SAR WGI, we have chosen not to include these uncertainties. However, should a comprehensive (multi-gas) framework for stabilization be adopted, a more detailed gas-by-gas assessment of halocarbon forcing may be required at a specific country level.

Because the calculations performed here run beyond 2100, some assumption must be made regarding halocarbon emissions after this date. If these emissions remain constant at their 2100 level, the forcing level would remain close to 0.3 W m^{-2}. This would stabilize halocarbon (primarily HFCs) concentrations at relatively high levels. For the reference cases we assume that halocarbon emissions remain constant at their 2100 levels. Hence, eventually, concentrations will remain constant in accordance with Article 2. We note, however, that the constant-2100 emissions assumption leads to a potential global mean forcing overestimate after 2100 of, eventually, up to 0.4 W m^{-2}.

For tropospheric ozone, in the absence of any projections, and again following SAR WGI (Section 6.3), we assume that the only forcing changes are those that arise from the ozone that is produced by methane induced changes in tropospheric chemistry. This term amounts to around 0.15 W m^{-2} by 2100 under IS92*a*, but is much less for the reference case of constant CH_4 emissions. Our assumption here may be unrealistic if nitrogen, hydrocarbon, or other ozone precursors associated with ozone concentrations increase due to a rise in anthropogenic pollution.

It should be noted that we are not suggesting that the reference cases in any way reflect predictions of the future, especially with regard to future SO_2 emissions, nor that they should be a target for policy. The point of the reference cases is to help assess the relative importance of CH_4, N_2O and SO_2 emissions in determining future global mean temperature and sea level change.

To quantify the sensitivity of equivalent CO_2 to other gases we consider perturbations from the reference cases in which annual CH_4 emissions increase or decrease linearly over 1990–2100 by a total of ±100 Tg(CH_4) (i.e., ±75 TgC) relative to 1990 and remain constant thereafter; annual N_2O emissions increase or decrease linearly over 1990–2100 by a total of ±2 Tg(N) relative to 1990 and remain constant thereafter; and annual SO_2 emissions increase or decrease linearly over 1990–2100 by

±50 per cent (i.e., 37.5 TgS) relative to their 1990 level and remain constant thereafter. For all three gases, these scenarios lead to concentration stabilization, effectively instantly for SO_2, over a few decades for CH_4, and over a period of centuries for N_2O. To put these perturbations into a wider context, they are compared with IS92*a*, *c* and *e* in Table 2. Note again that these perturbations should not be construed as representing particular future outcomes or policy targets.

Scenario	*CH_4 ($Tg(CH_4)$)*	*N_2O ($Tg(N)$)*	*SO_2 (% of 1990 level*
IS92*a*	410	4.1	+95%
IS92*c*	40	0.8	-28%
IS92*e*	566	6.2	+208%
Perturbation Case	±100	±2	±50%

Table 2. Emissions changes over 1990–2100 for CH_4, N_2O and SO_2 under IS92*a*, *c* and *e* compared with the perturbation values used in this study (Units: CH_4, $Tg(CH_4)$; N_2O, Tg(N); SO_2, percentage of the 1990 level of 75 TgS).

2.2.4 Stabilizing Equivalent CO_2 Concentration

Stabilizing the atmospheric concentrations of greenhouse gases, an explicit goal of Article 2, would not necessarily result in stabilizing the human caused perturbation in radiative forcing. This is because aerosols, which are not explicitly addressed by Article 2, also have radiative effects. If concentrations of both greenhouse gases and aerosols are stabilized, this would stabilize the human perturbation in global mean radiative forcing[6]. Note also that because aerosols are not uniformly mixed gases, the geographical distribution of emissions of aerosols and their precursors can have important effects on regional climate. Stabilizing the human perturbation in global mean radiative forcing is clearly different from stabilizing CO_2 concentration alone. Thus, while mitigation efforts may target members of a suite of greenhouse gases, impact studies must consider climates influenced by multiple gases and aerosols. "Equivalent CO_2" is a technique for considering multiple radiative forcing components in the aggregate.

In the calculations of future global mean temperature and sea level change given in SAR WGI (Chapters 6 and 7), the models were driven by the total radiative forcing, which was obtained by summing the forcings due to all anthropogenic trace gases (see Table 1). In global mean terms, this total forcing can be treated as if it came solely from changes in CO_2; i.e., from an "equivalent CO_2 concentration". The equivalent CO_2 concentration, C_{eq}, can be defined, therefore, from the relationship between actual CO_2 concentration and radiative forcing. In SAR WGI, the relationship used was that from the First IPCC Assessment Report (IPCC, 1990). The uncertainty in this relationship may be up to approximately ±20 per cent (see IPCC TP SCM, 1997).

Although the equivalent CO_2 concept is pedagogically useful and provides a means to compare the effects of CO_2 with other gases, it does have disadvantages. An important disadvantage arises from the non-linear relationship between radiative forcing and CO_2 concentration. This non-linear relationship means that, at higher CO_2 levels, it requires a larger CO_2 change to increase radiative forcing by the same amount. Because of this, radiative forcing changes can be added, but CO_2 equivalents can not be. We have therefore retained the use of radiative forcing as our primary variable.

A further disadvantage of the equivalent CO_2 concept is that, in the context of impact assessments, it addresses only the climate change aspect. Other impacts of increasing CO_2 (e.g., fertilization), sulphate aerosol (acidification), and ozone may also be important. Also with the equivalent CO_2 concept, as with radiative forcing, a global aggregate measure subsumes information about regional aspects of climate change that are critical in assessing impacts. It would be possible, for example, to impose a forcing pattern on the climate system that had zero global mean forcing, but which would lead to large changes in regional climate.

We now give equivalent CO_2 results for different concentration stabilization levels. We consider S350, S450, S550, S650 S750, and WRE1000, together with the constant 1990-level emissions reference cases for CH_4, N_2O and SO_2, and halocarbon emissions following the Montreal Protocol (see Section 2.2.2). To illustrate the dependence of equivalent CO_2 level on the pathway to CO_2 stabilization, we also consider WRE550. These reference case results are given in Figure 7, where the forcing values are given relative to 1990 (some 1.3 W m^{-2} above the pre-industrial level). In the year 2500, close to the point of equivalent CO_2 stabilization, the equivalent CO_2 concentrations vary from 26 ppmv (S350) to 74 ppmv (WRE1000) above the actual CO_2 level. In all cases, the forcing difference due to gases other than CO_2 is the same: 0.66 W m^{-2} over 1990 to 2500. As noted above, this is equivalent to differing amounts of CO_2 at different concentration levels because of the non-linearity of the equivalent CO_2/radiative forcing function.

Note that here the mid-1990 equivalent CO_2 level is 342 ppmv, slightly below the actual CO_2 level (354 ppmv). This is

[6] This will not eliminate climate variability because the climate system exhibits considerable natural variability, beyond anthropogenic influences.

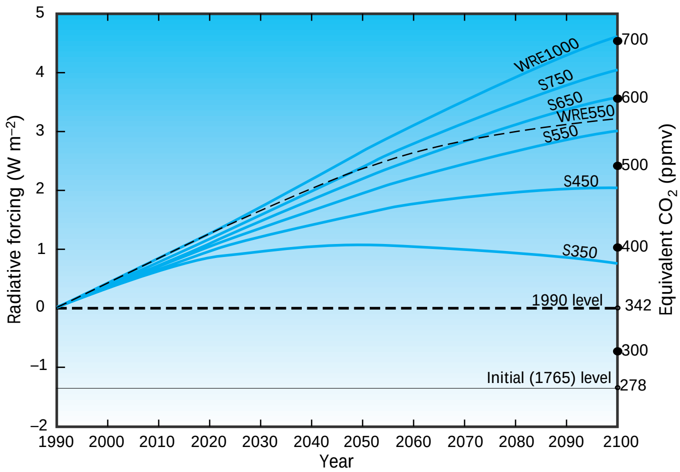

Figure 7. Radiative forcing from 1990 to 2100 (relative to 1990) for CO_2 concentrations following the S350, S450, S550, WRE550, S650, S750 and WRE1000 profiles (see Figure 4) and constant 1990 emissions of CH_4, N_2O and SO_2. For halocarbons, a single emissions scenario consistent with compliance with the Montreal Protocol is assumed. These assumptions are referred to in the text and in later captions as the "reference case". Equivalent CO_2 levels are shown by the dots on the right-hand axis. For the S450 (S650) profile for example, the CO_2 concentration in 2100 is 450 (575) ppmv (from Figure 4), but the additional effect of other greenhouse gases and SO_2 gives an equivalent CO_2 concentration of 473 (604) ppmv. These results were produced using the Wigley and Raper simple climate model (see IPCC TP SCM, 1997), and the radiative forcing/concentration relationships given in IPCC (1990) and subsequent updates.

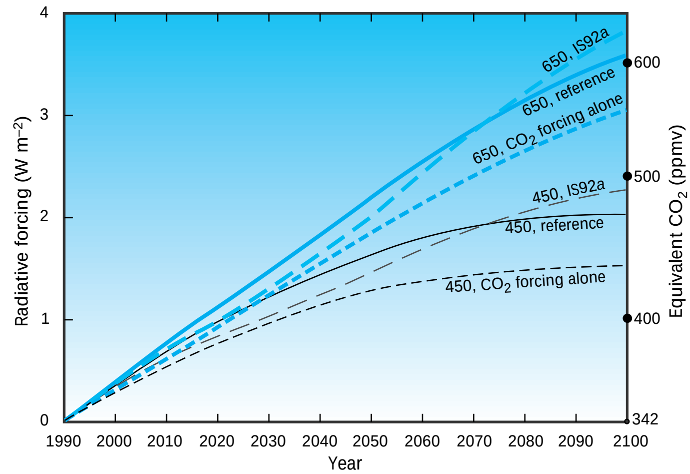

Figure 8. The effect of different non-CO_2 gas emission profiles on radiative forcing (and equivalent CO_2) for the S450 and S650 concentration profiles (see Figure 4). The short dashed lines give the "CO_2-alone" results; the solid lines the "reference case" (see Figure 7) and the long dashed lines give results where CH_4, N_2O and SO_2 emissions increase according to IS92*a* to 2100 and then stabilize (the "IS92*a* case"). Note that, initially, the radiative forcing for the reference case is less than for the "IS92*a* case". This is due to the negative forcing effect of aerosols. Note also that, for the CO_2-alone cases, the equivalent CO_2 levels are less than the actual CO_2 levels because of differences in their 1990 values.

because, in 1990, the negative forcing due to aerosols more than offsets the positive forcing due to non-CO_2 greenhouse gases. This value is, however, quite uncertain due mainly to uncertainties in the magnitude of aerosol forcing. For aerosol forcing uncertainties of ±0.5 W m^{-2} in 1990, the 1990 equivalent CO_2 level varies between 316 and 370 ppmv.

The overall sensitivity to the assumptions regarding the emissions of non-CO_2 gases is shown in Figure 8, for S450 and S650. Here, the same reference cases (Figure 7) are shown together with cases where IS92a emissions are used for CH_4, N_2O and SO_2 out to 2100 with constant emissions thereafter. In this second case, the eventual forcing increment from 1990 due to non-CO_2 gases is 1.13 W m^{-2} (compared with 0.66 W m^{-2} for the reference case). The equivalent CO_2 levels in 2100 are 491 ppmv (S450) and 627 ppmv (S650) compared with 473 ppmv (S450) and 604 ppmv (S650) for the reference cases. Figure 8 also shows the forcing due to CO_2 alone.

The results presented in Figures 7 and 8 are characterized and summarized in Table 3. This shows radiative forcing changes from 1765 and equivalent CO_2 levels for CO_2 stabilization levels of 350 ppmv to 1 000 ppmv under three different assumptions regarding the forcing effects of other gases: no other-gas effects (i.e., CO_2 changes alone), the reference case (constant CH_4, N_2O, and SO_2 emissions), and the extended IS92*a* case. Results are shown at the date of CO_2 stabilization (which varies according to stabilization level).

The above calculations are presented to illustrate the importance of other gases in determining the equivalent CO_2 level, and the overall level of uncertainty involved in determining their contribution. None of the cases studied (CO_2 alone, constant 1990 emissions, or IS92*a* based emissions for CH_4, N_2O and SO_2) should be taken as a particular future scenario, nor as a policy recommendation. The results show that the concentration stabilization levels chosen for CH_4, N_2O and SO_2 may have a significant influence on future equivalent CO_2 changes and on the equivalent CO_2 stabilization level. Individual sensitivities are addressed in the next section.

As a final point in this section, we note that equivalent CO_2 levels do not stabilize in our examples, even by 2500. Small but noticeable forcing changes (of order 0.1–0.3 W m^{-2}) occur after the point of CO_2 stabilization (viz. 2100 in S450, 2200 in S650), due mainly to the long lifetime of N_2O, which leads to significant concentration changes for this gas after emissions stabilize in 2100. Changes after 2500, however, are very small.

CO_2 stabilization level (year)	*Radiative forcing ($W\ m^{-2}$) Equivalent CO_2 (ppmv)*	*CO_2 only*	*CO_2 plus the effect of other greenhouse gases and aerosols*	
			Reference	*IS92a to 2100, then contant emissions*
350	ΔF ($W\ m^{-2}$)	1.25	1.82	2.19
(2050)	CO_2 equiv.	339	371	394
450	ΔF ($W\ m^{-2}$)	2.83	3.35	3.59
(2100)	CO_2 equiv.	436	473	492
550	ΔF ($W\ m^{-2}$)	4.09	4.67	5.04
(2150)	CO_2 equiv.	532	583	619
650	ΔF ($W\ m^{-2}$)	5.15	5.75	6.16
(2200)	CO_2 equiv.	629	692	739
750	ΔF ($W\ m^{-2}$)	6.05	6.67	7.10
(2250)	CO_2 equiv.	726	801	858
1000	ΔF ($W\ m^{-2}$)	7.86	8.50	8.97
(2375)	CO_2 equiv.	968	1 072	1 154

Table 3. Equivalent CO_2 (ppmv) and radiative forcing (from 1765) (ΔF) at the point of CO_2 stabilization, for various assumptions about non-CO_2 greenhouse gases and aerosols. The reference case assumes constant emissions for SO_2, N_2O and CH_4 after 1990. The "CO_2 only" column assumes changes after 1990 are in CO_2 only (as in SAR WGI). Note that the equivalent CO_2 level at CO_2 stabilization in these cases differs from the CO_2 stabilization level because of differences between the 1990 CO_2 and equivalent CO_2 levels.

2.2.5 Equivalent CO_2 Sensitivities

Section 2.2.4 provides estimates of equivalent CO_2 that include the collective effects of CH_4, N_2O, SO_2 and the halocarbons. Here we consider the influences of CH_4, N_2O, and SO_2 separately. To do this, we use emissions perturbations about the constant 1990 emissions reference cases.

For CH_4 (Figure 9a), a perturbation in annual emissions from 1990 to 2100 of ±75 TgC (±100 Tg(CH_4)) changes radiative forcing by approximately ±0.20 $W\ m^{-2}$ at concentration stabilization. This translates to equivalent CO_2 differentials of approximately ±15 ppmv for S450 and ±22 ppmv for S650. For annual N_2O emissions, a perturbation of ±2 Tg(N) from 1990 to 2100 changes forcing by ±0.16 $W\ m^{-2}$ at concentration stabilization, and gives concentration differentials of ±12 ppmv for S450 and ±18 ppmv for S650 (see Figure 9*b*).

Sulphur dioxide sensitivities occur in two ways. First, there is the basic sensitivity to emissions uncertainties (Figure 10*a*). At concentration stabilization, perturbations of ±50 per cent relative to 1990 in annual SO_2 emissions (i.e., ±37.5 TgS) lead to forcing differentials of -0.37/+0.45 $W\ m^{-2}$, which translates to equivalent CO_2 concentration differentials of -27/+36 ppmv for S450 and -40/+52 ppmv for S650 (note that the sign of the forcing or concentration differential is opposite to the sign of the emissions perturbation).

In addition to the influence of emissions uncertainties, the effect of SO_2 on equivalent CO_2 concentrations is sensitive to the highly uncertain relationships between SO_2 emissions and radiative forcing. SO_2-derived sulphate aerosol affects radiative forcing both directly, under clear-sky conditions, and indirectly, through changes in cloud albedo. The central estimate of direct sulphate aerosol forcing for 1990 was calculated in SAR WGI as -0.4 $W\ m^{-2}$, an estimate of -0.8 $W\ m^{-2}$ was used in Section 6.3 of SAR WGI for the indirect forcing. When combined with a carbonaceous (soot) aerosol forcing of +0.1 $W\ m^{-2}$, this gives a total sulphate aerosol forcing of -1.1 $W\ m^{-2}$. To assess the sensitivity to uncertainties in this quantity, we use the range of ±0.1 $W\ m^{-2}$ for direct forcing and ±0.4 $W\ m^{-2}$ for indirect forcing (giving a total sulphate (plus soot) aerosol forcing range of -1.1 ± 0.5 $W\ m^{-2}$).

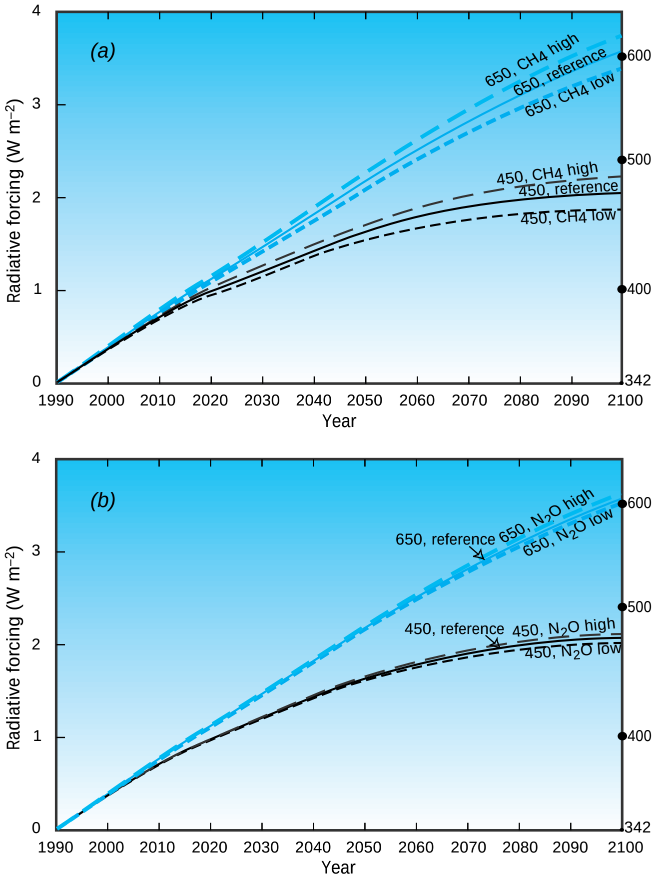

Figure 9. (*a*) The sensitivity of radiative forcing (and equivalent CO_2 concentration) to CH_4 emissions for the S450 and S650 concentration profiles (see Figure 4). The "CH_4 low"/"CH_4 high" curves assume annual CH_4 emissions decrease/increase linearly by 100 Tg(CH_4) over 1990 to 2100 (see Table 4); (*b*) The sensitivity of radiative forcing (and equivalent CO_2 concentration) to N_2O emissions for the S450 and S650 concentration profiles (see Figure 4). The "N_2O low"/"N_2O high" curves assume annual N_2O emissions decrease/increase linearly by 2 Tg(N) over 1990 to 2100 (see Table 4).

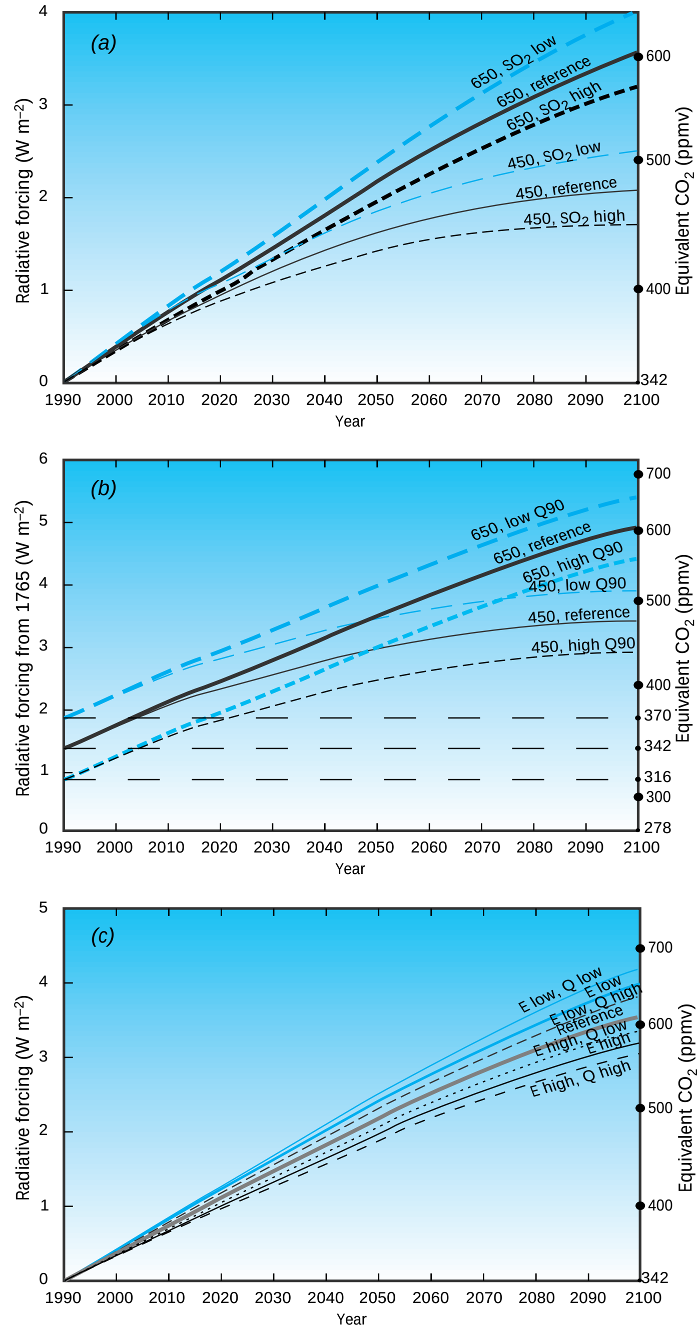

Figure 10. (*a*) Sensitivity of radiative forcing (and equivalent CO_2 concentration) to SO_2 emissions for the S450 and S650 concentration profiles. The solid lines give the "reference" cases; the short/long dashed lines show the "high SO_2/low SO_2" cases where emissions increase/decrease linearly by ± 50 per cent over 1990-2100; (*b*) Sensitivity of radiative forcing (and equivalent CO_2 concentration) to sulphate aerosol forcing in 1990 (relative to pre-industrial times) of -0.6, -1.1 and -1.6 W m^{-2}, respectively. Note that the radiative forcing values in this Figure are relative to pre-industrial, (*c*) The combined effects on radiative forcing (and equivalent CO_2 concentration) of sensitivity to SO_2 emissions and 1990 aerosol forcing for the S650 concentration profile only. E high/E low indicates increasing/decreasing emissions of SO_2 from 1990 to 2100 (these are the same as the corresponding curves in Figure 10*a*); Q high/Q low indicates high/low 1990 aerosol forcing (these are the same as the corresponding curves in Figure 10*b*).

The way this emissions/forcing uncertainty manifests itself initially in our calculations is in the 1990 equivalent CO_2 level. As noted earlier, whereas the "best guess" value of C_{eq}(1990) is 342 ppmv, the range corresponding to ±0.5 W m^{-2} in the 1990 aerosol forcing level is 316-370 ppmv. For future forcing, if we use the reference case of no change in SO_2 emissions, then the emissions/forcing uncertainty has no effect — zero emissions change means zero forcing no matter what the emissions/forcing relationship is. The 1990 forcing uncertainty is simply propagated "as is" into the future (Figure 10*b*).

If, however, future SO_2 emissions increase or decrease from their 1990 level (as in the emissions perturbation cases considered in Figure 10*a*), then the emissions/forcing uncertainty *does* affect future aerosol forcing. This is illustrated in Figure 10*c*, where (for the S650 case only) we show the uncertainties associated with both emissions and forcing together.

The bold curve in the centre is the reference SO_2 emissions case (no change from 1990), for which there is no emissions/forcing uncertainty band. The upper three curves correspond to the case of decreasing SO_2 emissions (by 50 per cent over 1990-2100) and give results for low, mid and high values of the 1990 sulphate aerosol forcing level (-1.1 ± 0.5 W m^{-2}). High 1990 forcing leads to a larger departure from the reference case. The lower three curves are for the case where SO_2 emissions increase by 50 per cent over 1990-2100. Here, the high 1990 forcing case must again lead to a larger (this time, negative) departure from the reference case.

2.3 Temperature and Sea Level Consequences of Stabilizing CO_2 Concentrations

2.3.1 Temperature and Sea Level Analyses: Methodology

The CO_2 concentration stabilization profiles described above together with the scenarios introduced for other gases have been used as inputs to simplified climate models that assess the global mean temperature and sea level consequences. This is only a first step towards addressing the full climate implications of stabilization. To do so comprehensively requires, at least, that regional-scale changes in temperature and sea level, and changes in other climate variables (such as rainfall or soil moisture) be considered. However, climate models are not yet sufficiently accurate to allow confident prediction of such regional, multivariate influences.

The present analysis includes CO_2, together with a number of possible combinations of other gas influences, as shown in Table 4. This approach was chosen to give some insights into the sensitivities of temperature and sea level to the assumptions regarding future greenhouse gas and SO_2 emissions. The approach is not meant to span the full range of possibilities. For each combination we compute four variables:

(*a*) Radiative forcing (W m^{-2});

(*b*) The equivalent CO_2 concentration associated with the particular combination of other gases;

(*c*) Global mean temperature changes;

(*d*) Global mean sea level changes.

Constituent	*Concentration/emission cases considered*	
CO_2	S350, 450, 550, 650, 750	
	WRE550, 1000	
CH_4	Reference:	Constant emissions after 1990 at 1990 level*
	Low:	Linear decrease by 100 Tg(CH_4) over 1990–2100, constant emissions after 2100
	High:	Linear increase by 100 Tg(CH_4) over 1990–2100, constant emissions after 2100
N_2O	Reference:	Constant emissions after 1990 at 1990 level*
	Low:	Linear decrease by 2 Tg(N) over 1990–2100, constant emissions after 2100
	High:	Linear increase by 2 Tg(N) over 1990–2100, constant emissions after 2100
SO_2	Reference:	Constant emissions after 1990 at 1990 level†
	Low:	Linear decrease by 50 per cent over 1990–2100, constant emissions after 2100
	High:	Linear increase by 50 per cent over 1990–2100, constant emissions after 2100
Halocarbons	SAR WGI to 2100§, constant emissions after 2100	
Tropospheric O_3	As SAR WGI: no direct changes after 1990. CH_4-induced changes included with CH_4	

* With emissions adjusted to balance the 1990 budget, as in SAR WGI: Chapter 6.

† 75 TgS/yr as in the IS92 scenarios.

§ A synthesis of emissions as given in Chapter 2 of SAR WGI, with other minor species as given in Chapter 6. Stratospheric ozone effects accounted for as in Chapter 6.

Table 4. Emissions cases considered in the sensitivity studies.

Results for (*a*) and (*b*) have been given in Section 2.2; this section considers the global mean temperature and sea level implications. Rates of change may be estimated graphically from the results provided.

In addition, we need to consider uncertainties in the response of the climate system to external forcing, due largely to uncertainties in the climate sensitivity (we consider three cases, following SAR WGI (Section 6.3); viz. ΔT_{2x} = 1.5, 2.5 and 4.5°C), and sea level rise uncertainties due to uncertainties in modelling ice-melt (SAR WGI: Chapter 7). For the latter, we span the range by considering low (ΔT_{2x} = 1.5°C, combined with low ice-melt), mid (2.5°C, mid ice-melt), and high sea level rise cases (4.5°C, high ice-melt). This gives three sets of climate/sea level output for each forcing case. The results given use the Wigley and Raper (1992) models (see also Raper, *et al.*, 1996) as employed in SAR WGI (Section 6.3). In SAR WGI a model developed by de Wolde and colleagues (e.g., de Wolde, *et al.*, 1995) was used, but their climate model has a fixed sensitivity for temperature change at doubled CO_2 of 2.2°C (ΔT_{2x} = 2.2), which precludes its use in the present context. For information on model structure and intermodel differences, see IPCC TP SCM (1997).

Because of the large number of model simulations and the number of response variables, we present only a subset of the results here to illustrate the possible consequences. [Because of the potential interest in the detailed results, full results from all carbon cycle and climate model calculations will be made available electronically via the World Wide Web (or alternatively, on diskette).]

2.3.2 *Implications of Stabilization of Greenhouse Gases for Temperature and Sea Level*

The results presented here provide a more unified view of the issues related to stabilization than is available from any single chapter in SAR WGI. The bulk of these results are for a climate sensitivity (ΔT_{2x}) of 2.5°C, a mid-range value. If the true value were lower or higher, the results would scale accordingly, as discussed below. In addition, we emphasize that the results shown are globally averaged: both impacts and mitigative actions are sensitive to regional patterns of climate and sea level change, because regional opportunities and vulnerabilities are highly variable.

The temperature and sea level results given here were computed using relatively simple models. As discussed in IPCC TP SCM (1997), these models are designed to reproduce, with reasonable fidelity, the globally averaged behaviour of complex models. They have also been compared to historical and/or present day observations. They, in common with more complex models, do not include all possible interactions and climate feedbacks, but they do reflect our current state of knowledge.

The primary calculations use the reference case of constant 1990 level emissions for CH_4, N_2O, and SO_2 (see Table 4). This facilitates the comparison between different CO_2 stabilization levels and pathways, and is consistent with the equivalent CO_2 results given earlier. Emissions for these gases under the IS92 scenarios differ markedly from the reference case (see Tables 1 and 2). In addition to the reference cases, we assess the sensitivity of the various temperature and sea level results to the emissions levels of CH_4, N_2O, and SO_2, by considering different emissions cases for these gases.

We have noted above that the future emissions trajectories of the non-CO_2 trace gases (CH_4, N_2O, SO_2) can have a marked effect on the total forcing associated with any CO_2 stabilization profile. For example, if the actual CO_2 concentration were to stabilize at 450 ppmv, and methane emissions continue to increase, the radiative forcing would be substantially higher than that associated with CO_2 alone. Higher temperature and sea level changes would also be expected, as shown below.

Global mean temperature and sea level change results for 1990 to 2100 are shown in Figures 11 to 15 (for results to 2300 see Appendix 1). These are changes from the present only (nominally from 1990). To obtain the anthropogenic change in global mean temperature from 1880, based on the central estimate of historical forcing used in SAR WGI, 0.2-0.5˚C should be added. To obtain the change from pre-industrial times, a further 0.1-0.2˚C should be added.

It should be noted that global mean quantities are only indicators of the overall magnitude of potential future climate change: regional temperature changes may differ markedly from the global mean change, and changes in other variables, such as precipitation, are not related in any simple or direct way to global mean temperature change (see SAR WGI: Chapter 6). Regional sea level changes may also differ from the global mean due to land movement and/or oceanic circulation effects (see SAR WGI: Chapter 7).

Figures 11*a* and *b* show temperature and sea level changes from the present for CO_2 stabilization levels of 350, 450, 550, 650, 750 and 1000 ppmv using the reference case for other gases (constant 1990 level emissions for CH_4, N_2O and SO_2). A climate sensitivity of 2.5°C and mid ice-melt parameter values (see SAR WGI: Chapters 6 and 7) are used in these calculations, which are directed towards showing how temperature and sea level changes vary according to the chosen stabilization level. For the 550 ppmv case, both the "S" and "WRE" results are given to illustrate the sensitivity of the changes to the pathway taken towards stabilization. Out to around 2050, the WRE550 results show greater warming and sea level rise than even the S750 case (but not the 1000 ppmv case, because this was constrained to lie always equal to or above the WRE550 CO_2 concentration). Rates of change may be derived from Figures 11*a* and *b*; over the next fifty years rates of temperature change range from 0.1 to 0.2˚C/decade.

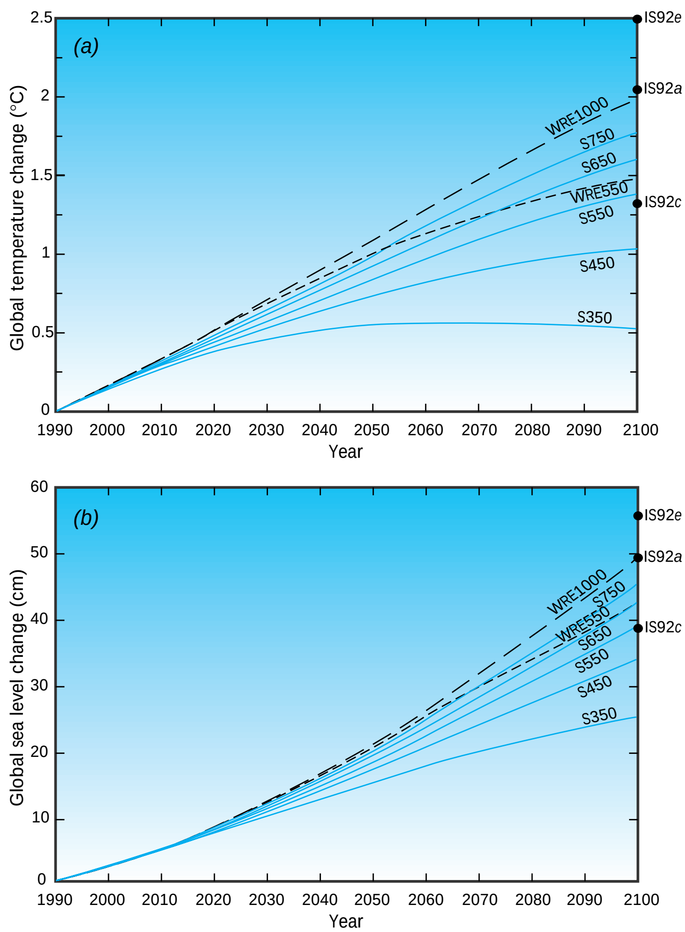

Figure 11. (*a*) Projected global mean temperature when the concentration of CO_2 is stabilized following the S profiles and the WRE550 and 1 000 profiles shown in Figure 4. CH_4, N_2O and SO_2 emissions are assumed to remain constant at their 1990 levels and halocarbons follow an emissions scenario consistent with compliance with the Montreal Protocol (i.e., the reference case). The radiative forcing (and equivalent CO_2) from which the global temperatures were derived were shown earlier in Figure 7. The climate sensitivity is assumed to be the mid-range value of 2.5˚C. For comparison, results for the IS92*a*, *c* and *e* emissions scenarios are shown for the year 2100. To obtain the anthropogenic change in global mean temperature from 1880, based on the central estimate of historical forcing used in SAR WGI, 0.2-0.5˚C should be added. To obtain the change from pre-industrial times, a further 0.1 - 0.2˚C should be added; (*b*) As for (*a*), but for global sea level change using central ice-melt parameters. All results were produced using the Wigley and Raper simple climate/sea level model (see IPCC TP SCM, 1997).

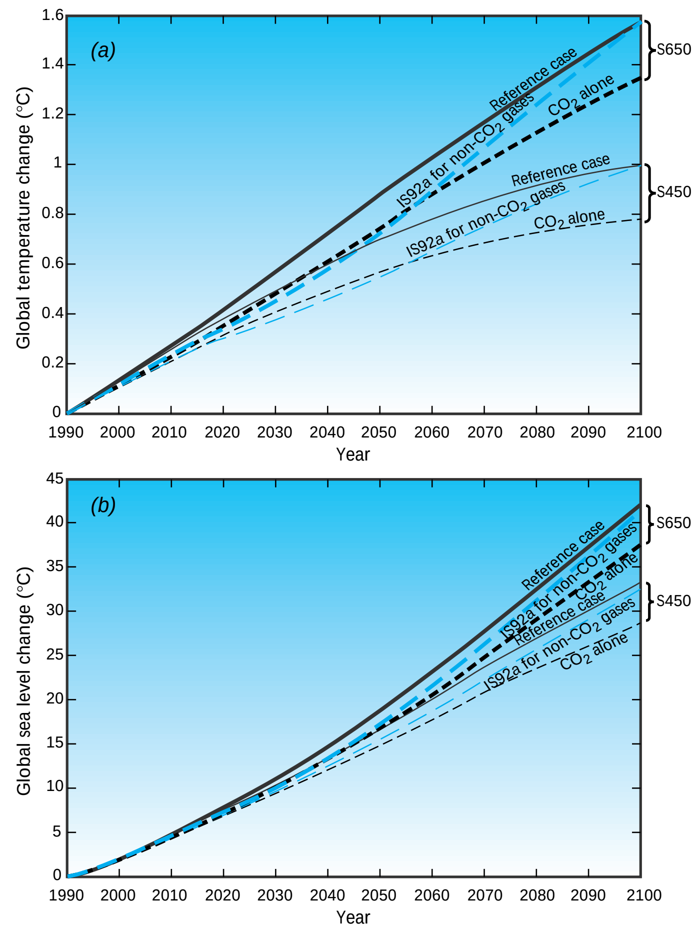

Figure 12. (*a*) The effect of different non-CO_2 gas emission profiles on global temperature change for the S450 and S650 concentration profiles (see Figure 4). The solid lines give the "reference " results; the short dashed lines the "CO_2 alone" results and the long dashed lines give results where CH_4, N_2O and SO_2 emissions increase according to IS92*a* to 2100 (the "IS92*a* case"). The climate sensitivity is assumed to be the mid-range value of 2.5˚C; (*b*) As for (*a*), but for global sea level change. Central values of the ice-melt parameters are assumed.

Figures 12*a* and *b* illustrate how the emissions of non-CO_2 gases might influence future global mean temperature and sea level change (for CO_2 stabilization levels of 450 ppmv and 650 ppmv). The cases shown are the reference case used in Figure 12; the case where all emissions (other than CO_2) follow IS92*a* to 2100; and the case where only CO_2 changes are considered from 1990 — i.e., where the radiative forcings for all other gases remain at their 1990 levels. Only the last case was considered in SAR WGI (see Figures 6.26 and 7.12). The importance of other gases is clearly seen from this Figure. Differences between the reference case and the case with IS92*a* emissions for other gases exceed the differences between S450 and S650 out to around 2050. The IS92*a* results are (to around 2050) lower than the others due to the global mean offsetting effect of increasing SO_2 emissions in this scenario: but this hides important regional details and it does not necessarily mean that the severity of climate changes associated with this case (in the sense of their impacts) would be less.

The results in Figures 11 and 12 are for "best guess" climate and ice-melt model parameters only. Figure 13 shows 450 ppmv and 650 ppmv results for different climate sensitivities (1.5, 2.5 and 4.5°C) coupled (for sea level rise) with low, mid and high ice-melt model parameters respectively. Uncertainties related to model parameter uncertainties for any given stabilization level are much larger than the differences between the 450 ppmv and 650 ppmv stabilization level results, particularly for sea level.

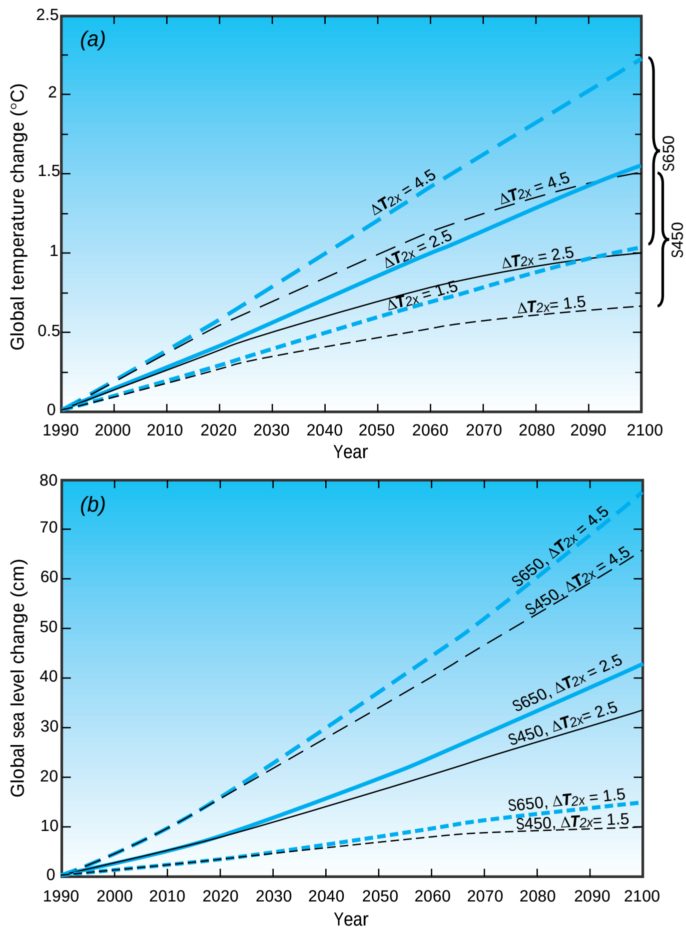

Figure 13. (*a*) The effect of climate sensitivity uncertainties on global mean temperature for the S450 and S650 CO_2 concentration profiles and the reference case for non-CO_2 gases. The range of climate sensitivity *(ΔT_{2x})* is 1.5 to 4.5˚C with a mid-range value of 2.5˚C. For the same range in climate sensitivity, the global mean temperature change from 1990 to 2100 for the IS92*a* emissions scenario is between 1.4 and 2.9˚C with a mid-range value of 2.0˚C; (*b*) As for (*a*), but for global mean sea level change. The low, mid and high values of climate sensitivity are combined with low, mid and high ice-melt parameters, respectively, to give extreme ranges. For the same range in climate sensitivity and ice-melt parameteres, the global mean sea level rise from 1990 to 2100 for the IS92*a* emissions scenario is between 19 and 86 cm with a mid-range value of 49 cm.

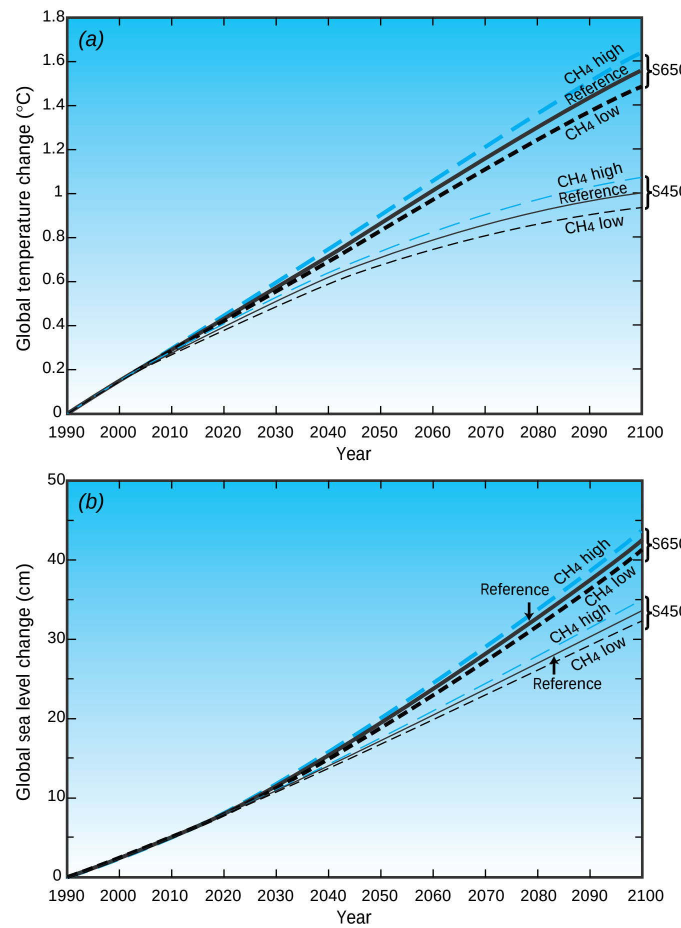

Figure 14. (*a*) Sensitivity of global mean temperature change to CH_4 emissions for the S450 and S650 concentration profiles (see Figure 4). The solid lines give the "reference" results; the "CH_4 low"/"CH_4 high" curves assume annual CH_4 emissions decrease/increase linearly by 100 Tg(CH_4) over 1990 to 2100 (see Table 4). The radiative forcing (and equivalent CO_2) from which the global temperatures were derived were shown earlier in Figure 9*a*; (*b*) As for (*a*), but for global sea level change. Central values of the ice-melt parameters are assumed.

For planning purposes, reducing model parameter uncertainties would clearly be advantageous. These are uncontrollable aspects of the climate/sea level system, however, while the stabilization level is potentially controllable. The comparison in Figure 13, therefore, provides a graphic illustration of the extent of potential control relative to overall uncertainties in the climate and sea level projections.

Figures 14 and 15 show the sensitivity of the 450 ppmv and 650 ppmv results to gas-specific uncertainties in future emissions: a change over 1990–2100 of ±100 Tg(CH_4) about the reference CH_4 emissions case in Figure 14, and a change over 1990–2100 of ±50 per cent (i.e., 37.5 TgS) about the reference SO_2 emissions case in Figure 15. (The same sensitivity cases were considered in the assessment of forcing and equivalent CO_2 uncertainties in Section 2.3.1.) N_2O sensitivity is not shown because, for the ±2 Tg(N) perturbations considered previously, this is appreciably less in the near-term than for CH_4 due to the long lifetime of N_2O relative to CH_4 (compare Figures 9*a* and 9*b*).

In the context of this sensitivity analysis, the long-term effects of CH_4 and SO_2 for the considered perturbations are relatively small compared with the differences between the results for different stabilization levels (see Figures A4 and A5 in Appendix 1). However, the short-term effects are, relatively,

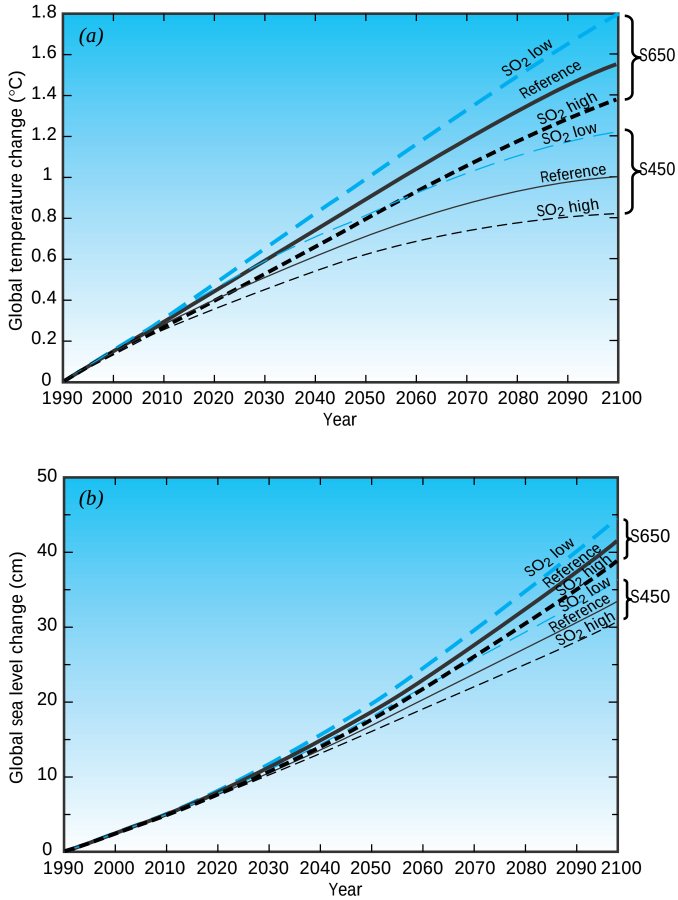

Figure 15. (*a*) Sensitivity of global mean temperature change to SO_2 emissions for the S450 and S650 concentration profiles (see Figure 4). As in Figure 10*a*, the solid lines give the "reference" cases; the short dashed lines show the "high SO_2" cases where emissions increase linearly from 75 TgS/yr in 1990 to 112.5 TgS/yr in 2100 and the long dashed lines show the "low SO_2" cases where emissions decrease linearly to 37.5 TgS/yr in 2100. The radiative forcing (and equivalent CO_2) from which the global temperatures were derived were shown earlier in Figure 10*a*. (*b*) As for (*a*), but for global sea level change. Central values of the ice-melt parameters are assumed.

much larger (compare Figures 11 and A2). This is because both CH_4 and SO_2-derived aerosol have much shorter response times than CO_2. The full differential effects on climate related to different CO_2 stabilization targets therefore take much longer to manifest themselves compared with the more rapid responses to CH_4 and SO_2 emissions changes.

Although we cannot yet characterize the differences among stabilization levels and pathways in terms of their degree of risk, it is clear, as noted in SAR WGI (Section 6.3) and in Wigley, *et al.* (1996) that the choice of both stabilization level and pathway affects the magnitudes and rates of future climate and sea level change. Future emissions of other greenhouse gases also influence future climate and sea level appreciably, generally leading to larger changes than from CO_2 emissions alone. Thus, mitigation of these other-gas emissions is a valuable component of a programme designed to prevent dangerous interference with the climate system. In the long-term (beyond 2100), uncertainties in the future emissions of CH_4, N_2O and SO_2 have effects that are generally less than those associated with the differences between different CO_2 stabilization levels. In the short-term (to around 2050), however, the importance of other-gas emissions is, relatively, much larger. Uncertainties in future CH_4 and SO_2 emissions lead to climate change uncertainties that exceed those due to different CO_2 concentration profiles.

The situation with regard to SO_2 emissions is more complex than that for greenhouse gas emissions because of their extreme spatial heterogeneity. The cooling effect of SO_2 emissions cannot be considered as merely offsetting the warming effect of greenhouse gas emissions.

3. IMPACTS AND MITIGATION COSTS ASSOCIATED WITH STABILIZING GREENHOUSE GASES

3.1 Impacts Associated with Different Emissions Trajectories

Article 2 of the UN/FCCC (see Section 1.1) explicitly acknowledges the importance of natural ecosystems, food production and sustainable economic development in determining whether "dangerous anthropogenic interference in the climate system" occurs. Based on information contained in SAR WGI and WGII, the rates and levels of climate change likely to be associated with the emission trajectories presented in Section 2 of this paper could have large effects on natural resource systems in a variety of regions. A great deal is known about the response of particular systems in particular locations, and both substantial risks and potential benefits can be identified. Currently, it is not possible to integrate this information into an assessment of global impacts associated with different stabilization levels or emissions trajectories, because regional scale climate change projections are uncertain, our current understanding of many critical processes is inadequate, systems are subject to multiple climatic and non-climatic stresses, and very few studies have considered dynamic responses to steadily increasing concentrations of greenhouse gases or consequences of increases beyond a doubling of equivalent atmospheric CO_2 concentration. Also, the simple climate model projections are not suitable for generating scenarios for impact studies, as they only produce globally averaged quantities. The global mean temperature and sea level projections shown in Section 2 are, as noted, only indices of climate change.

3.1.1 The Importance of Impacts in Decision Making on Stabilization

Approaches for incorporating information about potential impacts of climate change in decisions about a stabilization target are discussed in SAR WGIII (Chapters 5 and 6). In most of these approaches, the net value of impacts is defined as the difference in welfare between a future with and without anthropogenic climate change. In one approach, generally referred to as "cost-benefit analysis," potential negative impacts, benefits, and costs of adaptation are compared to the potential costs of mitigation; the object is to maximize net benefits (the benefits of reduced climate change minus the costs of emissions reductions). Mitigation is justified up to the point that its expected costs do not exceed its expected benefits (the value of the potential negative impacts avoided plus the value of any "secondary benefits" of mitigation).

In another framework, called the "sustainability approach", highest priority is given to avoiding a particular level of stress to key systems, activities or regions. To do so, society identifies a target level of change such as an absolute magnitude of temperature change or a rate of change per decade that would lead to unacceptable risks in the future; radiative forcing and atmospheric stabilization targets are then defined to avoid unacceptable levels of change. Approaches have been developed in both frameworks that attempt to deal with a variety of critical issues such as risk, uncertainty, irreversibility, economic valuation of non-market impacts, comparing of present and future costs and equity (SAR WGIII: Section 6.1.2).

Both sustainability and cost-benefit approaches require detailed information on impacts, although the character of the required information differs among approaches. The cost-benefit approach needs to reduce a diverse set of impacts in different settings and systems to a common (often monetized) metric. There are some applications of this approach that compare gains and losses in different systems without standardising to a common unit of analysis. In theory, monetization enables comparison of gains and losses in different sectors and regions. Unfortunately there is a great deal of uncertainty in monetized aggregate assessments of impacts and the benefits of mitigation, even for national or sectoral studies, let alone at a global level. Moreover, there exist few if any estimates of "the benefits curve," and most of the estimates that do exist are little more than single point estimates (SAR WGIII: Section 5.4.1). For these and other reasons, the cost-benefit approach cannot identify the appropriate level of mitigation with any certainty. The sustainability approach does not reduce impacts to a common metric, and so it cannot compare effects across physical systems and socio-economic circumstances. Moreover, including the costs of mitigation is difficult. The sustainability approach, however, does allow analysis of individual physical impacts.

Given that the level of impacts vary tremendously among locations and across time, and that some countries (usually developing countries) derive much higher proportions of their national incomes from climate-sensitive sectors (e.g., subsistence farming) and have more limited resources for adaptation, comparison of the relative acceptability of a given stabilization target or emissions trajectory will be extremely difficult with either analytical approach, especially as such comparisons involve numerous ethical and political issues.

3.1.2 Assessment of Potential Biophysical Impacts in SAR WGII

A great deal is known about the potential sensitivity and vulnerability of particular terrestrial and aquatic ecosystems, water management systems, agriculture, human infrastructure and human health. Current scientific and technical information is summarized in SAR WGII (Chapters 1 to 18), although it is difficult at present to relate this to specific future climate scenarios.

A representative, but necessarily incomplete sample of the potential impacts highlighted in SAR WGII includes:

(*a*) *Forests:* Changes in temperature and water availability projected by general circulation models (GCMs) at equilibrium for doubled equivalent CO_2 suggest that a substantial fraction (a global average of one-third, varying by region from one-seventh to two-thirds) of the existing forested area of the world will undergo major changes in broad vegetation types — with the greatest changes occurring in high latitudes and the least in the tropics. Climate change is expected to occur at a rapid rate relative to the speed at which forest species grow, reproduce, and re-establish themselves (SAR WGII: Summary for Policymakers (SPM) (Section 3.1) and Chapter 1). Multiple stresses to forests, including ozone and SO_2 acidification, as well as climate and CO_2 change, may have significant additional consequences;

(*b*) *Mountain ecosystems:* The altitudinal distribution of vegetation is projected to shift to higher elevation; some species with climatic ranges limited to mountain tops could become extinct because of disappearance of habitat or reduced migration potential (SAR WGII: SPM Section 3.1 and Chapter 5). The change in mountain ecosystems brings changes to the regulator function of altitudinal vegetation, altering the hydrological patterns in many regions;

(*c*) *Aquatic and coastal ecosystems:* The geographical distribution of wetlands is likely to shift with changes in temperature and precipitation. Some coastal ecosystems are particularly at risk, including saltwater marshes, mangrove ecosystems, coastal wetlands, sandy beaches, coral reefs, coral atolls and river deltas. Changes in these ecosystems would have major negative effects on tourism, freshwater supplies, fisheries and biodiversity (SAR WGII: SPM Section 3.1 and Chapters 6, 9 and 10);

(*d*) *Hydrology and water resources management:* Models project that between one-third and one-half of existing mountain glacier mass and a considerable area of permafrost could disappear over the next hundred years. The reduced extent of glaciers and depth of snow cover would also affect the seasonal distribution of river flow and water supply for hydroelectric generation and agriculture. Relatively small changes in temperature and precipitation, together with non-linear effects on evapotranspiration and soil moisture, can generate relatively large changes in runoff, especially in semi-arid regions. The quantity and quality of water supplies already are serious problems today in many regions, including some low-lying coastal areas, deltas and small islands, which makes these regions particularly vulnerable to any additional reduction in indigenous water supplies (SAR WGII: SPM Section 3.2 and Chapters 7, 10 and 14);

(*e*) *Food and fibre:* Existing studies show that on the whole, global agricultural production could be maintained relative to baseline production in the face of climate change projected under doubled equivalent CO_2 equilibrium conditions. This conclusion takes into account the beneficial effects of CO_2 fertilization but does not allow for changes in agricultural pests and the possible effects of changing climatic variability. However, there may be increased risk of hunger and famine in some locations; many of the world's poorest people — particularly those living in subtropical and tropical areas and dependent on isolated agricultural systems in semi-arid regions — are at the greatest risk (SAR WGII: SPM Section 3.3 and Chapters 13 and 16);

(*f*) *Human infrastructure:* Climate change will clearly increase the vulnerability of some coastal populations to flooding and erosional land loss. Some small island nations and other countries will confront greater vulnerability because their existing sea and coastal defence systems are less well established. Countries with higher population densities would be more vulnerable. Storm-surges and flooding could threaten entire cultures. For these countries, sea level rise could force internal or international migration (SAR WGII: SPM Section 3.4 and Chapters 9, 11, 12 and 17);

(*g*) *Human health:* Climate change is likely to have wide ranging and mostly adverse impacts on human health, with significant loss of life. Direct health effects include increases in mortality and illness (predominantly cardio-respiratory) due to an anticipated increase in the intensity and duration of heat waves. Temperature increases in colder regions should result in fewer cold-related deaths. Indirect effects of climate change, which are expected to predominate, include increases in the potential transmission of vector-borne infectious diseases (e.g., malaria, dengue, yellow fever and some viral encephalitis) resulting from extensions of the geographical range and season for vector organisms. Limitations on freshwater supplies and on nutritious food, as well as the aggravation of air pollution, will also have human health consequences (SAR WGII: SPM Section 3.5 and Chapter 18).

3.1.3 *Economic Assessment of Impacts*

Economic assessments of climate change impacts are an integral input to cost-benefit studies and other decision-making frameworks which are used to compare the potential costs and benefits of various courses of action. These studies are assessed in SAR WGIII (Chapter 6), which is the basis for this section.

Monetary values for impacts resulting from a doubled equivalent CO_2 climate have been estimated for a number of sectors in the market economy. Standard measures, such as consequences for per capita gross domestic product (GDP), are widely agreed to be inadequate for weighing the potential consequences of climate change, because although some effects are amenable to monetary valuation, others are not easily valued in monetary terms. There are some estimates for some non-market impacts where no accepted method exists that can be used to monetize those impacts (e.g., value of a life, species loss, new species assemblages), and for combined market and non-market effects in some sectors (e.g., forest loss in lumber and public use value). Net climate change impacts include both market and non-market impacts, as far as they can be quantified, and in some cases include adaptation costs. Impacts are expressed in net terms to account for the fact that there may be some beneficial effects of climate change, even though this may obscure issues of distributional equity. The incomplete nature of the impact estimates presented here must be borne in mind when evaluating the full welfare implications of climate change.

The available studies reviewed in SAR WGIII estimate economic losses associated with a 2.5°C global warming (the mid-range estimate of equilibrium global temperature increase associated with a doubling of equivalent CO_2 concentrations) on a world similar to today's (i.e., similar demographic characteristics, social structures, economic conditions) as follows:

(*a*) Developed country impact: 1–1.5 per cent of national GDP annually;

(*b*) Developing country impact: 2–9 per cent of national GDP annually.

The studies reviewed by WGIII aggregated these estimates in proportion to GDP, for a global total of 1.5–2 per cent GDP. These aggregated cost ranges are based on a large number of simplifying and controversial assumptions. They represent *best-guess* central estimates from relatively limited studies that attempt to include both market and non-market impacts, and in some cases also adaptation costs and they do not span the (large) range of uncertainty. The cost ranges are also imperfect in that GDP does not measure human and societal well-being accurately. Such aggregation faces numerous difficulties (SAR WGIII: Chapters 3 and 6) and was subject to severe reservations in the SAR WGIII Summary for Policymakers .

Existing estimates are rudimentary for several reasons. In addition to many of the problems that affect impact assessments in individual sectors, as noted above and in SAR WGII, additional uncertainties include:

(*a*) Estimates are predominantly for the United States and other Organisation for Economic Cooperation and Development (OECD) countries, and many regional and global estimates are based on extrapolations of these results. Material relating to other countries is sparse, although increasing. Hence, there is currently limited knowledge of regional and local impacts;

(*b*) Estimates of monetized impacts are for doubled equivalent CO_2 concentration scenarios, usually based on the present day economy and expressed as a percentage of GDP. Simply projecting percentage losses is a somewhat unsatisfactory approximation, because future impacts will depend on economic, demographic and environmental developments that will make future conditions very different from those of today. Some of the effects of climate change are likely to grow more than proportionately with GDP (e.g., the economic value of non-market goods) and others less than proportionately (e.g., agriculture);

(*c*) There are difficulties in measuring the economic value of impacts, even where the impacts are known. This is particularly the case for non-market impacts and the impacts in developing countries. Some regard monetary valuation of such impacts as essential to sound decision making, while others reject valuation of impacts, such as loss of human life or biodiversity, on ethical grounds;

(*d*) Calculating a global aggregate of impacts involves difficult questions about equity among countries, especially given income and other social differences. Simply aggregating GDP estimates means that equivalent impacts in two countries receive a different weight, based heavily on national economic product. The ethical issues involved in such aggregation raise difficulties of consistency that are not explicitly addressed in existing studies (SAR WGIII: Chapters 3 and 6);

(*e*) There are difficulties in setting discount rates, which are the analytical tool economists use to compare economic effects that occur at different points in time. This is important because climate change impacts are likely to impose costs on future generations.

The practical application of these estimates to climate change decision making is difficult, not only because of the uncertainty of the estimates themselves, but also because of the global and intergenerational nature of the problem. Some systems in some regions may benefit from climate change for some period of time, whereas many others will suffer adverse impacts; thus impacts will be distributed unequally. Climate change will affect an extremely diverse mix of human societies, some of which have less potential to adapt than others, and will thus suffer more than others. An evaluation entails trade-offs among impact categories, regions, nations, generations and individuals. Various techniques exist to make such trade-offs visible and manageable, but the actual decision regarding which impacts are most costly is a political one. Within well developed institutional/economic/political systems, mechanisms for making trade-offs and providing compensation to the losers exist. Internationally and inter-temporally, existing mechanisms are much weaker. Currently, the knowledge of climate change impacts is not sufficiently developed to make these trade-offs clear.

3.1.4 Uncertainties in Projecting Impacts of Different Trajectories

At the extreme ends of the range, higher target concentrations and more rapid changes in radiative forcing generally can be expected to have larger impacts on natural and human systems than trajectories that assume a slower accumulation of forcing and lower stabilized concentrations. It is not currently possible, however, to determine how the impacts that may be associated with one stabilization target or emissions trajectory may differ from those associated with another target or trajectory. For many reasons, there is not a simple relationship between emissions and atmospheric concentrations of greenhouse gases and aerosols, on the one hand, and potential impacts on the other. The reasons include:

(*a*) Altered patterns of radiative forcing and global mean changes in climate will have different effects on climate conditions in different regions. These local and regional conditions, including changes in the length of growing seasons, the availability of water, and the incidence of disturbance regimes (extreme high temperature events, floods, droughts, fires, and pest outbreaks) have important impacts on the structure and function of both natural and human-made environments;

(*b*) Some systems are more vulnerable to changes in regional climate than others—e.g., human systems are more adaptive, hence on average less vulnerable, than natural systems; forested systems require longer periods than grassland systems to establish themselves and hence are less likely to be able to migrate to new locations with suitable conditions, as temperature and precipitation patterns shift;

(*c*) The relative vulnerability of individual regions is likely to vary. Typically, systems are more vulnerable in developing countries, where economic and institutional circumstances are less favourable than in developed countries. People who live in semi-arid regions, upland regions, low-lying coastal areas, water-limited or flood-prone areas, or on small islands are particularly vulnerable to climate change. Sensitive areas such as river flood plains and coastal plains have become more vulnerable to hazards such as storms, floods and droughts as a result of increasing population density and economic activity;

(*d*) Impacts are not a linear function of the magnitude and rate of change; for some species (and hence systems), thresholds of change in temperature, precipitation or other factors may exist which, once exceeded, lead to discontinuous changes in viability, structure or function. This suggests that small changes in local climates may have a disproportionately large impacts;

(*e*) Most existing studies are limited to analysis of impacts that would result from changes associated with a doubled equivalent CO_2 equilibrium climate; very few studies have considered dynamic responses to steadily increasing concentrations of greenhouse gases or stabilization scenarios, and fewer still have examined the consequences of increases beyond a doubling of equivalent atmospheric CO_2 concentrations. Even fewer studies have assessed the implications of multiple stress factors, such as O_3, SO_2 acidification, or other pollutant stressors in the presence of climate and CO_2 change.

In conclusion, the ultimate concentration of greenhouse gases reached in the atmosphere, as well as the speed at which concentrations increase, is likely to influence impacts, because a slower rate of climate change will allow more time for systems to adapt. Knowledge is not currently sufficient, however, to point to a clear threshold rate and magnitude of change.

3.2 Mitigation Costs of Stabilizing CO_2 Concentrations

Previous sections of this Technical Paper explore physical aspects of different stabilization levels and consider their climatic impacts. We now turn to the *costs* associated with stabilizing concentrations of greenhouse gases. These costs depend largely on the *level* of stabilization and *pathway* towards it. We focus on CO_2 (the largest single contributor to radiative forcing, and the gas on which there is by far the most extensive literature) from the combustion of fossil fuels, which is its largest anthropogenic source.

Factors that affect CO_2 mitigation costs include:

(*a*) Future emissions in the absence of policy intervention (“baselines”);

(*b*) The concentration target and route to stabilization, which determine the carbon budget available for emissions;

(*c*) The behaviour of the natural carbon cycle, which influences the emissions carbon budget available for any chosen concentration target and pathway;

(*d*) The cost differential between fossil fuels and carbon-free alternatives and between different fossil fuels;

(*e*) Technological progress and the rate of adoption of technologies which emit less carbon per unit of energy produced;

(*f*) Transitional costs associated with capital stock turnover, which increase if carried out prematurely;

(*g*) The degree of international cooperation, which determines the extent to which low cost mitigation options in different parts of the world are implemented; and

(*h*) Assumptions about the discount rate used to compare costs at different points in time.

The particular policies and measures used to implement emission reductions, the degree of flexibility permitted to re-allocate control responsibility across sources/countries, research and development efforts, technology transfer efforts, the types of infrastructure investments societies make (e.g., mass transit vs. expanded highway systems), as well as the concentration level chosen for stabilization, will influence the actual costs incurred.

3.2.1 Economic Considerations Associated with Stabilizing CO_2 Concentrations

3.2.1.1 The Amount of Carbon to be Removed

The costs of a carbon constraint depend on the emissions "baseline", i.e., how emissions are projected to grow in the absence of policy intervention. The higher the baseline, the more carbon must be removed to meet a particular stabilization target, thus the greater the need for intervention. Figure 16*a* shows anthropogenic CO_2 emissions for the six IS92 baseline scenarios. The differences in emissions are generated by different assumptions about population, economic growth, the cost and availability of energy supply- and demand-side alternatives, and other factors.

Emissions grow in all but one of the IS92 scenarios. This is consistent with the overwhelming majority of studies recently reviewed in SAR WGIII. Of the dozens of studies surveyed, all but a few showed a rising emissions baseline. Emissions grow because the studies forecast that economic growth increases emissions faster than reductions in energy intensity and fuel-switching to less carbon intensive sources reduce emissions.

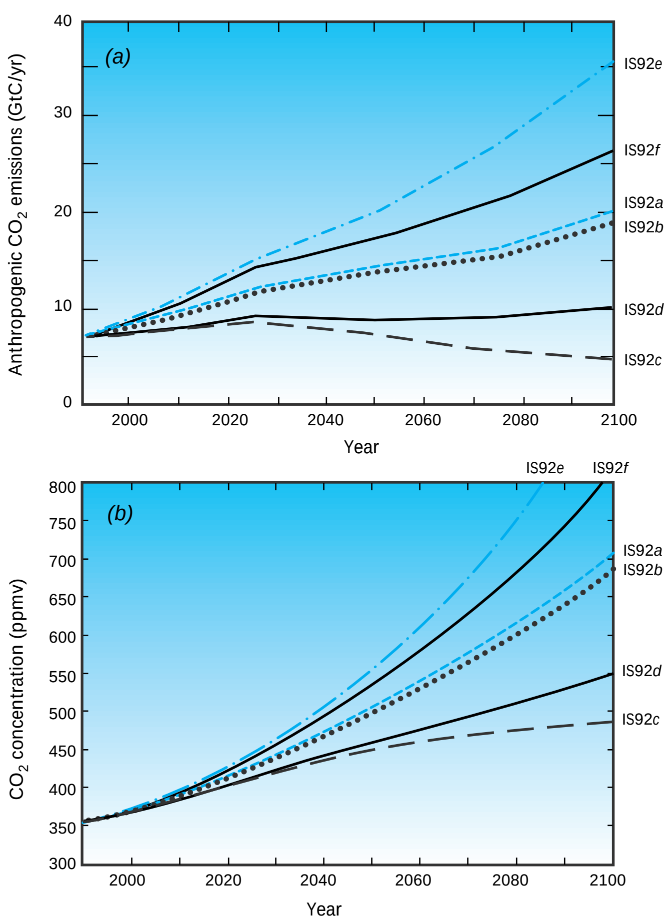

Figure 16. (*a*) Total anthropogenic CO_2 emissions under the IS92 emissions scenarios; (*b*) The deduced atmospheric CO_2 concentrations for the IS92 emissions scenarios calculated using the Bern carbon cycle model (see SAR WGI (Section 2.1)) (taken from SAR WGI: Technical Summary).

The rising baseline does not imply that there are no economically-attractive alternatives to fossil fuels — on either the supply-side or demand-side of the energy system. Such options typically are included in sizeable quantities in most economic analyses. A growing baseline only means that these options are not implemented at a rate sufficient to arrest the growth in carbon emissions. This may be due to an insufficient supply of no-regrets options.

Figure 16*b* translates the emission scenarios into CO_2 concentrations. None of the six scenarios leads to stable concentrations before 2100, although IS92*c* leads to a very slow growth in CO_2 concentration after 2050. IS92*a, b, e* and *f* all double the pre-industrial CO_2 concentration before 2070.

3.2.1.2 The Stabilization Target

The costs of a carbon constraint are also sensitive to the concentration stabilization target. As a first approximation, a stabilization target defines an amount of carbon that can be emitted between now and the date at which the target is to be achieved (the "carbon budget"). Table 5 shows the "carbon budgets" to the year 2100 associated with the 450, 550, 650, 750 and 1 000 ppmv stabilization profiles (see Figure 6 for the cumulative emissions from which the carbon budgets were derived) . The lower the stabilization target, the smaller the carbon budget (i.e., the smaller the cumulative emissions amount).

The size of this "carbon budget" is an important determinant of mitigation costs. Lower stabilization targets require smaller carbon budgets, which require a greater degree of intervention. Table 5 compares the carbon budget for the stabilization level and paths from Figures 5 and 6 to the accumulated anthropogenic CO_2 emissions for the IS92 emission scenarios.

3.2.1.3 Cost Differential Between Fossil Fuels and Carbon-free Alternatives

The cost of stabilizing CO_2 concentrations also depends on the cost of fossil fuels relative to carbon-free alternatives. For a given energy demand, the cost of reducing energy-related CO_2 emissions depends on the cost difference between the available fossil fuels and the carbon-free alternatives at the time when global CO_2 emissions are reduced.

The cost differential between conventional fossil fuels (e.g., conventional crude oil, natural gas, and coal) and carbon-free alternatives is forecast to narrow, although how much remains uncertain and widely debated. During the next hundred years, the cost of conventional fossil fuels should increase as these resources are exploited, and the least expensive and most accessible coal deposits are mined. At the same time, improvement in

Case IS92 scenarios	Accumulated CO_2 emissions 1991 to 2100 (GtC)	Stabilization at	Accumulated CO_2 emissions 1991 to 2100 (GtC) "S" concentration profiles*	Accumulated CO_2 emissions 1991 to 2100 (GtC) "WRE" concentration profiles†
c	770	450 ppmv	630	650
d	980	550 ppmv	870	990
b	1430	650 ppmv	1030	1190
a	1500	750 ppmv	1200	1300
f	1830	1000 ppmv	-	1410
e	2190			

* As in IPCC94 (Chapter 1)

† Profiles that allow emissions to follow IS92a until at least the year 2000 (Wigley, *et al*., 1996)

Table 5. Total anthropogenic CO_2 emissions accumulated from 1991 to 2100 inclusive (GtC). All values were calculated using the carbon budget for the 1980s (IPCC94: Chapter 1) and the Bern carbon cycle model.

basic science, engineering, and institutional arrangements should reduce the cost of carbon-free technologies (and unconventional fossil fuels).

The degree to which cumulative emissions exceed conventional crude oil and natural gas resources gives some indication of the contribution these fuels make to total energy consumption (see Table 9 of the IPCC Technical Paper on Technologies, Policies and Measures for Mitigating Climate Change (IPCC TP P&M, 1997) for estimates of global energy reserves and resources[7]). If cumulative emissions associated with a stabilization target are equal to or lower than the cumulative emissions that would result from the combustion of conventional oil and gas resources, these fuels will probably be an important component of total energy supply during the transition period to carbon-free alternatives. On the other hand, if cumulative emissions associated with a stabilization target are significantly greater than the cumulative emissions that would result from the combustion of conventional crude oil and natural gas resources, these fuels will probably be a relatively small component of total energy supply during the transition period. The cost difference between fossil fuels and carbon-free alternatives will be smaller in the latter case. While the cost premium for carbon-free alternatives is likely to be smaller for higher stabilization levels, total energy demand is higher so the net effect on transition costs is not clear.

However, we cannot predict how the absolute level of the cost differential between unconventional fossil fuels and carbon-free alternatives will change over time. Technical change will probably reduce the costs of unconventional fossil fuels and carbon-free alternatives, but the rate of technical change is likely to differ. Technical gains that reduce the costs of unconventional fossil fuels relative to carbon-free alternatives will increase transition costs by increasing the cost differential between fossil fuels and carbon-free alternatives, whereas technical changes that reduce the costs of carbon-free technologies have the opposite impact.

Differences between the costs of available fossil fuels affect transition costs in a similar manner.

3.2.1.4 The Emissions Pathway

As indicated in Figure 5 and described in Section 2.2.1.2, the same concentration target (see Figure 4) can be achieved through several emission pathways. Emissions in the near-term can be balanced against emissions in the long-term. On the other hand, higher early emissions decrease the options to adjust emissions later on. In Figure 5, the dashed lines (the WRE profiles) show higher emissions in the early years, although a more rapid transition from increasing to decreasing emissions. The pathways associated with the solid lines (the S profiles) allow higher emissions later on, but have lower emissions in the early years. Thus, as explained in Section 2.2.1.2, for a given stabilization level, there is a "budget" of allowable accumulated carbon emissions and the choice of pathway to stabilization can be viewed as a problem of how to best (i.e., with the greatest economic efficiency and least damaging impacts) allocate this carbon budget over time.

The differences in the emission paths for the same stabilization level are important because costs differ among pathways. SAR WGIII identifies the following factors that affect the costs of alternative pathways: (*a*) the treatment of existing and future capital stock; (*b*) the prospects for technical progress; (*c*) the discount rate; and (*d*) the carbon budget.

[7] The focus here is on resources because they represent the quantities, both known and unknown, that remain to be combusted.

Capital stock, capital stock turnover and new investments

Mitigation costs depend on the lifespan of existing plants and equipment. The lifespan for energy producing and using capital stock (for example, power plants, housing and transport) is not fixed. It is influenced by factors such as maintenance costs and reliability, which tend to change over time. Nevertheless, energy-related capital stock is typically long-lived and premature retirement is apt to be costly. To avoid premature retirement, mitigation efforts can be spread more evenly over time and space. To reduce the cost of any stabilization target, SAR WGIII stresses the need to focus on new investments and replacements at the end of the economic life of plant and equipment (i.e., at the point of capital stock turnover).

The focus on new investment does not imply "doing nothing". Acting too slowly — not even undertaking low cost measures — may increase the costs of a stabilization path by requiring more rapid action later on. This may include the need to retire, prematurely, capital stock that is constructed in the interim. For example, deferring mitigation for a couple of decades would allow global fossil fuel emissions to increase significantly (e.g., IS92*a* and several other scenarios). But to stabilize concentrations below 450 ppmv, emissions would have to be brought back down to 1990 levels by about 2040 and lower thereafter. This might require society to replace much of the stock constructed in the interim, and these costs need to be weighed against any economic benefits gained from the deferment.

The optimal rate at which capital stock is replaced reflects broader questions about the inertia of energy systems. For example, different investments have different time implications. Constructing new, very long-lived, carbon-intensive infrastructure may raise the costs of limiting emissions many decades from now. Discouraging investments such as inefficient buildings, or other urban infrastructure that may encourage a wide range of carbon-intensive activities, could be important now in lowering the long-run costs of stabilizing atmospheric concentrations even at higher levels. However, the issue of inertia and how it affects different investments is not well understood.

As indicated by Figure 5, a 450 ppmv limit would require reductions in global emissions starting very soon, while higher limits would delay the need for restrictions. While emissions increases in some countries can be offset by declines within others over some period of time, emission growth must eventually be curtailed in all regions to meet the limit.

Technical progress

The cost of a stabilization path also depends on how technology affects the cost of abating emissions at a point in time and over time. In general, the cost of an emission pathway increases with the amount of emissions that must be abated at any point in time. However, technological changes should reduce the unit cost per unit reduction over time.

Abatement costs at any point in time rise with the quantity of emissions abated at that time. The suite of abatement technologies described in SAR WGII can be considered as forming a "supply curve". Clearly, it is cheapest to take the least-expensive measures first and to work up the "supply curve" using more costly measures as required to meet the objective.

Technical change is likely to reduce abatement costs over time. The rate of this reduction may depend on the stabilization level and emission pathway. Stabilization levels and emission pathways that imply more immediate reductions may stimulate development of new, lower carbon technologies: "induced" technology development. This increases long-run flexibility and lowers the long-run costs of a carbon constraint, but at a near-term price. According to this argument, rather than wait for technology development to lower future mitigation costs, early emission constraints induce the private sector to undertake appropriate research and development, including the switching of research and development investment away from exploration and development of carbon-intensive resources and technologies.

Induced (endogenous) technical change depends on the stimulation of innovation by price signals, which is likely to be greatest in well functioning markets. In the early stages of technology development, it is difficult to establish ownership of research results; therefore the private sector often is reluctant to invest in adequate research and development. The prospects of future markets is unlikely to overcome this problem entirely. This well known market failure is often used to justify government involvement in research and development, and such research and development may be very important in promoting the development of technologies early on.

Government research and development and emission constraints are not the only levers policy makers can exercise to influence the rate of technology development, diffusion and dissemination. Tax incentives and the support of "protected" markets, such as premium payments for renewable energy, may also encourage the private sector to invest in carbon-free energy and the development of associated industries. Technology diffusion and dissemination may also be inhibited by market failures and require specific policies to overcome.

In reality, a mix of all these measures — greatly increased government research and development, support for technology distribution, explicit market supports, and appropriate emission constraints — probably will act together to stimulate the technology needed to lower the costs of stabilizing atmospheric CO_2 concentration. The literature assessed in SAR WGIII does not give a clear indication as to the appropriate mix of policies and the implications for emission pathways.

International cooperation

The least expensive mitigation options are often associated with new investments. To take advantage of these opportunities, a cost-effective approach would adopt low cost mitigation measures wherever new investments are made throughout the world. Mechanisms such as emissions trading or joint implementation may be used to implement this strategy in a manner that facilitates the distribution of mitigation costs among countries while promoting cost effectiveness. This approach, commonly referred to as "where" flexibility, works because the climate benefits of CO_2 emission reductions do not depend on their location.

Discount rate

With regard to mitigation costs (the subject of this section), a positive discount rate lowers the present value of the costs incurred. This is because it places a lower weight on investments made in the future. Indeed, the further in the future an economic burden (here, emission reductions) lies, the lower the present value of costs. In a wider context, discounting reduces the weight placed on future environmental impacts relative to the benefits of current energy use. Its use makes serious challenges, such as rapid switching of energy systems in the future, seem easy in terms of present dollars and may affect consideration of intergenerational equity.

Carbon budget

Carbon emissions may follow different pathways to meet a certain stabilization target (as shown by Figures 5 and 6). If no major disruption of the processes that govern the uptake of CO_2 by the ocean and the land biosphere occurs, then long-term total cumulative emissions for a given stabilization pathway are essentially independent of the pathway towards a stabilization target (see Figure 6 and Section 2.2). However, the allocation of emissions in time depends on the pathway. Emissions in the next decades can be notably higher for pathways that follow IS92*a* initially (see Figures 6 and 7). Thus, the requirements for higher cost carbon-free alternatives are reduced in the short-term and stronger emission reductions are delayed into the future.

However, there are risks associated with emission pathways that follow IS92*a* initially. Higher earlier emissions and implied higher concentrations and rates of concentration increase may disrupt the physical and biogeochemical processes governing the flow of carbon. This may mean that emissions must be lower than expected to meet a certain stabilization target. In addition, higher earlier emissions will lead to faster rates of climate change, which may be costly. Pathways that imply higher emissions initially may have a more rapid transition from increasing to decreasing emissions, which tends to increase mitigation costs.

3.2.2 Modelling the Costs of Stabilizing CO_2 Concentrations

Modelling mitigation costs is a daunting task. It is difficult to forecast the evolution of the energy-economic system over the next decade. Projections over a century or more must be treated with considerable caution. Nevertheless, such exercises can provide useful information. The value however, lies not in the specific numbers, but in general results that are useful for policy making.

3.2.2.1 Studies Available at the Time of the SAR WGIII

Until recently, proposals for dealing with climate change tended to focus on emissions rather than concentrations: for example, returning emissions to 1990 levels by 2000, or a 20 per cent reduction by 2005. As a result, few analyses had examined the economics of stabilization at the time of SAR WGIII. Those that had are reviewed in Chapters 9 and 10 of SAR WGIII and are described below. (Subsequently a number of additional studies have been undertaken, but, in accordance with the guidelines for Technical Paper preparation, they are not reviewed here.)

Several authors have explored the cost-effectiveness of a particular CO_2 concentration target. For example, Nordhaus (1979) and Manne and Richels (1995) identify least-cost mitigation strategies for meeting a range of alternative concentration targets. They found that the least-cost mitigation path initially involves modest reductions from the emissions baseline. Higher concentration targets allow emissions to follow the baseline for longer periods.

Richels and Edmonds (1995) and Kosobud, *et al.,* (1994) examined alternative emission pathways for stabilizing atmospheric concentrations. Their results indicate that pathways involving modest reductions in the early years, followed by sharper reductions later on, are less expensive (in terms of mitigation costs) than those that require substantial reductions in the short-term given their assumptions concerning technical change, capital stock turnover, discount rate and the effect of the carbon budget. The timing of emission reductions is known as "when" flexibility.

Higher stabilization targets allow more flexibility in the rate of departure from the baseline. However, regardless of the rate of departure from the baseline, a stabilization pathway is not a "do nothing" or "wait and see" strategy. First, each concentration path still requires that future capital equipment be less carbon-intensive than under a scenario with no carbon limits. Given the long-lived nature of energy producing and energy using equipment, this has implications for current investment decisions. Second, new supply options typically take many years to enter the marketplace. To have sufficient quantities of low cost, low carbon substitutes in the future would require a sustained commitment to research, development and demonstration today. Third, any available no-regrets measures for reducing emissions are assumed to be adopted immediately, which may require government action.

3.2.2.2 Limitations of Existing Studies

Two aspects of the above studies arouse considerable debate: the goal, and the reliance on highly simplified models of the energy-economic system. With regard to the former, the authors stress that their focus has been on mitigation costs, with particular attention to the least-cost path for meeting a particular concentration target. They emphasize that it is also important to examine the environmental consequences of choosing one emission path over another. Different emission paths imply not only different mitigation costs, but also different benefits in terms of averted environmental impacts, as well as the injection of novel environmental issues, such as those that might occur if biomass fuels become more important.

The analyses are also limited by their treatment of uncertainty. Uncertainty regarding the ultimate target is likely to persist for some time. Under these conditions, policy makers must identify a prudent near-term hedging strategy that balances the risks of acting too slowly against the costs of acting too aggressively. Although several of the studies cited in SAR WGIII attempt to assess the robustness of the near-term control decision to the long-term concentration target, they do not analyse the effects of uncertainty explicitly.

Some critics also dispute the methodologies that underlie these studies. They question the extent to which the models, which by necessity simplify the energy-economic system, capture the full complexity of capital stock, its interlinkages and other sources of inertia in the system. For example, existing models do not simulate the linkages among investments. Some investments we take today, like roads, last for a very long time and create a whole network of interlocking investments (e.g., the spatial pattern of industrial facilities and housing) that may affect the costs of emission constraints for years to centuries.

The models also simplify the process of technological change. The models assume that the rate of technological change is independent of the extent of emission controls. As noted earlier, if emission constraints induce technological innovation, the optimal level of emission reductions may be higher than otherwise. The notion of endogenous technological change is important — one that deserves more attention than it has received. It should be noted, however, that the size of the effect is far from clear.

3.2.3 Other Key Considerations

The choice of concentration target and route to stabilization is a very complex decision. Significant uncertainty persists regarding the proportion of the carbon budget that leads to stabilization. As noted in Section 2.2.1.3, the generation of models employed in SAR WGI simplified representations of biospheric plus oceanic uptake and ignore the potential for climate change to affect the rate of terrestrial and marine uptake. Because mitigation costs depend on the difference between emissions consistent with a given stabilization target and some baseline, ignoring the ecological or marine feedbacks can increase or decrease the emissions and mitigation costs associated with a stabilization level. Given the scientific uncertainties in the carbon models, the uncertainty from oceanic and terrestrial feedbacks is likely to be ±100 GtC or more.

In practice, we do not know the appropriate stabilization level, and this makes the appropriate strategy still more complex. Stronger research and development policies, which are relatively cheap compared with the potential costs of rapid reductions in emissions, appear a good investment against a wide range of outcomes. In addition, early mitigation, particularly at the point of new investment, reduces the exposure of the economy to the possibly very high costs of discovering that we need to achieve a lower stabilization target than expected initially. Fuller implementation of no-regrets and low cost measures help, not only to reduce impacts, but also to prepare economies for stabilization.

3.3 Integrating Information on Impacts and Mitigation Costs

3.3.1 Introduction

Balancing the costs, impacts, and risks associated with stabilization at different levels and by different pathways is an extremely complex task, and one that ultimately must include a number of political judgements about levels of acceptable risk, different kinds of risks, and the weight to be given to different kinds of impacts (from both mitigation and climate change) on different people, in different countries, and at different times.

As noted earlier, sensible greenhouse policy requires decision makers to consider the costs and other implications of climate change policy measures together with what such measures might buy in terms of reducing the undesirable consequences of global climate change. In Section 3.1, we discussed the issue of impacts and how they may be reduced by adopting a lower stabilization target. In Section 3.2, we discussed mitigation costs associated with limiting anthropogenic CO_2 emissions to achieve stable atmospheric concentrations. This section discusses possible insights from integrating this and other relevant information contained in this paper.

3.3.2 The Need for Consistency and a Broad Perspective

It is important that the issues raized particularly in Sections 3.1 and 3.2 be applied consistently to both mitigation costs and climate impacts. Some important examples include:

Inertia. The inertia of the climate system means that emissions now may generate impacts for many years — or in the case of sea level rise, perhaps centuries. Greenhouse gases have a long atmospheric lifetime, and even draconian emissions changes would affect concentrations only slowly. Inertia in the existing capital stock that emits greenhouse gases also means that it would be very expensive to reduce emissions very rapidly. Both kinds of inertia emphasize the need for forward thinking, analysis, and action in terms of trajectories towards long-term goals, to minimize shocks to the system.

Technology development and other forms of innovation and adaptation have implications for both mitigation costs and impacts. Research and development directed at both mitigation and adaptation can be very beneficial. Deferring mitigation may allow greater time for development of cheaper mitigation technologies, but less time for adaptation to the corresponding impacts.

Time preferences are another important factor. The delay between emissions and consequent impacts means that a positive discount rate tends to reduce the present weight of impacts relative to abatement costs, and thus tends to favour a lesser overall degree of mitigation.

Climate surprises. There may be surprising outcomes in climate change, and thresholds in physical, biological or socio-economic systems that may be crossed — not taking early action makes such events more difficult to deal with.

Non-climate external impacts. We also need to consider the synergy between greenhouse gas mitigation strategies and the mitigation of other environmental externalities, such as local air pollution, urban congestion, or land and natural resource degradation. This may extend the range of mitigation options that can be considered as no-regrets measures or as measures that entail low net costs.

Other greenhouse gases and sources. An integrated analysis also must account for greenhouse gases other than CO_2 from fossil fuels:

(*a*) Deforestation may account for as much as 20 per cent of fossil fuel emissions at present (though its relative contribution is expected to decline), and reforestation may make important contributions to absorbing CO_2;

(*b*) Analysis shows that methane in particular could be an important greenhouse gas, for which there may be a number of cheap options for mitigation; and

(*c*) Attention must also be given to nitrous oxide and halocarbons, particularly given the very long lifetime of these gases.

Because these are all very complex issues — particularly relating to impacts and the many uncertainties surrounding ways of quantifying them — economics alone cannot provide unique answers concerning the correct balance in emission pathways. Nor, for the same and additional reasons, is it possible to reach clearly quantified conclusions about "optimum" stabilization levels.

3.3.3 Portfolio Analysis

Numerous policy measures are available to reduce risks to future generations from climate change. These include: (*a*) reductions in emissions to slow climate change; (*b*) research and development on new supply and conservation technologies that reduce future abatement costs; (*c*) continued research to reduce critical scientific uncertainties; and (*d*) investment in actions that assist human and natural systems to adapt to climate change. The issue is not one of "either-or" but one of finding the right blend (portfolio) of options. At a given point in time, policy makers must decide how much effort and financial support is allocated towards mitigation; how much towards public research and development and market incentives to foster technology development; how much towards reducing climate-related uncertainties; and how much towards helping societies adapt to climate change. These and other options outlined in SAR WGIII are summarized in the box across.

A key to selecting an optimal portfolio is understanding how the options interact. Particularly important is the relation between research and development investments and mitigation costs. In general, research and development investments reduce future mitigation costs. One example contained in SAR WGIII suggests that extensive development of economically-competitive alternatives to fossil fuels could reduce the mitigation costs for a 20 per cent reduction in CO_2 emissions (below 1990 levels) by approximately two-thirds. Such savings could free up resources needed to address the threat of climate change or to meet other societal needs. Conversely, embedded in all of the IS92 scenarios are expectations about technical progress on both the supply- and demand-sides of the energy system. These advances will not occur unless there are sustained research and development programmes on a variety of fronts — both in the public and private sectors.

Reducing scientific uncertainty also reduces costs. At the present time, the question of what constitutes "dangerous interference" with the climate system is unresolved. Because of the high cost of being wrong in either direction, the value of information about climate change is likely to be great. The literature indicates that information about climate sensitivity to greenhouse gases and aerosols, climate change impact functions, and variables such as the determinants of economic growth and rates of energy efficiency improvements, is most valuable.

Reliance on a portfolio of actions also applies within each category. For example, mitigation costs for some greenhouse gas sources are less expensive than others. SAR WGIII suggests that there may be many relatively inexpensive options for controlling industrial sources of methane and halogenated compounds, although agricultural sources of methane and N_2O may be more difficult. Reducing emissions using the least expensive options first reduces the total costs of mitigation. The potential for reducing CO_2 emissions by slowing deforestation and absorbing CO_2 by reforestation also may offer opportunities for lowering the costs of reducing CO_2 concentrations.

A PORTFOLIO OF ACTIONS

".. that Policy makers could consider .. to implement low cost and/or cost effective measures "

(Source: SAR WGIII: Summary for Policymakers.)

- Implementing energy efficiency measures including the removal of institutional barriers to energy efficiency improvements;
- Phasing out existing distortionary policies and practices that increase greenhouse gas emissions, such as some subsidies and regulations, non-internalization of environmental costs, and distortions in transport pricing;
- Implementing cost-effective fuel switching measures from more to less carbon-intensive fuels and to carbon-free fuels such as renewables;
- Implementing measures to enhance sinks or reservoirs of greenhouse gases such as improving forest management and land-use practices;
- Implementing measures and developing new techniques for reducing methane, nitrous oxide and other greenhouse gas emissions;
- Encouraging forms of international cooperation to limit greenhouse gas emissions, such as implementing coordinated carbon/energy taxes, activities implemented jointly, and tradeable quotas;
- Promoting the development and implementation of national and international energy efficiency standards;
- Planning and implementing measures to adapt to the consequences of climate change;
- Undertaking research aimed at better understanding the causes and impacts of climate change and facilitating more effective adaptation to it;
- Conducting technological research aimed at minimizing emissions of greenhouse gases from continued use of fossil fuels and developing commercial non-fossil energy sources;
- Developing improved institutional mechanisms, such as improved insurance arrangements, to share the risks of damages due to climate change;
- Promoting voluntary actions to reduce greenhouse gas emissions;
- Promoting education and training, implementing information and advisory measures for sustainable development and consumption patterns that will facilitate climate change mitigation and adaptation.

The appropriate portfolio of policy measures varies from country to country. Countries will select a portfolio that reflects their individual objectives and constraints. Each country will be interested in the impacts of the portfolio on different economic groups, international competitiveness, international equity and intergenerational equity. Nevertheless, there is a need for coordination across countries. A number of researchers have compared the costs of unilateral action and international cooperation and found large economic returns from international cooperation.

3.3.4 Sequential Decision Making

All too often, the climate issue is framed in terms of "act now" or "wait and see". This formulation of the decision problem is incorrect and potentially misleading because it obscures the choices that should be evaluated and their interaction over time. Because both climate change and new knowledge are continuous processes, actions to address climate change should be adjusted continuously based on new information.

The UN/FCCC recognizes the dynamic nature of the decision-making process. Its drafters envisaged climate policy as an ongoing process, not a "once and for all" event. The UN/FCCC requires periodic reviews "in light of the best available scientific information on climate change and its impacts, as well as relevant technical social and economic information". Based on these reviews, appropriate actions are to be taken, including the adoption of amendments to existing commitments.

Such a sequential decision-making process aims to identify short-term strategies in the face of long-term uncertainty. The next several decades will offer many opportunities for learning and mid-course corrections. The relevant question is not "what is the best course for the next 100 years" but rather "what is the best course for the next decade given some long-term objective?" The issue thus becomes one of selecting a well chosen portfolio of actions addressing climate change and adjusting it over time in light of improved information.

To implement a portfolio of actions to address climate change, governments must decide both the amount of resources to devote to this issue and the mix of measures they believe will be most effective. With regard to the former, the issue is how far to proceed beyond purely no-regrets options. As noted in SAR WGIII, "the risk of aggregate net damage due to climate change, consideration of risk aversion, and the application of the precautionary principle provide rationales for action beyond no-regrets". The decision on how much action to take depends on the "stakes", the "odds" and the costs of policy measures. The risk premium — the amount that a society is willing to pay to reduce a risk — ultimately is a political decision that differs among countries.

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Appendix 1

Temperature and Sea Level Consequences of Stabilization of CO_2 Concentrations from 1990 to 2300

Section 2.3 discussed the temperature and sea level implications of greenhouse gas stabilization, focusing on the period 1990 to 2100. In order to give a longer term perspective, the temperature and sea level results shown in Figures 11 to 15 (and discussed in Section 2.3) are presented in this Appendix, extended out to 2300 (Figures A1 to A5).

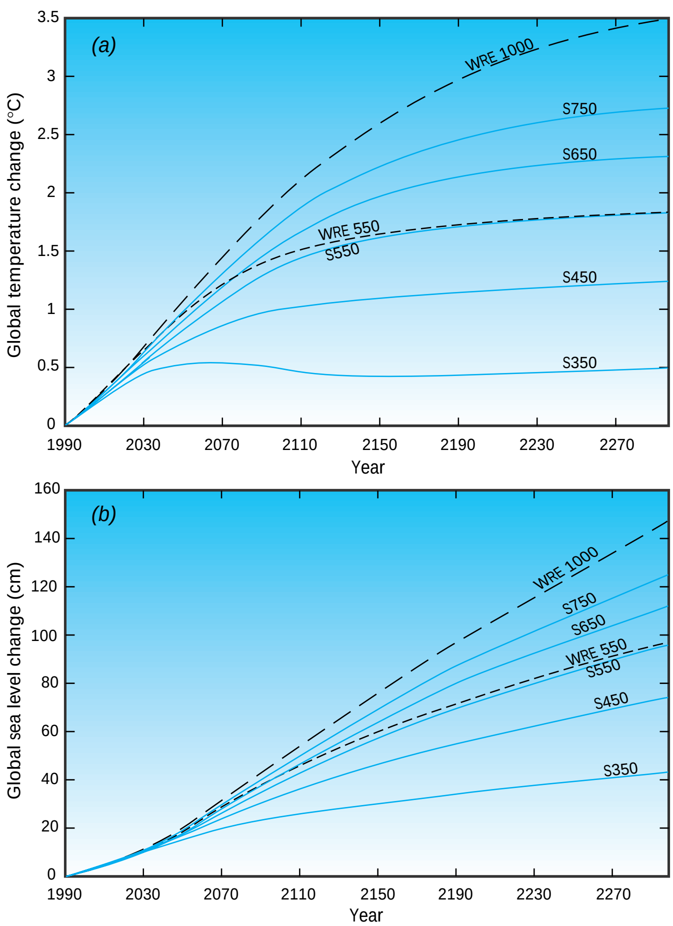

Figure A1. (*a*) Projected global mean temperature when the concentration of CO_2 is stabilized following the S profiles and the WRE550 and 1000 profiles shown in Figure 4. CH_4, N_2O and SO_2 emissions are assumed to remain constant at their 1990 levels and halocarbons follow an emissions scenario consistent with compliance with the Montreal Protocol until 2100 and then remain constant thereafter (i.e., the reference case); (*b*) As for (*a*), but for global sea level change and central ice-melt parameters. All results were produced using the Wigley and Raper simple climate/sea level model (see IPCC TP SCM (1997)). See Figure 11 for results from 1990 to 2100.

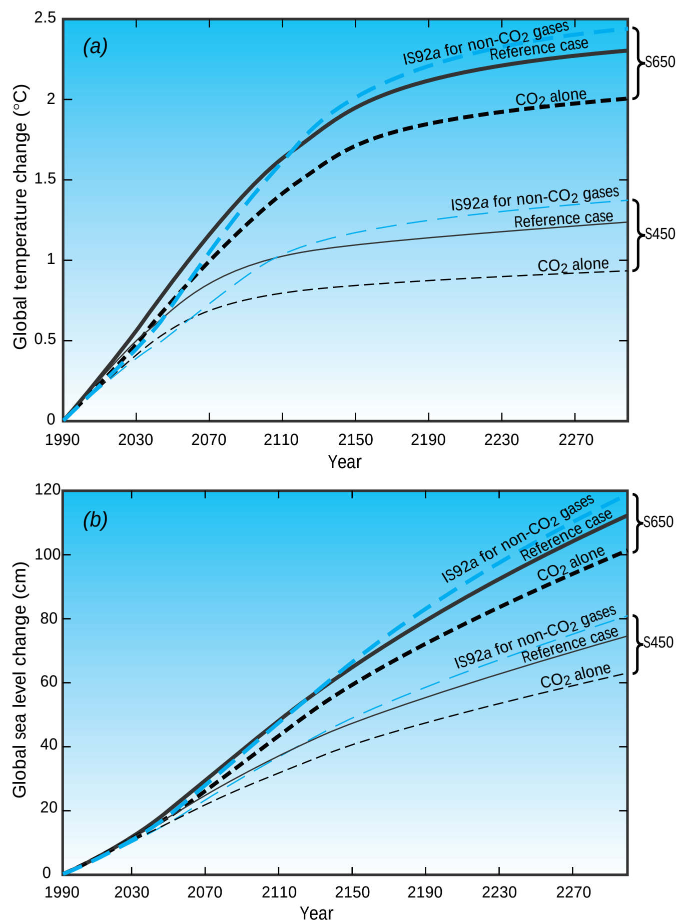

Figure A2. (*a*) The effect of different non-CO_2 gas emission profiles on global temperature change for the S450 and S650 concentration profiles (see Figure 2). The solid lines give the "reference" results; the short dashed lines the "CO_2 alone" results and the long dashed lines give results where CH_4, N_2O and SO_2 emissions increase according to IS92a to 2100 and then stabilize (the "IS92a case"). The climate sensitivity is assumed to be the mid-range value of 2.5˚C; (*b*) As for (*a*), but for global sea level change. Central values of the ice-melt parameters are assumed. See Figure 12 for results from 1990 to 2100.

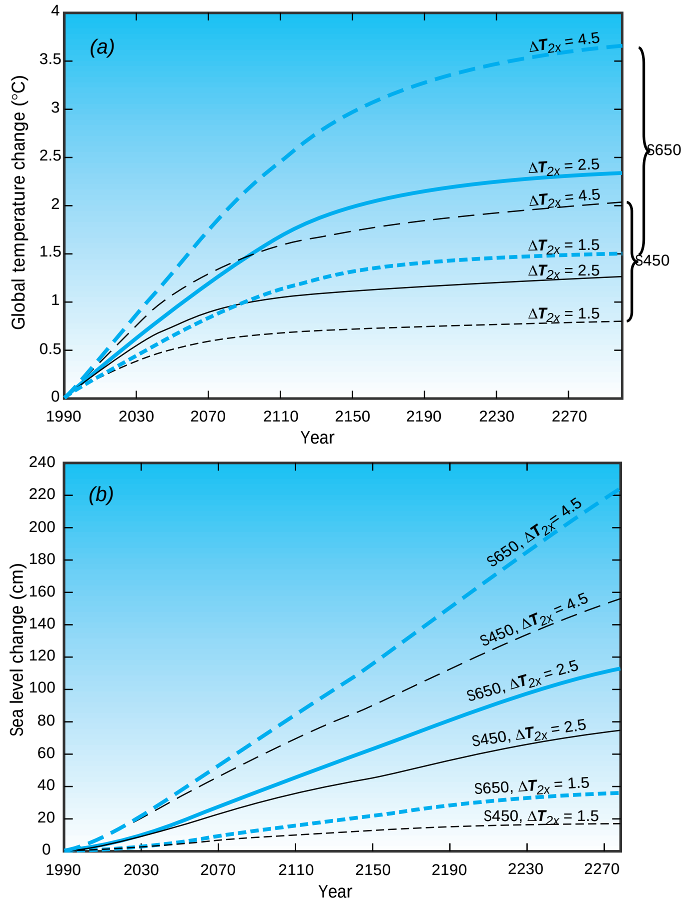

Figure A3. (*a*) The effect of climate sensitivity uncertainties on global mean temperature for the S450 and S650 CO_2 concentration profiles and the reference case for non-CO_2 gases. The range of climate sensitivity (ΔT_{2x}) is 1.5 to 4.5˚C with a mid-range value of 2.5˚C; (*b*) As for (*a*), but for global sea level change. The low, mid and high values of climate sensitivity are combined with low, mid and high ice-melt parameters, respectively, to give extreme ranges. See Figure 13 for results from 1990 to 2100.

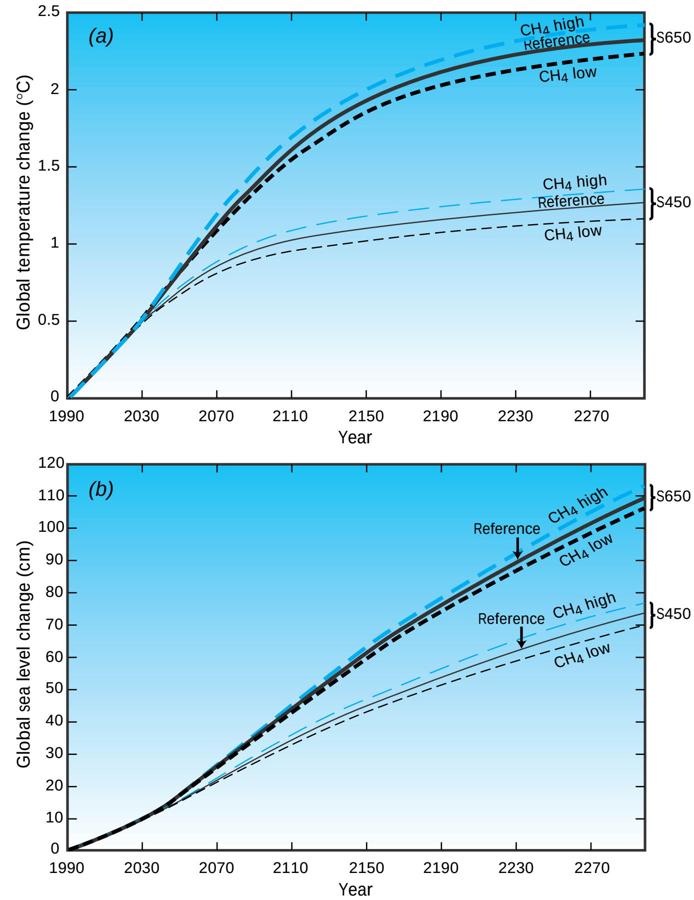

Figure A4. (*a*) Sensitivity of global mean temperature change to CH_4 emissions for the S450 and S650 concentration profiles (see Figure 4). The solid lines give the "reference" results; the "CH_4 low"/"CH_4 high" curves assume annual CH_4 emissions decrease/increase linearly by 100 Tg(CH_4) over 1990 to 2100 and then remain constant (see Table 4); (*b*) As for (*a*), but for global sea level change. Central values of the ice-melt parameters are assumed. See Figure 14 for results from 1990 to 2100.

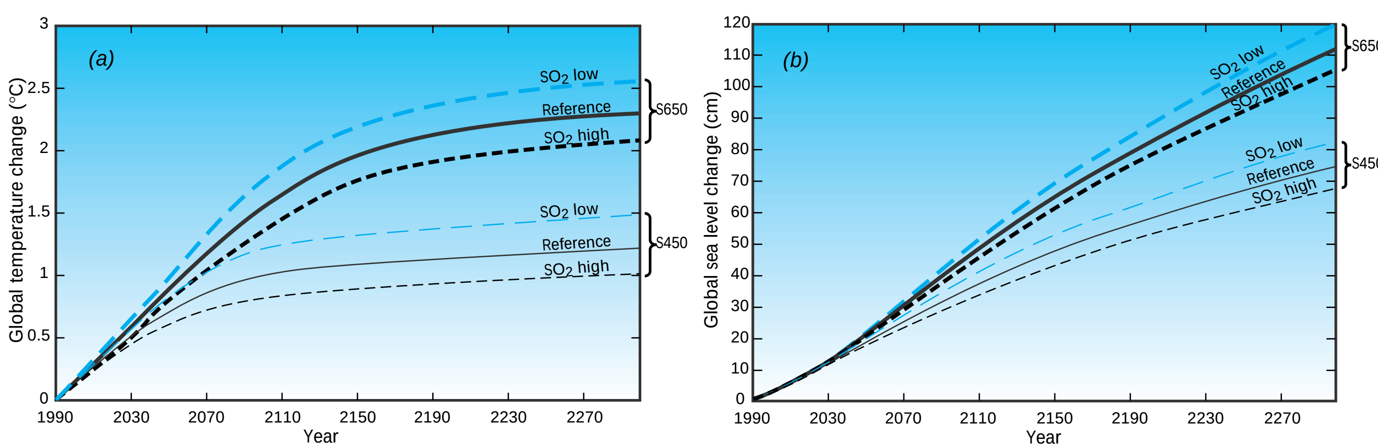

Figure A5. (*a*) Sensitivity of global mean temperature change to SO_2 emissions for the S450 and S650 concentration profiles (see Figure 4). The solid lines give the "reference" cases; the short dashed lines show the "high SO_2" cases where emissions increase linearly from 75 TgS/yr in 1990 to 112.5 TgS/yr in 2100 and then remain constant, and the long dashed lines show the "low SO_2" cases where emissions decrease linearly to 37.5 TgS/yr in 2100 and then remain constan; (*b*) As for (*a*), but for global sea level change. Central values of the ice-melt parameters are assumed. See Figure 15 for results from 1990 to 2100.

Appendix 2

GLOSSARY OF TERMS

Aerosol
A collection of airborne particles. The term has also come to be associated, erroneously, with the propellant used in “aerosol sprays”.

Biomass
The total weight or volume of organisms in a given area or volume.

Biome
A naturally occurring community of flora and fauna (or the region occupied by such a community) adapted to the particular conditions in which they occur (e.g., tundra).

Capital stocks
The accumulation of machines and structures that are available to an economy at any point in time to produce goods or render services. These activities usually require a quantity of energy that is determined largely by the rate at which that machine or structure is used.

Carbon cycle
The term used to describe the exchange of carbon (in various forms, e.g., as carbon dioxide) between the atmosphere, ocean, terrestrial biosphere and geological deposits.

Carbonaceous aerosol(s)
Aerosol(s) *(q.v.)* containing carbon.

Climate
Climate is usually defined as the “average weather”, or more rigorously, as the statistical description of the weather in terms of the mean and variability of relevant quantities over periods of several decades (typically three decades as defined by WMO). These quantities are most often surface variables such as temperature, precipitation, and wind, but in a wider sense the “climate” is the description of the state of the climate system.

Climate change (UN/FCCC usage)
A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.

Climate change (IPCC usage)
Climate change as referred to in the observational record of climate occurs because of internal changes within the climate system or in the interaction between its components, or because of changes in external forcing either for natural reasons or because of human activities. It is generally not possible clearly to make attribution between these causes. Projections of future climate change reported by IPCC generally consider only the influence on climate of anthropogenic increases in greenhouse gases and other human-related factors.

Climate sensitivity
In IPCC reports, climate sensitivity usually refers to the long-term (equilibrium) change in global mean surface temperature following a doubling of atmospheric CO_2 (or equivalent CO_2) concentration. More generally, it refers to the equilibrium change in surface air temperature following a unit change in radiative forcing (˚C/W m^{-2}).

Cloud condensation nuclei
Airborne particles that serve as an initial site for the condensation of liquid water and which can lead to the formation of cloud droplets.

CO_2 fertilization
The enhancement of plant growth as a result of elevated atmospheric CO_2 concentration.

Cryosphere
All global snow, ice and permafrost.

Damage function
The relation between changes in the climate and reductions in economic activity relative to the rate that would be possible in an unaltered climate.

Discount rate
The annual rate at which the effect of future events are reduced so as to be comparable to the effect of present events.

Diurnal temperature range
The difference between maximum and minimum temperature over a period of 24 hours.

Eddy mixing
Mixing due to small scale turbulent processes (eddies). Such processes cannot be explicitly resolved by even the finest resolution Atmosphere-Ocean General Circulation Models currently in use and so their effects must be related to the larger scale conditions.

Equilibrium response
The steady state response of the climate system (or a climate model) to an imposed radiative forcing.

Equivalent CO_2
The concentration of CO_2 that would cause the same amount of radiative forcing as the given mixture of CO_2 and other greenhouse gases.

External impacts/externalities
Impacts generated by climate change (or some other environmental change) that cannot be evaluated by a competitive market because of a lack of information and or the inability to act on that information.

Falsifiability rule
Science today recognizes that there is no way to prove the absolute truth of any hypothesis or model, since it is always possible that a different explanation might account for the same observations. In this sense, even the most well established physical laws are "conditional". Hence, with scientific methodology it is never possible to prove conclusively that a hypothesis is true, it is only possible to prove that it is false.

Feedback
When one variable in a system triggers changes in a second variable that in turn ultimately affects the original variable; a positive feedback intensifies the effect, and a negative feedback reduces the effect.

Flux adjustment
To avoid the problem of a coupled atmosphere-ocean general circulation model drifting into some unrealistic climatic state (e.g., excessively warm temperatures in the tropical Pacific ocean), adjustment terms can be applied to the fluxes of heat and precipitation (and sometimes the surface stresses resulting from the effect of the wind on the ocean surface) before being imposed on the model ocean.

Fossil fuel reserves
The quantity of a fossil fuel that is known to exist, based on geological and engineering evidence, and that can be recovered under current economic conditions and operating capabilities.

Fossil fuel resources
The quantity of fossil fuel that is thought to exist and that may be recoverable based on an explicit scenario for future economic conditions and operating capabilities.

GDP
Gross Domestic Product. The value of all goods and services produced (or consumed) within a nation's borders.

Greenhouse gas
A gas that absorbs radiation at specific wavelengths within the spectrum of radiation (infrared radiation) emitted by the Earth's surface and by clouds. The gas in turn emits infrared radiation from a level where the temperature is colder than the surface. The net effect is a local trapping of part of the absorbed energy and a tendency to warm the planetary surface. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere.

Halocarbons
Compounds containing either chlorine, bromine or fluorine and carbon. Such compounds can act as powerful greenhouse gases *(q.v.)* in the atmosphere. The chlorine and bromine containing halocarbons are also involved in the depletion of the ozone layer.

Infrared radiation
Radiation emitted by the Earth's surface, the atmosphere and by clouds. Also known as terrestrial and long-wave radiation. Infrared radiation has a distinctive spectrum (i.e., range of wavelengths) governed by the temperature of the Earth-atmosphere system. The spectrum of infrared radiation is practically distinct from that of solar *(q.v.)* or short-wave radiation because of the difference in temperature between the Sun and the Earth-atmosphere system.

Integrated assessment
A method of analysis that combines results and models from the physical, biological, economic and social sciences, and the interactions between these components, in a consistent framework, to project the consequences of climate change and the policy responses to it.

Lifetime
In general, lifetime denotes the average length of time that an atom or molecule spends in a given reservoir, such as the atmosphere or oceans. It is not to be confused with the response time of a perturbation in concentration. CO_2 has no single lifetime.

Marginal cost
The cost on one additional unit of effort. In terms of reducing emissions, it represents the cost of reducing emissions by one more unit.

Marine biosphere
A collective term for all living marine organisms.

Market damages
The value of damages generated by climate change (or some other environmental change) and evaluated based on information available to and usable by a competitive market.

Mitigation marginal cost function
The relation between the total quantity of emissions reduced and the marginal cost of the last unit reduced. The marginal cost of mitigation generally increases with the total quantity of emissions reduced.

Nitrogen fertilization
Enhancement of plant growth through the deposition of nitrogen compounds. In IPCC reports, this typically refers to fertilization from anthropogenic sources of nitrogen such as, man-made fertilizers and nitrogen oxides released from burning of fossil fuels.

"No-regrets" mitigation options
"No-regrets" mitigation options are those whose benefits, such as reduced energy costs and reduced emissions of local/regional pollutants, equal or exceed their cost to society, excluding the benefits of climate change mitigation. They are sometimes known as "measures worth doing anyway".

Non-market damages
Damages generated by climate change (or some other environmental change) and that cannot be evaluated by a competitive market because of a lack of information and/or the inability to act on that information.

Optimal control rate
The rate of intervention at which the net present value of the marginal costs of the intervention, equals the net present value of the marginal benefits of the intervention.

Parametrize (parametrization)
In climate modelling, this term refers to the technique of representing processes that cannot be explicitly resolved at the resolution of the model (sub-grid scale processes) by relationships between the area averaged effect of such sub-grid scale processes and the larger scale flow.

Photosynthesis
The metabolic process by which plants take CO_2 from the air (or water) to build plant material, releasing O_2 in the process.

Portfolio analysis
The mix of actions available to policy makers to reduce emissions or adapt to climate change.

Precautionary principal
Avoiding a solution that is irreversible, because the assumptions on which the solution is based may prove incorrect, in favour of a seemingly inferior solution that can be reversed.

Radiative damping
An imposed positive radiative forcing *(q.v.)* on the Earth-atmosphere system (e.g., through the addition of greenhouse gases) represents an energy surplus. The temperature of the surface and lower atmosphere will then increase and in turn increase the amount of infrared radiation being emitted to space, thus a new energy balance will be established. The amount that emissions of infrared radiation to space increase for a given increase in temperature is known as the radiative damping.

Radiative forcing
A simple measure of the importance of a potential climate change mechanism. Radiative forcing is the perturbation to the energy balance of the Earth-atmosphere system (in W m^{-2}) following, for example, a change in the concentration of carbon dioxide or a change in the output of the Sun; the climate system responds to the radiative forcing so as to re-establish the energy balance. A positive radiative forcing tends to warm the surface and a negative radiative forcing tends to cool the surface. The radiative forcing is normally quoted as a global and annual mean value. A more precise definition of radiative forcing, as used in IPCC reports, is the perturbation of the energy balance of the surface-troposphere system, after allowing for the stratosphere to re-adjust to a state of global mean radiative equilibrium (see Chapter 4 of IPCC94). Sometimes called "climate forcing".

Respiration
The metabolic process by which organisms meet their internal energy needs and release CO_2.

Soil moisture
Water stored in or at the continental surface and available for evaporation. In IPCC (1990) a single store (or "bucket") was commonly used in climate models. Today's models which incorporate canopy and soil processes view soil moisture as the amount held in excess of plant "wilting point".

Solar luminosity
A measure of the brightness of (i.e., the amount of solar radiation *(q.v.)* being emitted by) the Sun.

Solar radiation
Radiation emitted by the Sun. Also known as short-wave radiation. Solar radiation has a distinctive spectrum (i.e., range of wavelengths) governed by the temperature of the Sun. The spectrum of solar radiation is practically distinct from that of infrared *(q.v.)* or terrestrial radiation because of the difference in temperature between the Sun and the Earth-atmosphere system.

Spatial scales
Continental 10 - 100 million square kilometres (km^2).
Regional 100 thousand - 10 million km^2.
Local less than 100 thousand km^2.

Spin-up
"Spin-up" is a technique used to initialize an AOGCM. At present it is not possible to diagnose accurately the state of the coupled atmosphere-ocean system and therefore it is not possible to prescribe observed starting conditions for an experiment with an AOGCM. Instead, the atmosphere and ocean components of the model are run separately, forced with "observed" boundary conditions, followed perhaps by a further period of "spin-up" when the atmosphere and ocean are coupled together, until the AOGCM is near to a steady state.

Stratosphere
The highly stratified and stable region of the atmosphere above the troposphere *(q.v.)* extending from about 10 km to about 50 km.

Sustainable development
Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Terrestrial biosphere
A collective term for all living organisms on land.

Thermocline
The region in the world's ocean, typically at a depth of 1 km, where temperature decreases rapidly with depth and which marks the boundary between the surface and deep ocean.

Thermohaline circulation
Large-scale density-driven circulation in the oceans, driven by differences in temperature and salinity.

Transient climate response
The time-dependent response of the climate system (or a climate model) to a time-varying change of forcing.

Tropopause
The boundary between the troposphere *(q.v.)* and the stratosphere *(q.v.)*.

Troposphere
The lowest part of the atmosphere from the surface to about 10 km in altitude in mid-latitudes (ranging from about 9 km in high latitudes to about 16 km in the tropics on average) where clouds and "weather" phenomena occur. The troposphere is defined as the region where temperatures generally decrease with height.

Turn-over time
The ratio between the mass of a reservoir (e.g., the mass of N_2O in the atmosphere) and the rate of removal from that reservoir (e.g., for N_2O, the rate of destruction by sunlight in the stratosphere *(q.v.)*).

Volatile Organic Compounds (VOCs)
Any one of several organic compounds which are released to the atmosphere by plants or through vaporization of oil products, and which are chemically reactive and are involved in the chemistry of tropospheric ozone production. Methane, while strictly falling within the definition of a VOC, is usually considered separately.

Wet/dry deposition
The removal of a substance from the atmosphere either through being washed out as rain falls (wet deposition) or through direct deposition on a surface (dry deposition).

WGII LESS scenario
Scenarios developed for the SAR WGII to assess low CO_2-emitting supply systems for the world. The scenarios are referred to as LESS: Low-Emissions Supply System.

"When" and "where" flexibility
The ability to choose the time (when) or location (where) of a mitigation option or adaptation scheme in order to reduce the costs associated with climate change.

Appendix 3

ACRONYMS AND ABBREVIATIONS

AGCM	Atmosphere General Circulation Model
AOGCM	Atmosphere-Ocean General Circulation Model
CFCs	Chloro-flouro-carbons
COP-2	Second Conference of the Parties to the UN/FCCC
GDP	Gross Domestic Product
GFDL	Geographical Fluid Dynamics Laboratory
HCFCs	Hydro-chloro-fluoro-carbons
HFCs	Hyro-fluoro-carbons
IAM	Integrated Assessment Model
IIASA	International Institute for Applied Systems Analysis
IMAGE	Intergated Model to Assess the Greenhouse Effect
IPCC	Intergovernmental Panel on Climate Change
IS92	IPCC Emissions Scenarios defined in IPCC (1992)
OECD	Organization for Economic Cooperation and Development
OGCM	Ocean General Circulation Model
R&D	Research and Development
S Profiles	The CO_2 concentration profiles leading to stabilization defined in the 1994 IPCC Report (IPCC, 1995)
SAR	IPCC Second Assessment Report
SBSTA	Subsidiary Body of the UN/FCCC for Scientific and Technological Advice
SCM	Simple Climate Model
SPM	Summary for Policymakers
TPs	IPCC Technical Papers
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UV	Ultraviolet
VEMAP	Vegetation/Ecosystem Modelling and Analysis Project
VOCs	Volatile Organic Compounds
WEC	World Energy Council
WGI, II & III	IPCC Working Groups I, II and II
WMO	World Meteorological Organization
WRE Profiles	The CO_2 concentration profiles leading to stabilization defined by Wigley, *et al.* (1996)

Chemical symbols

Br	Atomic bromine
CFC-11	$CFCl_3$, or equivalently CCl_3F (trichlorofluoromethane)
CFC-12	CF_2Cl_2, or equivalently CCl_2F_2 (dichlorodifluoromethene)
CH_4	Methane
Cl	Atomic chlorine
CO	Carbon monoxide
CO_2	Carbon dioxide
HCFC-134a	CH_2FCF_3
HCFC-22	CF_2HCl (chlorodifluoromethane)
N_2O	Nitrous oxide
NO_x	The sum of NO & NO_2
O_3	Ozone
OH	Hydroxyl
S	Atomic sulphur
SO_2	Sulphur dioxide
SO_4^{2-}	Sulphate ion

Appendix 4

UNITS

SI (Système Internationale) Units

Physical Quantity	Name of Unit	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
thermodynamic temperature	kelvin	K
amount of substance	mole	mol

Fraction	Prefix	Symbol	Multiple	Prefix	Symbol
10^{-1}	deci	d	10	deca	da
10^{-2}	centi	c	10^{2}	hecto	h
10^{-3}	milli	m	10^{3}	kilo	k
10^{-6}	micro	μ	10^{6}	mega	M
10^{-9}	nano	n	10^{9}	giga	G
10^{-12}	pico	p	10^{12}	tera	T
10^{-15}	femto	f	10^{15}	peta	P
10^{-18}	atto	a			

Special Names and Symbols for Certain SI-derived Units

Physical Quantity	Name of SI Unit	Symbol for SI Unit	Definition of Unit
force	newton	N	kg m s^{-2}
pressure	pascal	Pa	kg $m^{-1}s^{-2}$ (=N m^{-2})
energy	joule	J	kg m^{2} s^{-2}
power	watt	W	kg m^{2} s^{-3} (= Js^{-1})
frequency	hertz	Hz	s^{-1} (cycles per second)

Decimal Fractions and Multiples of SI Units Having Special Names

Physical Quantity	Name of Unit	Symbol for Unit	Definition of Unit
length	ångstrom	Å	10^{-10} m = 10^{-8} cm
length	micron	μm	10^{-6} m
area	hectare	ha	10^{4} m^{2}
force	dyne	dyn	10^{5} N
pressure	bar	bar	10^{5} N m^{-2} = 10^{5} Pa
pressure	millibar	mb	10^{2} N m^{-2} = 1 Pa
weight	ton	t	10^{3} kg

Non-SI Units

°C	degrees Celsius (0°C = 273 K approximately) Temperature differences are also given in °C (=K) rather than the more correct form of "Celsius degrees"
ppmv	parts per million (10^{6}) by volume
ppbv	parts per billion (10^{9}) by volume
pptv	parts per trillion (10^{12}) by volume
bp	(years) before present
kpb	thousands of years before present
mbp	millions of years before present

The units of mass adopted in this report are generally those which have come into common usage, and have deliberately not been harmonized, e.g.,

kt	kilotonnes
GtC	gigatonnes of carbon (1 GtC = 3.7 Gt carbon dioxide)
PgC	petagrams of carbon (1PgC = 1 GtC)
MtN	megatonnes of nitrogen
TgC	teragrams of carbon (1TgC = 1 MtC)
TgN	teragrams of nitrogen
TgS	teragrams of sulphur

Appendix 5

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List of IPCC Outputs

I. IPCC FIRST ASSESSMENT REPORT (1990)

a) **CLIMATE CHANGE — The IPCC Scientific Assessment.** The 1990 report of the IPCC Scientific Assessment Working Group *(also in Chinese, French, Russian and Spanish).*
b) **CLIMATE CHANGE — The IPCC Impacts Assessment.** The 1990 report of the IPCC Impacts Assessment Working Group *(also in Chinese, French, Russian and Spanish).*
c) **CLIMATE CHANGE — The IPCC Response Strategies.** The 1990 report of the IPCC Response Strategies Working Group *(also in Chinese, French, Russian and Spanish).*
d) **Overview and Policymaker Summaries, 1990.**

Emissions Scenarios (prepared by the IPCC Response Strategies Working Group), 1990.

Assessment of the Vulnerability of Coastal Areas to Sea Level Rise — A Common Methodology, 1991.

II. IPCC SUPPLEMENT (1992)

a) **CLIMATE CHANGE 1992 — The Supplementary Report to the IPCC Scientific Assessment.** The 1992 report of the IPCC Scientific Assessment Working Group.
b) **CLIMATE CHANGE 1992 — The Supplementary Report to the IPCC Impacts Assessment.** The 1990 report of the IPCC Impacts Assessment Working Group.

CLIMATE CHANGE: The IPCC 1990 and 1992 Assessments — IPCC First Assessment Report Overview and Policymaker Summaries, and 1992 IPCC Supplement *(also in Chinese, French, Russian and Spanish).*

Global Climate Change and the Rising Challenge of the Sea. Coastal Zone Management Subgroup of the IPCC Response Strategies Working Group, 1992.

Report of the IPCC Country Study Workshop, 1992.

Preliminary Guidelines for Assessing Impacts of Climate Change, 1992.

III. IPCC SPECIAL REPORT, 1994

a) **IPCC Guidelines for National Greenhouse Gas Inventories** (3 volumes), 1994 *(also in French, Russian and Spanish).*
b) **IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations,** 1994 *(also in Arabic, Chinese, French, Russian and Spanish).*
c) **CLIMATE CHANGE 1994 — Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios.**

IV. IPCC SECOND ASSESSMENT REPORT, 1995

a) **CLIMATE CHANGE 1995 — The Science of Climate Change.** (including Summary for Policymakers). Report of IPCC Working Group I, 1995.
b) **CLIMATE CHANGE 1995 — Scientific-Technical Analyses of Impacts, Adaptations and Mitigation of Climate Change.** (including Summary for Policymakers). Report of IPCC Working Group II, 1995.
c) **CLIMATE CHANGE 1995 — The Economic and Social Dimensions of Climate Change.** (including Summary for Policymakers). Report of IPCC Working Group III, 1995.
d) **The IPCC Second Assessment Synthesis of Scientific-Technical Information Relevant to Interpreting Article 2 of the UN Framework Convention on Climate Change,** 1995.

(Please note: the IPCC Synthesis and the three Summaries for Policymakers have been published in a single volume and are also available in Arabic, Chinese, French, Russian and Spanish).

IV. IPCC TECHNICAL PAPERS

Technologies, Policies and Measures for Mitigating Climate Change — IPCC Technical Paper 1.
(also in French and Spanish)

An Introduction to Simple Climate Models used in the IPCC Second Assessment Report — IPCC Technical Paper 2.
(also in French and Spanish)

Stabilization of Atmospheric Greenhouse Gases: Physical, Biological and Socio-economic Implications — IPCC Technical Paper 3.
(also in French and Spanish)

IPCC Procedures for the Preparation, Review and Publication of its Technical Papers

At its Eleventh Session (Rome, 11-15 December 1995), the Intergovernmental Panel on Climate Change adopted by consensus the following procedures for the preparation of Technical Papers.

IPCC Technical Papers are prepared on topics for which an independent, international scientific/technical perspective is deemed essential. They:

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b) are initiated: (i) in response to a formal request from the Conference of the Parties to the UN Framework Convention on Climate Change or its subsidiary bodies and agreed by the IPCC Bureau; or (ii) as decided by the Panel;
c) are prepared by a team of authors, including a convening lead author, selected by the IPCC Bureau, in accordance with the guidelines of the selection of lead authors contained in the IPCC Procedures;*
d) are submitted in draft form for simultaneous expert and government review at least four weeks before the comments are due;
e) are revised by the lead authors based upon the comments reviewed in the step above;
f) are submitted for final government review at least four weeks before the comments are due;
g) are finalized by the lead authors, in consultation with the IPCC Bureau which functions in the role of an editorial board, based on the comments received; and,
h) if necessary, as determined by the IPCC Bureau, would include in an annex differing views, based on comments made during final government review, not otherwise adequately reflected in the paper.

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* Preparation of the first draft of a report should be undertaken by lead authors identified by the relevant Working Group bureau from those experts cited in the lists provided by all countries and participating organizations, with due consideration being given to those known through their publication or work. In so far as practicable, the composition of the group of lead authors for a section of a report shall reflect fair balance among different points of view that can reasonably be expected by the Working Group bureau, and should include at least one expert from a developing country.