

# The Garnaut Climate Change Review

# The Science of Stabilising Greenhouse Gas Concentrations

A commissioned report for the Garnaut Climate Change Review

by

The University of Melbourne Climate Adaptation — Science and Policy Initiative (CASPI) ARC Centre of Excellence for Mathematics and Statistics of Complex Systems (MASCOS)

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# **1** Anthropogenic climate change: the problem

#### 1.1 Overview

This report has been commissioned by the Garnaut Climate Change Review and builds on a previous report, *The Science of Climate Change* [4]. As that report concludes, in recent decades there has been a detectable change to the Earth's climate system. In particular, this is demonstrated by the increase in the average global surface air temperature but many other observations confirm this change. Scientific research into the possible causes of these observed changes demonstrates that increased concentrations of greenhouse gases (GHGs) in the atmosphere is very likely to have caused most of the increase in globally-averaged temperatures since the mid-20th century. The primary driver of the increased GHGs is human activity. This activity is extremely diverse, but key sources of these gases include burning fossil fuels for electricity generation and transport, and changes in land use. Population and economic growth and an associated rapid rise in energy demand have contributed significantly to the rapid increase in anthropogenic GHG emissions.

Many of the developing changes to the climate system threaten to produce significant impacts on the Earth's physical and biological systems. Amongst the range of potential impacts are water shortages, food insecurity, health issues, socio-economic impacts, and reduction of biodiversity. Any attempt at predicting these impacts requires some means of assessing the likely growth in GHG emissions and the consequences of that for the climate system.

The most authoritative and detailed information on climate change is that provided by the work of the Intergovernmental Panel on Climate Change (IPCC) and its series of four major reports (1990, 1995, 2001, 2007). The findings provide a comprehensive guide to the observed changes, attribution, and discussion of the issues and uncertainties. As with the earlier IPCC assessments, the 2007 assessment is published in the form of contributions from three Working Groups [39, 40, 41]. A further 'synthesis report' brought these conclusions together.

The present report focuses on the stabilisation of the concentration of long-lived greenhouse gases (LLGHGs) in the atmosphere. Increased atmospheric concentrations of the LLGHGs will result in further changes to the climate system. At high concentrations, this will lead to 'dangerous climate change' (DCC) or 'dangerous anthropogenic interference' (DAI). These terms come from Article 2 of the UNFCCC that defines the convention's *ultimate objective* as the *"stabilisation* of greenhouse gas concentrations at levels that would *avoid dangerous anthropogenic interference with the climate system*" while allowing sustainable development. The question of what may be considered to be dangerous is addressed in Section 3.

Since pre-industrial times human activities have increased emissions of greenhouse gases at a more rapid rate than would have occurred naturally. This has led to higher concentrations of these gases in the atmosphere. In turn, this has resulted in a change in the radiative balance of the Earth. Figure 1 shows 20th century concentrations of the main greenhouse gases and Figures 2 and 3 show the time history of the contributions of the main gases to creating a radiative imbalance.

The main LLGHGs are carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). Each of these occurs naturally in the atmosphere, and the concentration would naturally be determined by a balance being reached between production and emission of gas molecules, on the one hand, and destruction and absorption of the gas molecules, on the other. However, recently, concentrations of all of these gases have been increased by additional emissions from human activities. In addition to these naturally occurring LLGHGs there is a range of radiatively active gases most of which are entirely of human origin. These include the perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF<sub>6</sub>), and the ozone-depleting substances (ODS) - chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and halons. The human induced radiative forcing of the Earth's climate is largely due to the increases in the assembled increased concentrations of these LLGHGs. There is also a greenhouse warming from tropospheric ozone. Although tropospheric ozone is short-lived, it shows long-term trends in response to changes in other atmospheric constituents. Such constituents are termed 'indirect greenhouse gases.

In the absence of other increases, a doubling of  $CO_2$  would result in an increase in a global surface air temperature (SAT) of about 1.3 to 3.8°C at the time of doubling with further 'committed warming' to follow. With so-called business-as-usual emissions (IS92a), this concentration (560 ppm) could be reached by about 2065 ( $\pm$  5 years) [20: Fig 7.1]. However recent emission trends appear to be closer to the IS92e scenario or SRES A1FI cases [60] implying CO<sub>2</sub> doubling circa 2050 [20: Figure E.11, 35: Appendix II].

## **1.2** The context

This report focuses on potential future trajectories of GHG emissions, with attention being paid to trajectories which could contain this growth in order to stabilise the concentration levels below the threshold of 'dangerous climate change' (discussed in section 3.2). The results of this report are intended as inputs into subsequent considerations of the ecological, social and economic impacts of climate change, and also into economic analysis of the cost of mitigation. This report focuses on global emissions and stabilisation targets, and does not address the issue of how the task of reducing emissions should be allocated between nations. This 'partitioning' issue is a complex one involving issues of equity and distributive justice, and is to be dealt with in more detail in a subsequent report to the Garnaut Climate Change Review. We provide some brief preliminary comments on aspects of this issue later in Section 4.4.

This report is based on the state of scientific knowledge at the time of writing. The IPCC Fourth Assessment Report sets much of the context of this and provides the most broad-ranging and widely accepted background material on the science of climate change. Additional important reports which form part of the context of this study include the recent economic studies by Sir Nicholas Stern [63], and the House of Lords Economics Committee [29]. A number of scientific results that have appeared since the preparation of the IPCC assessment are noted.

Atmospheric GHG concentrations are a global scale phenomenon: they result from the combined activities of all nations, although there are wide differences between the levels of emissions from different countries. This report begins with an analysis of the observed overall



Figure 1: Atmospheric concentrations of the most important long-lived greenhouse gases,  $CO_2$  (upper),  $CH_4$  (centre) and  $N_2O$  (lower) over the last 300 years. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion air molecules, respectively, in an atmospheric sample. Data from CSIRO [47].

growth in emissions, the trends in emission growth, and the resulting implications for growth in concentrations and the requirements for stabilisation.

In Section 2, the relative significance of carbon dioxide and other GHGs are examined in terms of their concentrations, contributions to radiative forcing, and atmospheric lifetimes or residence times in the atmosphere (or effective residence times in the case of  $CO_2$ ).

In Section 3, the concept of 'dangerous climate change' is discussed, and the relationship between GHG concentrations and temperature are considered in the context of estimating the upper limits to emissions that the planet can avoid major changes in the climate system. Some of the targets for stabilisation concentrations, found in leading existing climate change policies, are also reviewed in relation to whether, and if so in what way, they are based on an assessment of what constitutes 'dangerous climate change'.

Scenarios proposed by the IPCC for the growth of future emissions are considered in Section 3. They are documented in the IPCC Special Report on Emissions Scenarios (SRES) [34] and so are referred to as the SRES Scenarios. Some relevant background information on these scenarios is included, along with a discussion of the corresponding emission trajectories and the assumptions used to develop them. Since these scenarios were generated circumstances have changed, particular with higher than anticipated economic growth rates in China and India. As will be discussed in further detail, this has led to a more rapid growth in carbon dioxide emissions. The result is that the current growth trend is at least tracking, and is likely to exceed, the highest growth scenario considered by the IPCC (the SRES high-growth scenario: A1FI).

This high growth rate which is now observed suggests that a re-assessment of the IPCC scenarios is required and that new set of projections need to be formulated that can be used to consider the consequences for the 'business-as-usual' case and potential adaptation and mitigation solutions.

In Section 4 some of the earlier work on stabilising concentrations is reviewed as a preliminary to developing the approaches introduced in this report. Historical emissions for  $CO_2$  are used as basis for developing extended emissions trajectories to meet  $CO_2$  stabilisation targets. These emissions trajectories are then used as inputs into a simple temperature response model, to show how global temperatures would follow the changing  $CO_2$  concentrations. In addition, the issues involved in considering  $CO_2$  emissions in combination with other significant greenhouse gas emissions are discussed in Section 4.3.

Section 5, added since the first version of this report, gives details of case studies that were provided for more detailed analysis in the Garnaut Climate Change Review.

Finally, key points are summarised in Section 6.

# 2 Analysing global change

#### 2.1 Historical changes

The growth in atmospheric concentrations of the three most important long-lived greenhouse gases (LLGHGs) over the last 3 centuries is illustrated in Figure 1, showing a steep rise in recent times. Ice-core data [47] show that prior to this, concentrations were relatively steady for 2000 years with little variation since the end of the last ice age. The recent increases are mainly associated with the burning of fossil fuels and changes in land use since pre-industrial times.

The increase in carbon dioxide from the pre-industrial level of about 280 ppm to 379 ppm in 2005 is an increase of 35.4%. The growth rate for atmospheric CO<sub>2</sub> was 1.9 ppm/yr from 1995 to 2005. The change for N<sub>2</sub>O is approximately 18%, from about 270 ppb to 319 ppb in 2005, with an approximately linear growth of 0.26% per year over the past few decades. For methane, the 2005 global average concentration of 1774 ppb was much higher than the pre-industrial interglacial level. CH<sub>4</sub> grew about 30% over much of the second half of the 20th century, but more recently its growth rate has declined substantially. There is a high degree of inter-annual variability, and the reasons for the decrease in growth rate and outlook for future changes are unclear [*39: Chapter 2 p142*].

Figure 2 shows the contributions to radiative forcing from the three mean anthropogenic greenhouse gases:  $CO_2$ ,  $CH_4$  and  $N_2O$ .



Figure 2: Combined radiative effect of  $CO_2$ ,  $CH_4$  and  $N_2O$  over the last 150 years, based on the values shown in Figure 1.

The concentrations of the Montreal Protocol gases (CFCs, HCFCs and chlorocarbons) peaked

in 2003 and are now declining. The fluorine-containing Kyoto Protocol gases (HFCs, PFCs and SF<sub>6</sub>) have increased rapidly. Their combined radiative forcing (RF) in 2005 was +0.017 Wm<sup>-2</sup>, and is increasing by about 10% per year [*39: WGI Chapter 2 p131*].

Figure 3 gives a semi-schematic version of Figure 2 based on values from successive IPCC reports and includes the contribution from CFCs with projections into the future assuming the SRES B1 scenario.

The combined radiative effect of the major greenhouse gases, as shown in Figures 2 and 3, can be summarised as an equivalent  $CO_2$  concentration, expressed in units of ppm  $CO_2$ -equiv. In particular, the atmospheric  $CO_2$  concentration was 379 ppm in 2005, but the combination of all the LLGHGs has the same radiative effect as a concentration of  $CO_2$  alone of 455 ppm. Allowing for the cooling effect of aerosols and other air pollutants reduces this 455 ppm  $CO_2$ -equiv to an effective 311–435 ppm  $CO_2$ -equiv [41: TS p27].



Figure 3: Partitioning of radiative forcing from long-lived greenhouse gases as function of time. (Data are based on [30: Fig 2.2] for the 20th century, and are corrected for revision in forcing for CO<sub>2</sub> and subsequent IPCC reports. SRES B1 [35: Appendix II] is used for for 2000–2100 with radiative forcing constant thereafter. Minor irregularities in the lines reflect the combination of disparate data sources and the coarse time steps reported in [30].)

Figure 4 shows, semi-schematically, the growth over time of warming associated with this greenhouse gas forcing. This shows the equilibrium warming associated with LLGHGs as the upper curve, the equilibrium warming associated with LLGHGs and aerosols as the central curve and the 'actual' warming as the lower curve. As can be seen, the warming is not fully realised at present — there is a sizeable commitment to future warming. As shown, two effects delay the occurrence of the equilibrium warming: the cooling effect (negative radiative forcing) of aerosols, and the lag between transient warming and equilibrium warming. As concentrations stabilise both these effects will be greatly reduced. This emphasises the importance of considering  $CO_2$ -equivalence in two ways: with aerosol contributions (for understanding the



Figure 4: Schematic of temperature relations for warming from greenhouse gases. The upper line shows the equilibrium warming expected from long-lived greenhouse gases (taken as proportional to the total forcing shown in Figure 3. However the effects of aerosols decrease this radiative forcing as shown by the central curve. Finally, while forcing is increasing, the warming lags behind its equilibrium value. However, under stabilisation, with reduced  $CO_2$  emissions, aerosols are expected to be greatly reduced, and the 'committed warming' will progressively occur.

present), and without aerosol contributions (for understanding future implications). Note that this is an illustrative example which excludes consideration of tropospheric ozone.

The schematic of the carbon cycle in Figure 6 captures one of the most important aspects of the carbon cycle. The atmospheric  $CO_2$  content has increased about 30%, from 597 GtC to 762 GtC. Correspondingly, the flux into the oceans has increased by about 30% from 70 GtC/yr to 92.2 GtC/yr. If this were the only ocean exchange, it would imply that over 60% of anthropogenic emissions would be lost to the oceans in about 8.5 years. However, as shown in Figure 6, the increase in carbon in the ocean surface has led to an increase in the  $CO_2$  flux returning from the ocean to the atmosphere. (The proportional increase in the return flux is greater than the proportional increase in ocean surface carbon because of non-linearities in ocean carbon chemistry, an effect quantified by what is called the buffer factor). The consequence of this return flux is that inputs of  $CO_2$  only decline on time scales much longer than 8.5 years, and the time scale is largely determined by how fast carbon mixes from the surface layer of the ocean into the deeper layers.

Thus  $CO_2$  in the atmosphere is determined by processes of repartitioning of carbon between atmospheric, oceanic and biospheric reservoirs. (On multi-millennial time scales, exchanges with sedimentary and geological reservoirs also become significant).



Figure 5: Partitioning of sources of  $CH_4$  and  $N_2O$ , distinguishing sources primarily from natural systems vs. those arising from human influence. Data from [*39: Table 7.6*].



Figure 6: From IPCC [39: Figure 7.3]. Global carbon cycle for the 1990s, showing fluxes between the various reservoirs in GtC/yr. Pre-industrial values for reservoir size and flux are shown in black, while anthropogenic perturbations are given in red, including emissions from fossil fuel use and land use changes. Although there is additional detail in this diagram, the principal reservoirs are known to be the terrestrial biosphere (vegetation, soil, detritus), the atmosphere, and the ocean (surface ocean, marine biota, intermediate and deep ocean).

## 2.2 Modelling global change

The general causal relation underlying human-induced climate change is:



This casual sequence, illustrated in Figure 7, can be quantified using simple climate models of the type described by the IPCC [33]. Our use of simple climate models closely follows modelling used by CSIRO in analyses of the so-called Brazilian Proposal [18]. In addition to explicit modelling, we supplement our calculations by analysing data sets reported in various IPCC assessments.



Figure 7: Causal chain, proceeding from emissions to global temperatures via various climate models for an arbitrary emissions scenario. From [*39: Figure 10.1*].

The way in which our model treats the various steps in the causal chain above is:

emissions Future emissions represent a choice for societies to make. (Much of the scope of the Garnaut Review is about analysing the consequences of potential choices). It is common to use the term 'projections' to represent conditional predictions, based on exploring the consequences of such choices. (The associated probabilities are thus conditional probabilities). Much of the analysis in this report addresses the question of how to choose emissions that ultimately lead to constant concentrations. The economic aspects of these targets lie outside the scope of our modelling.

**concentrations** Greenhouse gas concentrations are analysed in terms of the generic greenhouse budget relation:

increase = emissions - natural loss

For most gases, natural loss occurs through chemical destruction in the free atmosphere or at the earth's surface. For  $CO_2$  natural loss from the atmosphere occurs through a re-partitioning of carbon between the atmosphere, oceans and biosphere. Such re-partitioning occurs through changes in the large natural carbon fluxes between the atmosphere, oceans and biosphere, as illustrated in Figure 6.

- radiative changes In simple models, these are characterised in terms of radiative forcing. This is an approximation used both in simple climate modelling and for comparing the climatic effect of gases. The history of the scientific understanding of radiative forcing is given by R. Somerville et al., [39: Section 1.4.4, p108-110]. Forster et al., [39: Chapter 2, p129-234] give a current overview of the science of radiative forcing, including an introduction to the concept. For some of the calculations reported in this report, contributions for the non-CO<sub>2</sub> LLGHGs and ozone were derived from radiative forcing calculated for the respective scenarios as reported by the IPCC [35: Appendix II], and the aerosol contribution was taken as proportional to CO<sub>2</sub> emissions.
- **climate** For the present report, our analysis of climate change is restricted to calculations of temperature change using a simple climate model. The temperature is represented as a linear response to radiative forcing. Unless indicated otherwise, the response used by CSIRO (based on the HadCM3 model) is scaled to a median climate sensitivity of 3°C. Sensitivity calculations used the 33 to 67 percentile range of [2 to 4.5 °C] based on the 'likely' range given in AR4 and on model results presented in the IPCC 4th Assessment Report [*39: Figure TS.25*].

The modelling is subject to a number of uncertainties, as described in the following section.

Additional steps that lie outside the scope of our modelling include:

- **emissions modelling** Emissions are traced back to descriptions of sectorial systems for energy, agriculture etc., generally on a regional to national basis.
- **impacts** Impacts of climate change are outside the scope of this report. Results from simple climate models like that described here can be related to more detailed descriptions of climate change through techniques such as pattern scaling [51].

There are also feedback effects, as changes in temperature and precipitation affect natural systems, leading to additional emissions to the atmosphere and also affecting the processes of natural loss from the atmosphere.

A specific example of calculations following the causal sequence is shown in Figure 8 for two emission scenarios from the IPCC *Special Report on Emission Scenarios* [34], see section 3.3.



Figure 8: Example of sequence for SRES scenarios, A1B and A1FI. (a: top left)  $CO_2$  emissions, (b: top right)  $CO_2$  concentrations (c: lower left)  $CO_2$ -equivalent concentrations (including aerosols) (d: lower right) Warming, assuming a climate sensitivity of 3°C.

Part (a) shows the historical  $CO_2$  emissions over the 20th century with 21st century emissions specified by the SRES scenarios, A1B and A1FI. Part (b) shows the calculated  $CO_2$  concentrations. Part (c) includes the  $CO_2$ -equivalent concentrations, including aerosols in each case. The contributions for the non- $CO_2$  LLGHGs and ozone were derived from radiative forcing calculated for the respective scenarios as reported by the IPCC [*35: Appendix II*]. The aerosol contribution was taken as proportional to  $CO_2$  emissions. Part (d) shows the temperature increase for the two cases.

Since the analysis in this report addresses the question of how to choose emissions that ultimately lead to constant concentrations, the first step of the causal chain described above must be slightly varied. Since we are analysing targets for stabilisation we calculate emission trajectories, with a range of choices so that mitigation costs and options can be compared.

The general greenhouse gas budget relation between emissions and concentrations is:

In order to consider concentration targets, we rewrite this budget as

emissions = atmospheric increase + natural loss

or more specifically

allowable emissions = prescribed atmospheric increase + calculated natural loss

Consequently, the calculation of 'allowable emissions' requires a model that can calculate 'natural loss' and a specification of the prescribed concentrations over time (often termed a 'concentration profile' e.g. [20]).

For most gases the relation:

increase = emissions - natural loss

takes the form:

increase = emissions - destruction

Modelling the consequences of CO<sub>2</sub> emissions involves calculations based on the relation:

atmospheric increase = emissions - natural net loss

so that targets are calculated using:

allowable emissions = prescribed atmospheric increase + calculated natural net loss

This requires a model with the ability to calculate natural net loss. For  $CO_2$ , unlike most other greenhouse gases, the loss from the atmosphere will depend both on current conditions and on past changes. This is because net fluxes between the carbon reservoirs shown in Figure 6 depend on the amounts of carbon that have accumulated in the respective reservoirs. Technical issues of this transformation to 'inverse modelling' (i.e. deducing emissions) are noted in [20: Note A.6.D].

By definition, for all gases, stabilisation occurs when

increase = 0

allowable emissions = natural loss

Thus for non-CO<sub>2</sub> gases, stabilisation requires

allowable emissions = destruction

while for CO<sub>2</sub>

allowable emissions = calculated natural net loss

where the natural net loss will effectively go to zero<sup>1</sup> as the atmosphere, oceans and biosphere come to an equilibrium re-distribution of the carbon released by anthropogenic activity.

The primary results from this report are  $CO_2$  emission trajectories which we calculate by following prescribed concentration profiles. As a crude measure of implied climate change, we use a simple climate model to calculate temperature increases to characterise the associated impact. (This may also provide input to more detailed impact studies through techniques such as 'pattern scaling' [51]).

In addition, we present the rate of change of temperature, since:

(a) the adaptive capacity of human and natural systems will be under greater strain at higher rates of change;

(b) some impacts are purely transient phenomena.

An example of transient effects with particular importance for Australia is indicated by the work of Cai et al. [2]. Their modelling indicates that a multi-decadal decrease in rainfall in southern Australia is associated with the rate of increase of temperatures rather than being a specific consequence of higher temperatures. The modelling indicates that rainfall should revert to more 'normal' values once temperatures eventually stabilise at higher levels. While the warming is taking place there is a change in net heat flow into the oceans, whereas at equilibrium a balance (at a higher temperature) will mean a net heat flow similar to that which occurred prior to global warming. The difference in the amount of net heat uptake affects the north-south distribution of weather systems. This sort of transient effect, dependent on the rate of warming, is generally not captured by techniques such as 'pattern scaling' [51].

Given the range of uncertainty, our main results present median values and we present ranges as 33rd to 67th percentiles, reflecting the uncertainties described in the next section.

# 2.3 Treatment of uncertainty

The prediction of climate behaviour is subject to uncertainties related to both climate science and future policy choices.

Uncertainties that reflect policy choices in the context of climate mitigation include:

<sup>&</sup>lt;sup>1</sup>Actually to the small rate of loss into geological reservoirs.

- What target of CO<sub>2</sub>-equivalent stabilisation should be chosen to minimize the risk of 'dangerous climate change'?
- On which GHGs should mitigation efforts be focused?
- When should we act on mitigation? i.e. should we choose an emissions trajectory with deep early cuts, or wait until technology improves?

This report provides scientific background to aid in making these and other policy choices.

Uncertainties also exist in the understanding of the *science* of climate change, as illustrated in Figure 7. When proceeding along the chain from emissions to temperature, these uncertainties are successively compounded.

In order to address a comprehensive range of stabilisation cases we use computationallyefficient simple climate models as described in Section 2.2. Much of the work on which we draw uses similar simple climate models.

We will now briefly define and discuss some of the key scientific uncertainties in understanding climate change, and how we deal with them.

#### **2.3.1** Atmospheric response to CO<sub>2</sub> emissions

There are uncertainties involved in calculating atmospheric concentrations from emissions, as a fraction of  $CO_2$  emissions into the atmosphere are taken up by the ocean and the terrestrial biosphere. These can be characterised as uncertainties in the dynamic behaviour of the atmospheric carbon budget, expressed as a perturbation from pre-industrial equilibrium. This is illustrated by the first step in Figure 7 and can be quantified by the so-called 'airborne fraction', which is the fraction of emissions that remain in the atmosphere. The lower part of Figure 9 gives the responses to atmospheric emissions of  $CO_2$  of the sinks to terrestrial reservoirs (through photosynthesis quantified as Net primary Production, NPP), net sinks to the oceans, and the increased source from respiration (essential a delayed response to biomass increases arising from increased NPP). The ranges are quite large, although we note that the mean behaviour of the airborne fraction of  $CO_2$  emissions over decadal time frames is better constrained via observation than the behaviour of the individual sinks. The central part of Figure 9 characterises climate-to-carbon feedback processes acting to change these fluxes, with the sum of these feedback effects being given by the black band in the upper section.

Atmospheric concentrations of  $CO_2$  are tightly constrained via accurate observations which include direct measurements in recent decades and ice-core data. Since the combination of emissions and atmospheric response must combine to give this observed total, then if emissions in the past were higher than typically assumed, then a smaller fraction of the emissions had in fact remained in the atmosphere. Conversely, lower past emissions than assumed requires that a larger fraction remained airborne. Thus the various uncertainties shown in Figure 9 are not independent.



Uncertainties in Carbon Cycle Feedbacks

Figure 9: Uncertainties in the carbon budget, expressed in terms of the  $CO_2$  airborne fraction which characterises the atmospheric response to emissions. The lower group gives the direct responses for soil respiration, photosynthesis (i.e. Net Primary Production, NPP) and net ocean sink. The centre group characterises the magnitude and uncertainty of the climate–carbon feedback, from the C<sup>4</sup>MIP experiment (using SRES scenario A2 from 1850 until 2100).

Note however, that these various uncertainties are not independent. From [39: Fig 7.14].

#### 2.3.2 Radiative forcing

The concept of radiative forcing was introduced in Section 2.2. It is a useful method to quantify the *instantaneous* warming effect that can be attributed to greenhouse gases and aerosols.

Part (a) of Figure 10 shows the radiative forcing by various atmospheric constituents as of 2005, and one can see that the forcing due to  $CO_2$  is quite well understood, as is the forcing due to methane, nitrous oxide and halocarbons. The time evolution of these contributions is illustrated in Figures 2 and 3. Less well understood is the contribution of stratospheric and tropospheric ozone, and the role of aerosols in the atmosphere, which is quite uncertain (both in terms of their direct and indirect effects). Combining the various estimates of forcings gives part (b). The net radiative forcing due to anthropogenic causes can be seen to be almost certainly positive. The range of values which is considered 'very likely' is  $[0.6 \text{ to } 2.4 \text{ W/m}^2]$ .

Uncertainty in the amount of radiative forcing from GHGs is usually subsumed into the uncertainty associated with climate sensitivity, discussed later. Thus we do not need to treat this uncertainty directly in our modelling.



Figure 10: a) Summary of the principal components of the radiative forcing of climate change. All these radiative forcings result from one or more factors that affect climate and are associated with human activities or natural processes. The values represent the forcings in 2005 relative to the start of the industrial era (about 1750). Human activities cause significant changes in long-lived gases, ozone, water vapour, surface albedo, aerosols and contrails. The only increase in natural forcing of any significance between 1750 and 2005 occurred in solar irradiance. Positive forcings lead to warming of climate and negative forcings lead to a cooling. The thin black line attached to each coloured bar represents the range of uncertainty for the respective value. (AR4 WGI FAQ 2.1 Figure 2 p136) (b) Probability density function for the net amount of anthropogenic forcing. The mean, 10% and 90% values shown in the graph are the same as the last line in the table. (AR4, WGI, TS.5).

#### **2.3.3** Effect of climate on CO<sub>2</sub> partitioning: climate-to-carbon feedbacks

The effect of global temperatures on atmospheric  $CO_2$  is called *climate-to-carbon feedback*. This is an additional source of uncertainty as the IPCC states that it is not well constrained by models: "The magnitude of the positive feedback between climate change and the carbon cycle is uncertain." [*39: TS.5.5*].

Much of the  $CO_2$  emitted into the atmosphere is absorbed by sinks in the ocean and biosphere. Hence if the strength of these sinks is decreased then a greater percentage of  $CO_2$  would remain in the atmosphere. In the context of stabilisation of GHGs, a previously unrecognised positive feedback means that in order to stabilise concentrations of  $CO_2$  at a particular concentration, lower  $CO_2$  emissions are permissible compared to estimates based on current scientific understanding of the carbon cycle. A good discussion of the contribution of the uncertainty associated with climate–carbon feedbacks to uncertainty in estimations of the magnitude of future climate change is given by Barrie Pittock [55].

The coupled climate-carbon cycle model intercomparison project [22] (C<sup>4</sup>MIP), gives estimates of the size of the feedback under the A2 SRES scenario simulated from 1850 to 2100. Eleven Atmosphere-Ocean General Circulation Models (AOGCMs) were used to determine the effect of climate on  $CO_2$  absorption by ocean and land carbon sinks. The ranges of estimates for the magnitude of climate-to-carbon feedbacks are shown in Figure 9 with the label 'climate response'. The total effect is given at the top of the graph which shows large differences between models. Some key conclusions from this study are:

- All model simulations resulted in a larger amount of CO<sub>2</sub> remaining in the atmosphere.
- There was large variation between models: for some the additional amount of  $CO_2$  was negligible, while the outlying value saw an increase of 31%. Typical AOGCMs predicted extra amounts in the range of 10–20%.
- Most models predicted that the weakening of the terrestrial biosphere sink was the principal cause of the decreased uptake of atmospheric CO<sub>2</sub>.
- The feedback effect is non-linear, and increases with temperature.

The non-linearity in the climate-to-carbon feedback means that determining the feedback for other scenarios would require simulations by AOGCMs. This would be extremely expensive computationally. Given the wide range of values for the feedback size found by  $C^4$ MIP, it would also be of limited utility.

We note that there are recent indications that a consensus is emerging that the magnitude of climate-to-carbon feedbacks may well be towards the lower end of the C<sup>4</sup>MIP range. In contrast, Canadell et al. [3] recently found that the airborne fraction of CO<sub>2</sub> is increasing, and attributed this increase to earlier-than-expected climate-to-carbon feedbacks. As discussed in Section 4.2, an increasing airborne fraction is to be expected on the basis of higher emission growth rates [53, 15] and does not *necessarily* imply feedbacks. The large year-to-year variability

of the atmospheric fraction complicates things by making detection of a trend difficult and identification of a cause quite problematic.

Climate-to-carbon feedbacks are a topic of active and intense research, and as yet there are still significant uncertainties. As the science on this issue is still far from settled, we give a qualitative discussion since a quantitative analysis is beyond the scope of this report.

#### 2.3.4 Climate sensitivity

The response of climate to increased GHG concentrations is somewhat uncertain. The level of uncertainty is typically characterised in terms of the climate sensitivity (the amount of warming produced by doubling atmospheric equilibrium  $CO_2$  concentrations). Climate sensitivity combines two separate effects: the amount of radiative forcing produced by doubling  $CO_2$  concentrations, and the amount of warming produced by this additional radiative forcing.

Note that climate sensitivity does not capture transient effects in the temperature response function. Even when stabilisation of  $CO_2$ -equivalent concentration is achieved, global mean temperatures will continue to rise for some time afterwards. Eventually, the temperature will converge to the value given by the climate sensitivity. In this sense the climate sensitivity encapsulates the first order effect of concentrations on temperature.

Table 8.2 of IPCC WG I reports a range of climate sensitivities of  $2.1-4.4^{\circ}$ C for different AOGCMs. Most of this range is due to uncertainties in atmospheric response rather than in radiative forcing [66]. Cumulative probabilities for the climate sensitivity are shown from various sources in Figure 11. The IPCC has weighed the evidence to come up with a *likely* range of  $2^{\circ}$ C to  $4.5^{\circ}$ C, and central estimate of  $3^{\circ}$ C. The largest uncertainty involved is the extent to which aerosols have masked GHG radiative forcing during the 20th Century. Hence the estimated probability density function for climate sensitivity is skewed to the higher values.

The equilibrium climate sensitivity (or just 'climate sensitivity') defined above is mainly determined by the properties of the atmosphere and its interactions with the surfaces of the land, oceans and ice sheets. Consequently, early atmosphere-only models could estimate this equilibrium sensitivity. However the rate at which warming approaches its equilibrium value depends on things like how fast the oceans take up heat. Early climate modelling studies had to estimate these delays using uncoupled (off-line) ocean models of varying degrees of complexity. With the advent of coupled AOGCMs, direct modelling of transient responses became possible, and could be characterised by a 'transient climate response'. This is usually defined as the 'transient' warming' associated with doubling of CO<sub>2</sub> concentrations (or CO<sub>2</sub>-equivalent concentrations). This will depend on how rapidly the CO<sub>2</sub> is increasing. A 'standard' study, following protocol of the CMIP intercomparison, used a 1% per annum CO<sub>2</sub> increase. Results reported at a special IPCC workshop [38: fig 3, p6] suggest that this transient response is close to 50% of the equilibrium response. More extensive results in AR4 [39: fig 10.25] show a comparable ratio, but rather more scatter. For an equilibrium sensitivity of 3°C, transient sensitivities range from about 1.3 to 2.2°C. For rates of increase, slower than 1% per annum, ratios larger than 50% are expected for the ratio of transient response to equilibrium response, with the ratio going to 100% as the growth rate goes to zero.



Figure 11: Estimates of the probability distribution of the climate sensitivity from a number of studies using observed 20th Century warming (red), model climatology (blue), proxy evidence (cyan), and various AOGCMS (green). From IPCC, [*39: Ts Fig 25*].

In simple (highly-parameterised) climate models, there is the possibility of tuning the model to make independent changes to both independent and transient climate sensitivities. This capability means that comparisons between climate models need to be related in terms of both equilibrium and transient climate sensitivities.

For the modelling in this report, we have used a response representing the HadCM3 model, and tuned the equilibrium climate response (to 3°C unless indicated otherwise), without changing the ratio of equilibrium to transient response. In the cases considered here, approximately 2/3 of the equilibrium warming has taken place by the time that concentrations stabilise. This is comparable to other results such those of Haugan and Joos [28] or the 'WRE' study [70]. The figure of 2/3 is consistent with the multimodel average presented by the IPCC [39: Fig SPM-5] which, for concentrations held constant at 2000 levels, has 0.8°C warming from 1900 to 2000 and 0.4 °C warming from 2000 to 2100. Since these data are presented only to 2100, subsequent warming could lead to values of the transient-to-equilibrium ratio being lower than 2/3. This figure of 2/3 is apparently lower than in the FAIR-SiMCaP model as used by den Elzen and van Vuuren [12] where about 80% of warming has occurred at the time of stabilisation. Note that in cases with an 'overshoot' in radiative forcing, e.g. examples in [64], there is expected to be much less difference between equilibrium and transient forcing.

#### 2.3.5 Impacts of climate change

Although the effect of GHG emissions on concentrations, and thence on global mean temperature, is relatively well constrained, when making policy judgments it is necessary to know what adverse (or beneficial) impacts this warming will have on the environment and human activities. This is discussed in more detail in Section 3 in the context of assessing whether a given amount of warming constitutes 'dangerous' climate change.

Uncertainty in climate impacts does not directly influence the modelling of stabilisation of GHGs. However it does influence the choice of which stabilisation scenario to use in order to avoid a 'dangerous' level determined in terms of temperatures. (As noted earlier, assessment of impacts is outside the scope of this report.)

#### 2.3.6 Summary: what are the dominant sources of uncertainty?

We regard the range of estimates for climate sensitivity to be the dominant source of uncertainty. We treat this by using both the central estimate of  $3^{\circ}$ C and the limits of the IPCC 'likely' range of 2.0 °C and 4.5°C to obtain temperature time series from emission trajectories.

We expect uncertainties in the science of climate change to decrease as understanding of the science gets better and as more data are obtained (both by extending existing records and obtaining new classes of data such as better characterisation of aerosols). Risk analysis techniques can greatly aid the making of policy choices concerning stabilisation of GHGs under uncertainty.

## 2.4 Characterising gases

A number of gases in the atmosphere absorb infra-red radiation. The most important of these is water vapour (H<sub>2</sub>O) followed by carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and a number of artificially produced gases.

- The gases differ in their ability to absorb radiation at various frequencies.
- For those gases that are present at high concentrations, essentially all infra-red radiation is absorbed at some frequencies. Thus the incremental warming effect of the gas decreases as more and more absorption lines become saturated, giving a non-linear dependence of radiative forcing (and temperature) on concentration.
- The relative climatic importance of emissions of gases is influenced by the amount of time that a gas remains in the atmosphere. This varies greatly between gases.
- For many gases, the loss from the atmosphere can be described using a single 'atmospheric lifetime'. This is not the case for CO<sub>2</sub> where the net loss rate from the atmosphere depends on the amount (and distribution) of carbon in the oceanic and biospheric reservoirs. These distributions depend in turn on the past history of carbon re-partitioning.

Analysis of the trade-offs involved in different choices concerning the amount of mitigation of emissions of each gas requires some notion of how to compare gases. Ideally one wants a concept of equivalence. As noted in the introduction, the combined effect of multiple gases can be summarised as an equivalent  $CO_2$  concentration.

The whole issue of 'equivalence' is subject to significant difficulties.

- Two forms of equivalence have been defined in the literature: 'concentration equivalence' and 'emission equivalence'. The definitions from the IPCC Fourth Assessment [39: glossary] are reproduced in the glossary at the end of this report (see page 80). Concentration equivalence is defined in terms of radiative forcing; emission equivalence is defined in terms of radiative forcing over a specified time horizon.
- Each of these forms of equivalence is commonly referenced to CO<sub>2</sub> to define CO<sub>2</sub>equivalence. This is problematic since the non-linearity in the radiative forcing means that CO<sub>2</sub> is a 'moving target'.
  - For concentration equivalence, the IPCC definition [39: glossary] defines CO<sub>2</sub> to be a characterisation of a mixture of gases as a whole, not as a characterisation of the individual components.
  - For emission equivalence, definitions such as that used in the Kyoto Protocol are referenced to 1990 CO<sub>2</sub> concentrations. Thus the Kyoto definitions are progressively drifting away from the relative importance of emissions as concentrations increase.

- Normally the two forms of emission equivalence are distinguished by the units: (ppm CO<sub>2</sub>-equiv) for concentration equivalence and GtCO<sub>2</sub>/yr-equiv for emission equivalence. Sometimes carbon mass is used for units of emission equivalence (in GtC/yr-equiv). Forms such as cumulative equivalent emissions (in units of GtCO<sub>2</sub>-equiv) need to be carefully identified.
- The usage of concentration equivalence for a mixture of gases has evolved into two forms: that which includes only long-lived gases and that which includes all anthropogenic forcing. The latter is a reflection of instantaneous radiative forcing, while including only the long-lived (multi-year) components gives a measure of the 'commitment' to future radiative forcing.
- Since emission equivalence is defined in terms of the time-integrated effect, the equivalence has to be relative to a 'time horizon' over which the radiative effects are compared. Common use (and the use in the Kyoto Protocol and in national inventory reports) adopts a 100-year time horizon. The time-integrated effect of a unit emission, taking into account losses from the atmosphere is termed the 'absolute global warming potential' (AGWP). For comparing emissions, the 'global warming potential' (GWP) defined as a ratio of AGWPs relative to CO<sub>2</sub> is often used.

The view taken in this report is that  $CO_2$  equivalence in either form must be taken as a descriptive statistic that is usually unsuitable for use in further calculations. This conclusion follows from the discussion of GWP by Smith and Wigley [61, 62]. A specific example of how formal (i.e. Kyoto) emission-equivalence leads to non-equivalent changes is in the work of Reilly et al. [57] which analysed various mitigation strategies and concluded: under a more stringent emissions policy, the use of global warming potentials as applied in the Kyoto Protocol leads to considerably more mitigation of climate change than the — supposedly equivalent —  $CO_2$ -only control, thus emphasizing the limits of global warming potentials as a tool for political decisions.

Similarly, concentration-equivalence is of limited use for comparing gases since, as defined by the IPCC, it is a property of the mixture of gases, not of the components. Therefore in general,  $CO_2$ -equivalence is appropriate for summary statistics and **not** for analysis and computation.

Table 1 shows the relation between  $CO_2$  concentrations, equivalent  $CO_2$  concentrations and non- $CO_2$  radiative forcing giving the amount of additional radiative forcing for cases when the  $CO_2$  equivalent concentration is 50 ppm higher than the actual  $CO_2$  concentration. (Cases where actual  $CO_2$  and  $CO_2$ -equivalent differ by multiples of 50 ppm can be obtained by adding successive rows of the table.)

It can be seen that the non-linearities in the forcing-dependence are less than for the CO<sub>2</sub>dependence. For a CO<sub>2</sub> concentration,  $C_{CO2}$  in ppm, the contribution per unit of additional radiative forcing (in Wm<sup>-2</sup>) is given by  $C_{CO2}/5.35$ . Thus at 530 ppm CO<sub>2</sub> each additional 0.01 Wm<sup>-2</sup> of forcing adds about 1 ppm to the CO<sub>2</sub>-equivalent concentration. Table 2 shows the value of this linearisation factor for a range of actual CO<sub>2</sub> concentrations. The final column shows the correct value of the CO<sub>2</sub>-equivalent concentration for an additional 1 Wm<sup>-2</sup> of forcing. The linear approximation for an additional 1 Wm<sup>-2</sup> is given by the sum of the first two

Actual CO <sub>2</sub>	Equivalent CO <sub>2</sub>	Other Forcing
ppm	ppm CO <sub>2</sub> -equiv	$ m Wm^{-2}$
350	400	0.714
400	450	0.630
450	500	0.563
500	550	0.510
550	600	0.466
600	650	0.428
650	700	0.396
700	750	0.369

Table 1: Radiative forcing (in  $Wm^{-2}$ ) from non-CO<sub>2</sub> gases when equivalent CO<sub>2</sub> concentrations exceed actual CO<sub>2</sub> concentrations by 50 ppm. Consecutive lines can be added so that for example, 650 ppm CO<sub>2</sub>-equiv with 450 ppm CO<sub>2</sub> implies a non-CO<sub>2</sub> radiative forcing of (0.563+0.510+0.466) Wm<sup>-2</sup>.

Actual CO <sub>2</sub>	linear approximation	CO <sub>2</sub> -equiv
ppm	$(\text{ppm CO}_2\text{-equiv})/(\text{Wm}^{-2})$	ppm CO <sub>2</sub> -equiv for extra 1 $Wm^{-2}$
300	56.1	361.7
350	65.4	421.9
400	74.1	482.2
450	84.1	542.5
500	93.4	602.8
550	102.8	663.0
600	112.1	723.3
650	121.5	783.6
700	130.8	843.9
750	140.2	904.1

Table 2: Accuracy of linearised approximation to  $CO_2$  equivalence. Converting  $CO_2$  plus non- $CO_2$  radiative forcing to  $CO_2$ -equivalent using a linear approximation gives errors of about 10% for additional forcing in 1 Wm<sup>-2</sup>.

columns. It will be seen that the error is of order 10% of the non-CO<sub>2</sub> contribution. Given the limitations of the radiative forcing concept, especially for aerosols, this level of error is probably acceptable for many purposes.

# **3** Climate/concentration targets

# 3.1 What is dangerous climate change?

Given that greenhouse gas concentrations are increasing in the atmosphere, and the concern about the effects this will have on the Earth's human and natural systems ecosystems, the question naturally arises as to what is a 'safe level' of GHG concentration or conversely, what level might be regarded as 'dangerous'. Finding a credible answer to this may be important for setting targets as a basis for international agreement and national action.

The term 'dangerous climate change' derives from Article 2 of the United Nations Framework Convention on Climate Change, which states its 'ultimate objective' to be: "...stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." It adds that: "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'. However, the UNFCCC does not actually define what is meant by 'dangerous'.

While apparently a simple concept, there are a number of difficulties inherent in defining 'dangerous climate change' or 'dangerous anthropogenic interference' (DAI). What is considered 'dangerous' will depend on the standpoint from which the judgement is being made. An environmental change may be dangerous for a single species, but not for all species. It may be dangerous for humans in one part of the planet, but not for those in other parts. And it may be dangerous for those without the resources to adapt, but relatively safe for those who have the requisite resources.

Accordingly, what is to be considered 'dangerous' is largely a matter of normative judgement, and not just scientific assessment and will depend on what factors are given priority: "What is dangerous is essentially a matter of what society decides. It is not something that science alone can decide" [54].

The IPCC Third Assessment Report stated:

"The basis for determining what constitutes 'dangerous anthropogenic interference' will vary among regions depending both on the local nature and consequences of climate change impacts, and also on the adaptive capacity available to cope with climate change — and depends upon mitigative capacity, since the magnitude and the rate of change are both important. There is no universally applicable best set of policies; rather, it is important to consider both the robustness of different policy measures against a range of possible future worlds, and the degree to which such climate-specific policies can be integrated with broader sustainable development policies." [37: SPM p2].

Whilst what is considered dangerous may vary regionally, LLGHG concentrations are not regional — they are a global phenomena. One approach that this suggests is to accept that maintaining the 20th century global balance of ecosystems, biodiversity and environments is highly desirable, and that climate change as a result of human activity should not significantly change this balance.

Pachauri [54], the current IPCC chairman, argues that the broad issues associated with the impacts of climate change include:

- Human rights, which must be taken into account in a world where climate change impacts may be worse for those least able to cope (sea level rise for small island states, coastal flooding in Bangladesh, drought in Africa).
- Sustainable development, given the need to provide for future generations and not leave a disastrous legacy.
- Avoidance of irreversible impacts, for example, impacts involving species loss, coastal erosion, destruction of coral reefs, and collapse of the oceanic thermohaline circulation.
- Dangerous for whom or what? There is a need to to assess and quantify the likely impacts for people, animals and plants, and places.
- Dangerous by when? There is a need to consider the time scale over which change may occur. If the climate changes sufficiently slowly then adaptation may be possible, but rapid change may be very difficult to cope with.

The IPCC describes dangerous climate change in relation to *key vulnerabilities*. The identification of potential key vulnerabilities is intended to provide guidance to decision-makers for identifying levels and rates of climate change that may be associated with 'dangerous anthropogenic interference' (DAI) with the climate system (as it is described in the UNFCCC Article 2). Ultimately, the definition of DAI cannot be based on scientific arguments alone. No single metric can adequately describe the diversity of key vulnerabilities, nor determine their ranking. It involves other value judgements which nevertheless should be informed by the best scientific knowledge.

Chapter 19 of Working Group II's contribution to the IPCC's Fourth Assessment Report identifies seven criteria from the literature that may be used to identify key vulnerabilities, and then describes some potential key vulnerabilities identified using these criteria. The criteria are [40: Chapter 19, p.781]:

- magnitude of impacts;
- timing of impacts;
- persistence and reversibility of impacts;
- likelihood (estimates of uncertainty) of impacts and vulnerabilities and confidence in those estimates;
- potential for adaptation;

- distributional aspects of impacts and vulnerabilities; and
- importance of the system(s) at risk.

While defining and quantifying dangerous climate change is a complicated issue with many uncertainties, many scientists have attempted it. One of the earlier assessments was made in the late 1980s, by the Advisory Group on Greenhouse Gases (comprising the World Meteorological Organization, the International Council of Scientific Unions and the UN Environment Programme). The Advisory Group argued that warming above 2°C would cause a rapid increase in damage to ecosystems [58]. In 2006, Hansen et al. argued that a warming of 1°C relative to 2000 would produce dangerous climate change [27]. At the same time, Izrael and Semenov conclude that the maximum temperature increase relative to pre-industrial times should be  $2.5^{\circ}$ C, corresponding to an upper limit for CO<sub>2</sub> of 550 ppm [42].

#### 3.2 Stabilisation

A greenhouse gas is said to have 'stabilised' when its atmospheric concentration is constant. In the case of a group of GHGs, stabilisation is considered to occur when their combined radiative forcing (which can be expressed as carbon dioxide equivalent concentration) is maintained at a constant level. A stable concentration will result when GHG emissions by sources are balanced by sinks. Stabilisation targets for concentrations of LLGHGs are thus typically expressed in terms of carbon dioxide equivalent values (e.g. 450 ppm  $CO_2$ -equiv or 500 ppm  $CO_2$ -equiv).

In order to stabilise the concentration of atmospheric  $CO_2$  over time, emissions have to peak and then decline. The lower the desired  $CO_2$  stabilisation level, the faster emissions have to be reduced. For other gases, stabilisation of emissions will stabilise concentrations. Whether these emissions will need to be above or below present emission levels depends on the target concentration that is set. Mitigation efforts over the next 2 to 3 decades face a shrinking window of opportunity to contain emissions and achieve a stabilisation at or below a level regarded as dangerous. A target level of 450 ppm  $CO_2$ -equiv has been suggested as desirable (see discussion in section 3.4), but the world has already effectively passed that level of radiative forcing from LLGHGs. Consequently, a  $CO_2$ -equiv concentration overshoot and more rapid reduction in emissions would be necessary to achieve that target.

Other options might be 500 or 550 ppm  $CO_2$ -equiv, which might be more realistically achievable, but which are likely to carry higher risks of more severe climate change and consequent impacts. At higher levels of concentration risks are further increased because there is a greater likelihood that carbon cycle feedback effects will become significant. These may amplify the increase in emissions by triggering the release of emissions from non-anthropogenic sources, such as melting permafrost and the destabilisation of ocean bed methane hydrates. They may also reduce the effectiveness of sinks due to saturation (for example by reducing the rate at which carbon dioxide is dissolved in the oceans as they warm).

## 3.3 Scenarios

#### 3.3.1 Special Report on Emissions Scenarios (SRES)

In 1992 the IPCC released its first emissions scenarios. These provided inputs into global circulation models which in turn were used to produce climate change scenarios. In 1996 the IPCC decided to develop a new set of emission scenarios. This new set of scenarios was released in June 1998. Climate modellers then used these scenarios as a basis for assessing climate changes for use in the IPCC's Third Assessment Report. These scenarios were subsequently published in 2000 as the Special Report on Emissions Scenarios (SRES) [34].

Emission scenarios are a tool for creating pictures of how future conditions could possibly develop under certain conditions. They are not intended to be a forecast or prediction of how the future will develop. Such scenarios help scientists understand how a system can evolve over time. They can be used in developing scientific assessments, learning about complex systems, and contributing to climate change analysis. They can be used to assist climate modelling and assessment of possible impacts and the effects of different mitigation strategies. In particular, they can be used to analyse the effects of future GHG emissions and to develop and test the effects of different adaptation and mitigation policies.

An emissions scenario will be based on a set of assumptions about key relationships between variables, and drivers of change. Assumptions are made about population growth, changes in energy demand, energy intensity and efficiency, technological progress and socio-economic development. These are important basic inputs to climate models used for determining future climate patterns. They are central to generating different emissions trajectories and assessing their impacts on climate change.

The IPCC makes it clear that it has no basis for considering any of the scenarios as being any more likely than another. It is in this sense that they say that there "is no single most likely, *central* or *best-guess* scenario" [34: SPM p11]. Since the IPCC does not associate probabilities or likelihoods with any of the scenarios there is no business-as-usual scenario.

The SRES scenarios were designed to [34: TS]:

- cover the full range of radiatively important gases (including direct and indirect GHGs and SO<sub>2</sub>);
- have sufficient spatial resolution to allow regional assessments of climate change in the global context;
- cover a wide spectrum of alternative futures to reflect relevant uncertainties and knowledge gaps;
- use a variety of models to reflect methodological pluralism and uncertainty;
- incorporate input from a wide range of scientific disciplines and expertise from nonacademic sources through an open process;

- exclude additional initiatives and policies specifically designed to reduce climate change;
- cover and describe to the extent possible a range of policies that could affect climate change although they are targeted at other issues, for example, reductions in SO<sub>2</sub> emissions to limit acid rain;
- cover as much as possible of the range of major underlying driving forces of emission scenarios identified in the open literature;
- be transparent with input assumptions, modelling approaches, and results open to external review;
- be reproducible document data and methodology adequately enough to allow other researchers to reproduce the scenarios; and
- be internally consistent the various input assumptions and data of the scenarios are internally consistent to the greatest extent possible.

The SRES process involved a review of existing scenarios, with:

- review of emissions scenarios and their assumptions;
- analysis of main features and driving forces;
- formulation of narrative 'storylines'; and
- quantification of storylines.

From the review of previous scenarios and analysis, a set of new scenarios were developed, recognising that there are an infinite number of possible alternative futures that result from the range of possible future emissions and their driving forces. The SRES developed a set of four alternative scenario 'families', comprising 40 SRES scenarios, subdivided into six scenario groups. Each scenario family has a 'storyline' or narrative component and a set of associated quantifications. Each storyline describes a demographic, social, economic, technological, environmental and policy future for one of these scenario families. Within each family different scenarios explore variations of global and regional developments and their implications for GHG and SO<sub>2</sub> emissions [34: TS].

A schematic of the SRES scenarios is given in Figure 12 and the main features of the SRES scenarios are described below.

In addition to carbon dioxide, methane and nitrous oxide, there is a group of greenhouse gases produced primarily by human activity called halocarbons. This includes a number of ozonedepleting chemicals, such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and halons, whose production and use is controlled by the Montreal Protocol, as well as their replacement chemicals, primarily hydrofluorocarbons (HFCs), which have no ozone-depleting effect but are strong greenhouse gases. The SRES scenarios include decreasing concentrations of ozone-depleting chemicals through the 21st century and decreases in their radiative forcing,



Figure 12: Schematic illustration of SRES scenarios. Four qualitative storylines produce four scenario 'families', A1, A2, B1 and B2. From these, six scenario groups were formulated, one each for A2, B1 and B2, but three from A1: A1FI (fossil fuel intensive), A1B (balanced) and A1T (mainly non-fossil fuel). Further scenarios for each group resulted in a total of 40. Figure from [34: SPM, figure 1, p4].

together with increasing concentrations of HFCs and their radiative forcing. By 2050, there is little net change from the present in the radiative forcing due to halocarbons (about 0.34  $Wm^{-2}$ ), as the increased radiative forcing from HFCs is offset by reduced forcing from ozone-depleting chemicals. After 2050, the continuing increases in HFCs lead to small increases in total radiative forcing from halocarbons, but these are small by 2100 relative to the projected increases in radiative forcing due to increasing carbon dioxide [34].

#### **3.3.2 SRES storylines**

#### The Main Characteristics of the Four SRES Storylines and Scenario Families

"By 2100 the world will have changed in ways that are hard to imagine — as hard as it would have been at the end of the 19th century to imagine the changes of the 100 years since. Each storyline assumes a distinctly different direction for future developments, such that the four storylines differ in increasingly irreversible ways. Together they describe divergent futures that encompass a significant portion of the underlying uncertainties in the main driving forces.

They cover a wide range of key 'future' characteristics such as population growth, economic development, and technological change. For this reason, their plausibility or feasibility should not be considered solely on the basis of an extrapolation of current economic, technological, and social trends." [34: SPM, figure 1, p4].

The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into four groups that describe alternative directions of technological change in the energy system. Two of the fossil-intensive groups were merged in the SPM.

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

The **B1** storyline and scenario family describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The **B2** storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

## 3.4 Policies on dangerous climate change

Policymakers have also attempted to quantify dangerous climate change and the corresponding emission reduction targets.

Nicholas Stern's 2006 study of *The Economics of Climate Change* for the UK Government looks at the range of emissions stabilisation concentrations where both climate impacts and mitigation costs are low in relative terms, as shown schematically in Figure 14.

Using this approach, Stern picks a target for stabilisation of 450-550 ppm CO<sub>2</sub>-equiv. The upper limit is set by comparing the valuation of climate change impacts with the cost of mitigation. Anything higher would substantially increase risks of very harmful impacts but would reduce the expected costs of mitigation comparatively little. The lower bound is set by the level at which further tightening of the goal becomes prohibitively expensive [63: p 299].

The Government of California chose emission reduction targets which took into account work by others on dangerous climate change and the conclusion that corresponding targets are fairly readily achievable. In 2005 it announced that it would reduce the state's emissions to 2000 levels by 2010, to 1990 levels by 2020 and to 80% below 1990 levels by 2050 [24]. These targets were based on a report by the Tellus Institute. The report was subjected to review by various government departments [25]. The Tellus report [46] calls for 75-85% cuts in greenhouse gases in the long run. This conclusion was based on a 2001 report by the New England Governors and Eastern Canadian Premiers [7] which states that "the best science available at present indicates that attaining this goal [of avoiding dangerous climate change] will require reductions in GHG emissions of approximately 75-85% below current levels". The Tellus report also calls for cuts of 60-80% by industrialised nations by 2050. This conclusion was based on two reports by the Government of Germany (see below). The Tellus report then goes on to argue that California's emission reduction 'strategies recently underway' and 'strategies under construction' could reduce Californian greenhouse gas emissions to 2000 levels by 2010 and to 8% above 1990 levels by 2020 (i.e. close to the targets the government then committed to). It also argued that a set of long term strategies could reduce emissions to 9% percent below 1990 levels by 2020.

The Tellus report does not give bibliographic details of the German Government reports upon which it relied. The German Government's National Climate Protection Programme 2005 commits to a 60-80% target for industrialised countries (with a 1990 baseline). This commitment draws upon a European Council (Environment) decision which chooses the same target in order to avoid climate warming of 2°C above pre-industrial levels [23]. Whilst bibliographic details are not given for this decision, it is reasonable to assume it arose from the 2647th European Council (Environment) meeting, held on 10/3/05. This meeting called for global emissions to peak within two decades and then be reduced by "at least 15% and perhaps by as much as 50% by 2050 compared to 1990 levels". It then went on to argue that industrialised nations should be making 60-80% reductions by 2050 "in view of the global emissions reductions required" and in reference to "common, but differentiated responsibilities". This latter reference is to a key element of the United Nations Framework Convention on Climate Change which argues that while all nations have a responsibility to address the issue, industrialised nations need to take the lead, given that they are responsible for the vast majority of emissions [8].

The above statement by the European Council (Environment) is part of the European Union's strategy to achieve avoidance of dangerous climate change, where it has set the warming to be avoided as a maximum global mean temperature increase of  $2^{\circ}$ C above pre-industrial levels [9]. The  $2^{\circ}$ C target was originally set at the 1939th EU Council of Ministers meeting in Luxembourg on June 25 1996 [6]. It has been referred to many times since then, including confirmation by the European Council in March 2007 [9]. The EU's adoption of a  $2^{\circ}$ C target in 1996 was in turn based on the IPCC's Second Assessment Report [6]. Its 2007 confirmation of this target was based on both the Second Assessment Report and more recent studies, such as the Third Assessment Report, which have "further underpinned the arguments for keeping within this limit" [21].

In order to achieve the above targeted constraint to warming, the European Council concluded that atmospheric concentrations of greenhouse gases need to be stabilised at well below 550 ppm CO<sub>2</sub>-equiv. It notes that if greenhouse gas concentrations were stabilised at around 450



Figure 13: Implications of climate uncertainty in comparing costs of impacts vs. mitigation. Lines show temperature vs concentration relation at various percentiles on the distribution of climate sensitivity from two different estimates of the distribution of uncertainty in the climate sensitivity. Curves based on Murphy et al., [52]. Impacts analysis is most readily undertaken for a particular temperature, corresponding to a range of concentrations (defined by how a horizontal line cuts the distribution). Mitigation analysis is most readily undertaken for a target concentration, corresponding to a range of temperatures (defined by how a vertical line cuts the distribution).

ppm CO<sub>2</sub>-equiv there would be a 50% chance of keeping warming below  $2^{\circ}C$  [5].

Stern concludes that "across the current body of evidence, two approximate global turning points exist, at around  $2-3^{\circ}$ C and  $4-5^{\circ}$ C above pre-industrial" [63: p. 293]. The IPCC's Fourth Assessment report correlates temperature increases with climate change impacts in Table 3.

Figure 13 captures the difficulty in comparing the costs of impacts vs mitigation. Mitigation costs are most directly related to the target concentration. Impacts costs are most directly related to the amount of warming. There is, as shown, significant uncertainty in the amount of warming expected as a function of concentration. The various lines in Figure 13 show the concentration-to-temperature relation at various percentiles of the distribution of climate sensitivity from two different estimates. Impacts analysis is most readily undertaken for a particular temperature, corresponding to a range of concentrations (defined by how a horizontal line, e.g. the dashed line for 3°C, cuts the distribution). Mitigation analysis is most readily undertaken for a target concentration, corresponding to a range of temperatures (defined by how a vertical line, e.g. the dashed line for 600ppm, cuts the distribution).

To further clarify the significance of this difficulty, Figure 14 shows a schematic of costs of impacts and mitigation (as functions of target concentration), loosely based on Figure 13.3 of the



CO<sub>2</sub>-equiv target

Figure 14: Costs of impacts vs. mitigation, modified from Stern [63: Fig 13.3]. At a specific  $CO_2$ -equiv target, uncertainties in impacts will include a large contribution arising from uncertainties in the amount of warming (see Figure 13).

Stern Report [63]. The solid lines show the type of behaviour expected (with the conventional optimum being when marginal costs = marginal benefits). This analysis would apply under conditions of certainty — in terms of Figure 13 if one knew which 'climate sensitivity' line applied. However, in terms of impacts, there is a large uncertainty arising through climate uncertainty — predominantly through uncertainties in the climate sensitivity. Similarly, the mitigation costs will have a range of uncertainty due to the uncertainties in the economic modelling.

# 3.5 An Australian perspective on targets to avoid dangerous climate change

As noted above, any choice of a target based on an assessment of dangerous climate change is ultimately a question which needs to take into account values and priorities, not merely science. For Australians, any answer to the question of what constitutes a dangerous increase in climate change needs to be based not only on global but also local considerations. For example, for Australians, the implications for the southern part of Australia of increased severity and frequency of drought might be an important concern. That is, it may take into account specific impacts that will occur in Australia, as well as the way that global impacts will in turn affect Australia. However, it would also be expected that Australians would not be merely concerned

$\overline{\text{CO}_2}$	CO <sub>2</sub> -equiv	Peaking year	Changes in global	Warming	Warming
concentration	concentration	$\mathrm{CO}_2$	emissions in 2050	(sensitivity	(sensitivity
		emissions	(% of 2000 emissions)	of 2.9°C)	of 4.5°C)
ppm	ppm	year	%	°C	°C
350-400	445-490	2000-2015	-85 to -50	1.9–2.3	3.0-3.6
400-440	490-535	2000-2020	-60 to -30	2.3 - 2.7	3.6-4.2
440-485	535-590	2010-2030	-30 to +5	2.7 - 3.1	4.2-4.8
485-570	590-710	2020-2060	+10 to +60	3.1-3.9	4.8-6.0
570-660	710-855	2050-2080	+25 to +85	3.9-4.7	6.0-7.2
660-790	855-1130	2060-2090	+90 to +140	4.7-5.8	7.2-9.1

Table 3: Stabilisation levels, cuts in emissions, and equilibrium climate response for two values  $(2.9^{\circ}C \text{ and } 4.5^{\circ}C)$  of the climate sensitivity. Adapted from [41: Table 3.5, Ch. 3]. This represents a variety of studies and so the ranges reflect a combination of scientific uncertainty and choices of stabilisation pathway.

with impacts on their own local environment and economy. Australians have shown a concern for the fate of other peoples, and other species worldwide. So it might be expected that these concerns would also influence their decision on what should be considered dangerous.

While each country may thus reach a different view of what constitutes a dangerous level of climate change, only a global consensus can use this to produce a global target for the control of greenhouse gas emissions. In this sense, although Australia may have a view on what constitutes a dangerous level of greenhouse gas emissions, but if this is to be used in setting targets, its use will be in a global discussion about what the global target should be. Once such a target has been selected and agreed upon, it can be used to set an agreed Australian emissions target, as Australia's contribution to the global emissions control program. That Australian target can then in turn be used as the end point of emissions trajectories which could take Australia from today to such a target.

We are thus faced with a choice, firstly as to the target we wish to work towards for emissions stabilisation, and secondly, out of the family of available trajectories, the one that we wish to follow. Deciding this will require Australians to take into account the global context of Australia, as well as Australian priorities and capacities. In particular it requires consideration of three questions:

(i) What emissions trajectory do Australians want the world to follow? The answer will involve a value judgement about how much risk locally and globally Australians believe might be acceptable.

(ii) What are the options available to Australia in helping influence that direction? The answer to this will involve judgements about the best ways in which Australians can influence global attitudes and decisions, and at what costs. Choices include playing a leadership role in encouraging the behaviour we seek, or lagging and leaving that to others. There will be costs and benefits as well as ethical and political considerations associated with these choices.
(iii) What options will be available and what strategies should Australians adopt as the world make its decisions about emissions trajectories? Answers here will depend on what we think those decisions might reasonably be, when they might occur, and the advantages and disadvantages of innovating in advance of them, or lagging to await the outcomes.

It is clear that the setting of a target for Australia is thus a social as well as scientific question. Nevertheless, for the social processes of judgement to be optimal, the decision makers (whether the whole community or political leaders) need to be informed by the best relevant science. Some of the relevant technical considerations are covered in other reports to the Garnaut Review (for example, the reports dealing with the Science of Climate Change, and Impacts of Climate Change on Australia). We briefly discuss some of the other issues that need to be taken into account in reaching such a judgement later in this report.

# 4 Emission targets

## 4.1 Earlier work on stabilising concentrations

Although the 1990 IPCC Assessment included calculations of emissions required for stabilisation of  $CO_2$  at 450 ppm [30: Figure 1.8], it was in the 1994 IPCC report on *Radiative Forcing of Climate Change* [31] that an extensive range of cases was presented. This work was described in detail in a CSIRO technical paper [20].

Some strengths of this '1994' study were:

- Eighteen different carbon cycle models were analysed in the study and so the results give an important indication of the extent of model uncertainty. Some models reported in [20] were excluded from presentation in the IPCC report because they captured aspects of the carbon cycle different from those relevant to multi-decadal change under specified forcing. The model descriptions [20: Appendix C] note such issues.
- A comprehensive range of stabilisation target concentrations was considered 350, 450, 550, 650 and 750 ppm although not all models were applied to all cases (see [20: Table D.1]).
- The study included, to a limited extent, consideration of 'calibration uncertainty' and its implications for CO<sub>2</sub> projections.

Some weaknesses of the '1994' study were:

- The transition to stabilisation was very abrupt, with the rate of change of emissions being discontinuous at the time of stabilisation.
- Only a limited range of cases of different approaches to stabilisation was considered, with only one or two possible pathways to stabilisation for each target concentration. The only alternative cases were of delayed commencement of reductions for only two target levels: 450 ppm and 550 ppm.
- The study is now of limited current relevance since the approach to stabilisation didn't happen, although the 'delayed' cases were used as examples for discussion of emissions trading [16]. Cases with higher target concentrations (and thus a slower transition to stabilisation) retain more relevance than cases with lower targets.

The analysis of these stabilisation cases for the IPCC report was mainly confined to the relation between emissions and concentrations of  $CO_2$ . The consequences for global temperature and sea level were calculated by Wigley [69]. As discussed in Section 4.3.2, this represented the effect of aerosols and non-CO<sub>2</sub> gases by scaling the CO<sub>2</sub> radiative forcing by 1.23. Thus 550 ppm CO<sub>2</sub> becomes 643.4 ppm CO<sub>2</sub>-equiv.

These stabilisation pathways were updated by cases known as WRE (from the authors: Wigley, Richels and Edmonds) [70]. These were the main cases used in the IPCC Second Assessment Report [32]. The main refinement was:

• A less abrupt transition to stabilisation, initially following IS92a. This was the objective in constructing these cases.

The disadvantages of the 'WRE' cases are that:

- again, only a single case was considered for each target concentration; and
- the pathways lacked reproducible description.

The temperature and sea-level consequences of the IPCC and WRE stabilisation cases were presented only for the 550 ppm CO<sub>2</sub> case. In this case, the effect of non-CO<sub>2</sub> gases was treated by scaling radiative forcing by 1.33 (implying 687.2 ppm CO<sub>2</sub>-equiv) and sulphate aerosols treated separately as either constant or as scaled to CO<sub>2</sub> emissions (rather than concentrations). Comparison of the WRE 550 ppm case and the earlier IPCC pathways [70: Figure 3] indicated that the more gradual phase-in of mitigation led to temperatures being about 0.2°C higher around 2100 (i.e. a 21st century growth rate 0.002°C/yr higher) but that the warming from the two cases was essentially the same by 2200.

Hansen et al. [26] proposed a scenario with relatively small climate change, where radiative forcing is reduced by reductions in non-CO<sub>2</sub> gases, without reducing CO<sub>2</sub> emissions (although the growth of CO<sub>2</sub> emissions is restrained). This is discussed further in Section 4.3.

Although the specification of the SRES scenarios notionally excluded actions for climate mitigation, the B1 storyline oriented to sustainability (see Section 3.3.2), leads to a low emissions scenario that can inform analysis of stabilisation cases. The reference case tabulated by the IPCC [*35: Appendix II, Table II.3.11*] has a radiative forcing of 4.19 Wm<sup>-2</sup> in 2100 (i.e. 617 ppm CO<sub>2</sub>-equiv). For the present report, the B1 scenario provides our main case for analysing the non-CO<sub>2</sub> contributions to radiative forcing (see Section 4.3).

A number of studies of scenarios leading to stabilisation are reported in the IPCC Fourth Assessment (Mitigation) [41: Chapter 3]. These mainly address mitigation through a 'bottom-up' approach based on specific mitigation measures.

The Stern Report presents some illustrative stabilisation cases [63: Figure 8.6] based on work by Meinshausen [50]. The presentation is complicated by issues of  $CO_2$ -equivalence since the target is 550 ppm  $CO_2$ -equiv (using concentration equivalence) while the emissions are presented as  $GtCO_2$ -equiv, implying emission equivalence. As discussed below, these illustrative scenarios include some relatively abrupt changes in emissions compared to those presented here (for  $CO_2$ ). This seems to be the reason that the 'Stern' examples require higher percentage rates of emission reduction in the approach to stabilisation.

The 1994 study for the IPCC included the case of stabilisation of  $CO_2$  at 350 ppm, i.e. at about the contemporary value. Given the unrealistic nature of emission reduction required to

achieve instant stabilisation (see Figure 15 below), the  $CO_2$  profile was specified as having a concentration 'overshoot', rising to 400 ppm before returning to 350 ppm. Most models in the study found that following this profile would require negative emissions (i.e. active extraction of  $CO_2$  from the atmosphere) starting between 2060 and 2090 [20: Figure E.1]. While such measures have been proposed, e.g. biofuel use followed by  $CO_2$  sequestration, there seems to be little real scope for setting achievable objectives based on any significant 'overshoot' of the target  $CO_2$  concentration.

While the Stern report considers some stabilisation pathways with an overshoot in terms of  $CO_2$ -equivalent concentrations [63: Box 8.2], the majority of the overshoot is in the non- $CO_2$  contributions to the radiative forcing.

## 4.2 Calculating CO<sub>2</sub> emission trajectories

The principle of the 'inverse' calculations that determined an emission trajectory given a prescribed concentration profile was described in Section 2.1 as:

allowable emissions = prescribed atmospheric increase + calculated natural net loss

In principle,  $CO_2$  could be allowed to grow to a target level and then emissions instantly reduced so as to prevent overshoot of the target. The first IPCC assessment presented such a calculation [30: Figure 1.8, p15] showing that stabilisation would require an immediate 60% reduction from 1990 emissions followed closely by a further reduction of 20% of the 1990 emissions. Figure 15 presents a more current version, showing the emissions required to stabilise  $CO_2$  at 390 ppm, with reductions beginning around the present time.

The IPCC 'instant stabilisation' case was, of course, presented as an illustration of the difficulties of stabilising  $CO_2$ , not as a proposed practical course of action. Realistic emission reduction proposals need, at the very least, to avoid requiring instantaneous changes in global emissions. The 1994 IPCC study proposed profiles that avoided sudden jumps. However, the prescribed concentration profiles required sudden changes in reduction rate at the time of stabilisation.

A new approach, developed at MASCOS, avoids some of the problems of earlier specifications of stabilisation profiles by using smoothing splines:

- discontinuities in rates of change of emissions are avoided and an overall smoothness of changes is required;
- a family of alternative pathways is produced for each target concentration this makes it possible to explore the consequences of alternative reduction schedules in a systematic way;
- the specification can be given in a form that can be recalculated as required.



Figure 15: Emission pathway for 'immediate' stabilisation of  $CO_2$  after a period of growth. Stabilising at 390 ppm beginning approximately 2005.

The left side of Figure 16 shows families of alternative  $CO_2$  concentration trajectories, leading to stabilisation at 450 ppm, 500 ppm and 550 ppm. The corresponding emissions are shown in the right-hand side of the figure. The definitions of the concentration profiles from which these were derived are given in [19]. As the target concentration is lowered, the choices available for a smooth transition to stabilisation become progressively fewer.

Various earlier studies have considered the emissions required for stabilisation of  $CO_2$  at higher target concentrations [20, 70, 41]. There are two important points to note:

- Such targets are less relevant in the context of avoiding dangerous climate change, especially once the additional effects of non-CO<sub>2</sub> forcing is included.
- For higher concentrations, earlier calculations (e.g. [20]) retain more relevance. For stabilisation at low concentrations, early mitigation is required and so options that were analysed in the 1990s are now highly impractical or outright impossible. Higher concentration targets can be achieved with a more gradual phase-in of mitigation, and earlier studies that generally assumed such gradual action remain applicable.

Figure 17 shows the 'tradeoffs' involved in the different choices of pathway to stabilisation. The tradeoffs can be seen visually in the families of plots — we characterise them in terms of 'peak  $CO_2$  emissions' and 'maximum annual percentage reduction rate'. In plotting these two quantities, Figure 17 notes (approximately) the year in which this maximum reduction rate is required.

A number of illustrative stabilisation pathways are described in the Stern Report [63: Table 8.2] based on work by Meinshausen et al. [50]. These are indicated as requiring higher reduction rates then those shown in Figure 17. The difference is that the pathways discussed by



Figure 16: Upper: Families of concentration profiles (left) for stabilisation of  $CO_2$  at 450 ppm, 500 ppm and 550 ppm.  $CO_2$  emissions (right) required to give these concentration profiles.

Meinshausen take the form of rapid reductions from peak growth rather than a more gradual transition between growth and reduction. The Stern Report notes the possibility of more gradual changes (i.e. the type of pathway considered here) noting "The height of the peak is also crucial. If early action is taken to substantially slow the growth in emissions prior to the peak, this will significantly reduce the required rate of reductions following the peak." [63: p200].

This 'trade-off' means that over the longer term, the integrated  $CO_2$  emissions for a given target concentration will be approximately independent of the specific pathway. Table 4 illustrates this by showing the cumulative emissions between 2005 and 2150 for a number of the pathways considered in this report.

Figure 18 shows, for one of the stabilisation cases (the dashed line in the 550 ppm case in Figure 16), how the natural net loss of carbon evolves in time. The total allowed emissions (black line,



Figure 17: Tradeoffs between peak  $CO_2$  emissions and subsequent maximum reduction for stabilising  $CO_2$  at 450, 500 and 550 ppm. The points are annotated with the year in which this maximum reduction is required.

with long dashes) correspond to the balance of the natural net loss and the atmospheric increase rate (solid red curve, corresponding to the slope of the concentration profile, converted from ppm to GtC). The natural net loss is the sum of net ocean uptake (blue line with shorter dashes) and a net accumulation in the biosphere (green line: shorter widely-spaced dashes). It will be seen that under stabilisation profiles, both these loss processes decline in time. This is because as atmospheric concentrations stop growing, the carbon imbalance between atmosphere, ocean and biosphere declines. (There are also small effects from non-linearities in the uptake processes). The decline in uptake by the biosphere is quite rapid, while the ocean continues to be a (declining) carbon sink for many centuries. These issues are noted in general terms in the Stern Report [63: pp 196–197] giving illustrative examples (in units of GtCO<sub>2</sub>/yr rather than GtC/yr as here). The results in the present report (a) illustrate a wider range of cases, and (b) assume a smoother commencement of mitigation than the Stern examples, thus allowing higher emissions around 2100. Thus our range of emissions to balance natural uptake is 1.5 to 2.5 GtC/yr in 2200 (depending on concentration target and chosen pathway) which is generally higher than the 1.5 GtC/yr (5 GtCO<sub>2</sub>/yr) quoted by Stern [63: p 197]. (Somewhat confusingly, Stern gives units in terms of  $CO_2$ -e, even though the discussion refers only to  $CO_2$ ).

The issue of weakening sinks has been noted, particularly in recent work by Canadell et al. [3]. To clarify the issues, we note the various distinct aspects of weakening of sinks of  $CO_2$ :

• Under declining CO<sub>2</sub> emissions, the imbalance in the partitioning of carbon between

Target:	420	450	500	550
i	549	713	939	1084
ii	550	717	957	1130
iii	-	_	966	1162
iv	-	_	972	1182
v	-	_	975	1194
vi	_	_	977	1200
vii	-	_	_	1204
viii	_	_	_	1206

Table 4: Integrated  $CO_2$  emissions in GtC for the period 2005 to 2150 for various target concentrations and pathways shown in Figure 16. Cases shown in bold are used in the case studies described in Section 5. The pathways i, ii, iii, etc., are numbered in order of increasing peak emissions in Figure 16.

atmosphere, oceans and biosphere gradually declines. As the system approaches a new equilibrium partitioning, with higher amounts of carbon in each of the reservoirs, the net fluxes decline to zero. This is the main process determining the changes shown in Figure 18 and is represented in all carbon cycle models that characterise decadal time-scales.

- Under increasing  $CO_2$  concentrations, the *proportional* sinks will decrease as the sustained emissions growth rate increases. Again this is a characteristic of essentially all carbon cycle models. The effect can be quantified in terms of how the airborne  $CO_2$  fraction increases as the emission growth rate increases [15: Figure 2].
- Even under increasing CO<sub>2</sub> concentrations, the ability of terrestrial systems to respond by taking up more carbon is expected to decline. This effect is explicitly considered in the present modelling [18] in terms of limits on enhanced photosynthesis. However, any additional decline, arising from insufficient availability of nutrients to support additional growth, has not been considered. There are significant uncertainties in the rate of this decline (particularly regarding any contribution from such nutrient limitation), but these will have little influence on the results presented here — the rapid decline of the net biospheric sink, as shown in Figure 18 is mainly determined by the shorter time-scales of turnover of the biosphere, compared to the oceans.
- Under increasing CO<sub>2</sub> concentrations, chemical effects reduce the proportion of carbon taken up by the oceans. This non-linearity in the chemistry is represented explicitly in the present modelling [18].
- A number of feedback processes either directly weaken CO<sub>2</sub> sinks, or increase sources (thus decreasing *net* sinks). These include:
  - temperature effects on ocean chemistry that lead to a proportional decline in the ocean sink as ocean carbon concentrations increase;
  - changes in terrestrial ecosystems in response to changes in temperature and precipitation are expected to change turnover rates for terrestrial carbon;



Figure 18: Evolving  $CO_2$  budget, in GtC/yr, for the stabilisation case shown as the dashed line in the 550 ppm case in Figure 16, which corresponds to the total emissions shown here as the black line (longer dashes). This total is the sum of an atmospheric increase rate (solid red line), an ocean carbon increase rate (blue line — shorter dashes) and (green, short, widely-spaced dashes) a rate of accumulation in terrestrial biota (exclusive of land-use change).

 changes in climate are expected to affect ocean circulation, thus affecting oceanic CO<sub>2</sub> uptake.

None of these three feedback processes are included explicitly in the present modelling, but to the extent that these process operated over the 20th century, their effect is being captured implicitly in the models. This is because the carbon components of simple climate models are tuned to match 20th century changes in  $CO_2$ .

Given concentration profiles, the corresponding temperatures were calculated. Corresponding cases in plots of concentrations, emissions (in Figure 16) and temperature increases (for each particular stabilisation level in Figure 19) are identified by the line colour and/or style in the graphs. The left-hand column of Figure 19 shows the contribution of  $CO_2$  changes to global warming. Several points need to be noted:

- These are transient responses. Since the temperature rises by a little over 2°C in a 550 ppm (close to doubling), and the model has a climate sensitivity of 3°C, about 30% of the warming has not been realised at the time of stabilisation.
- These results are presented as the warming from specified profiles of CO<sub>2</sub>. By definition, they could equally well be regarded as consequences of profiles of equivalent CO<sub>2</sub>. However, specification of a profile for equivalent CO<sub>2</sub> does not specify what the corresponding mix of emissions should be unless very specific additional assumptions are made.

- The 3°C climate sensitivity is the median value from the IPCC assessment. We have adopted the [2 to 4.5 °C] 'likely' range from the IPCC.
- There is a smaller additional uncertainty associated with the proportion of committed warming. This has not been considered explicitly here.
- The right-hand column of Figure 19 shows the rates of change of temperature for various cases. These are the slopes of the curves on the left of the figure, and so the various remarks above also apply to these curves. The rates of change of temperature will be relevant for systems whose adaptive capacity depends on the rate of climate change. Therefore these results are important inputs to studies of climate impacts.



Figure 19: Contribution to temperature increase (left) and rate of temperature increase (right) from  $CO_2$  for selected pathways to stabilisation at 450, 500 and 550 ppm (top to bottom) for climate sensitivity of 2.0°C, 3.0°C, 4.5°C.

## 4.3 Combined gas targets and trajectories

#### 4.3.1 Issues

The appropriate treatment of the contribution of non- $CO_2$  gases and aerosols depends on the type of question that is being asked. In going from emissions to temperature changes,  $CO_2$  dominates and so approximations in the treatment of the other gases will have only a small influence on the results. In contrast, when going from targets for temperature (or radiative forcing) to gas emissions, small differences in the partitioning of forcing can imply large differences in the emissions of particular gases.

At stabilisation, the partitioning of radiative forcing between different gases is largely a matter for society to choose on socio-economic grounds. In analysing climate consequences, details of the choice do not matter, and approximations such as fixed ratios of non-CO<sub>2</sub> gases can be (and have been) used (subject of course to the need to avoid errors based on misuse of the CO<sub>2</sub>equivalence concept [61, 62, 57, 43]). If, however, one wants to analyse the relative costs of choices, then making a fixed decision about which case to analyse precludes the comparison.

All these comparisons need to be made in the context of great uncertainty about climate sensitivity and the climatic effect of aerosols.

#### 4.3.2 Some previous work

Many of the early multi-gas studies were mainly concerned with obtaining an analysis that went beyond  $CO_2$  in assessing future climate change. Therefore, as described above, the precise partitioning between non- $CO_2$  gases was of minor significance. In calculating temperatures corresponding to the 1994 IPCC stabilisation cases, Wigley [69] accounted for the contributions of non- $CO_2$  gases and aerosols as a 23% addition to the radiative forcing from  $CO_2$  (so that 550 ppm  $CO_2$  became 643 ppm  $CO_2$ -equiv). Similarly, the WRE study [70] used a scaling of 1.33 to convert forcing from  $CO_2$  into total radiative forcing from all gases. Thus 550 ppm  $CO_2$  became 687 ppm  $CO_2$ -equiv, the difference being that the WRE study had an explicit representation of sulphate aerosols with the aerosol contribution scaled to  $CO_2$  emissions rather than  $CO_2$  forcing (which reflects  $CO_2$  concentrations). This choice is a reflection of the short atmospheric residence time of aerosols (particularly in the troposphere) which means that atmospheric aerosol levels are closely related to emissions.

Swart et al., [64] characterised non- $CO_2$  contributions by applying a scaling factor to post-2100 emissions. Since  $CO_2$  emissions drop in stabilisation scenarios, so did all others, and so  $CO_2$  stabilisation corresponded to declining total radiative forcing. This approximately balanced the long-term 'committed warming' and so temperatures were quasi-stable earlier than under cases where radiative forcing was stabilised.

Meinshausen [49] analysed a case that can be regarded as an 'intermediate' between fully specifying ratios of non-CO<sub>2</sub> components vs. analysing them independently in terms of costs vs. benefits. The approach was to analyse the individual constituents across the distribution defined by the SRES scenarios and treat this as a distribution of relative ease of mitigation. Composite

Gas	Lifetime	Radiative Forcing		AGWP ( $T = 100 \text{ yr}$ )	AGWP (T = $\infty$ )
		by concentration	by mass		
	yr	(W/m <sup>2</sup> )/ppm	$(W/m^2)/kg$	(W/m <sup>2</sup> )yr/kg	(W/m <sup>2</sup> )yr/kg
$CO_2$	N.A.†	$1.41 \times 10^{-2}$	$1.84 \times 10^{-15}$	$8.69 \times 10^{-14}$	$\infty$
$CH_4$	12	$3.7  imes 10^{-1}$	$1.31\times10^{-13}$	$2.17\times10^{-12}$	$2.18\times10^{-12}$
$N_2O$	114	3.03	$3.89\times10^{-13}$	$2.59\times10^{-11}$	$4.43\times10^{-11}$

Table 5: Relative importance of emissions of long-lived GHGs for different time frames specified by a time horizon, T. Note that radiative forcing measures the immediate response, i.e. T = 0. † As noted earlier [30: Table 1.1, footnote 4], 'atmospheric lifetime' as a concept is not applicable to CO<sub>2</sub>, and as the time horizon increases, the AGWP of CO<sub>2</sub> continues to grow, at least on timescales of millennia. Adapted from [39: Table 2.14, Chapter 2].

scenarios were constructed by selecting pathways with gas emission ratios selected on the basis of being at comparable points on the cost distribution.

Hansen et al. [26] proposed a scenario with relatively small climate change, where radiative forcing was reduced by reductions in non-CO<sub>2</sub> gases, without greatly reducing CO<sub>2</sub> emissions in the short-term. This is discussed further below.

#### 4.3.3 Analysis

Stabilisation of climate involves steadily-decreasing emissions of  $CO_2$  in the long term, in order to stabilise atmospheric  $CO_2$  concentrations. In contrast, constant concentrations of other gases can be achieved by holding emissions constant.

The equilibrium atmospheric content,  $M_{\eta}$ , of a gas  $\eta$ , with lifetime,  $\tau_{\eta}$ , is given by

$$M_{\eta} = E_{\eta} \times \tau_{\eta}$$

when the emissions are fixed at  $E_{\eta}$ . The relative radiative importance of concentrations is in proportion to the instantaneous radiative forcing (see columns 3 and 4 of Table 4.3.3) so the relative importance of emissions is in proportion to the AGWP with a very long time horizon. These factors are listed in the rightmost column of Table 4.3.3. Since CO<sub>2</sub> cannot be described in terms of a single lifetime, this type of relation cannot be applied to CO<sub>2</sub>.

As noted in section 2.4, for a specified  $CO_2$  concentration the dependence of  $CO_2$  equivalence on the amount of non- $CO_2$  forcing is only weakly non-linear. Thus at 530 ppm  $CO_2$ , an additional 0.1 Wm<sup>-2</sup> corresponds to about an additional 10 ppm  $CO_2$ -equiv. However the additional 0.5 Wm<sup>-2</sup> shown in either Figure 21 or 20 would increase a 530ppm  $CO_2$  to 582 ppm  $CO_2$ equiv, while adding an extra 1 Wm<sup>-2</sup> with 530ppm  $CO_2$  would give 640 ppm  $CO_2$ -equiv.



Figure 20: Radiative forcing from constituents other than  $CO_2$  and  $CH_4$  in the SRES B1 scenario. From [*35: Appendix II*]. Note that at 530 ppm  $CO_2$ , and additional 0.1 Wm<sup>-2</sup> corresponds to an additional 10 ppm  $CO_2$ -equiv.

#### 4.3.4 Some results

In this section we look at a restricted set of cases that captures some of the important issues.

- (i) The SRES B1 as an example of relatively stable forcing from the non-CO $_2$  atmospheric constituents.
- (ii) An analysis of the Hansen et al. 'alternative' scenario noted above with consideration of the implications beyond the 2050 horizon considered by Hansen.
- (iii) Analysis of the combined effect of  $CO_2$  and aerosols assuming that aerosol content is proportional to  $CO_2$  emissions.

Figure 20 shows the radiative forcing for the SRES B1 scenario for the various constituents apart from  $CO_2$  and  $CH_4$ . The aerosol components are split into 'black carbon' (BC with positive forcing) and sulphate ( $SO_4^{2-}$ ) and organic carbon (OC) both of which have a negative forcing. The gases are N<sub>2</sub>O and O<sub>3</sub>, with the 'other' category including the halocarbons and SF<sub>6</sub>. It will be seen that the estimated total is about 0.5 Wm<sup>-2</sup> over the 21st century, but it must be appreciated that (a) this is subject to considerable uncertainty regarding the climatic impact of aerosols and (b) to some extent (see example below) aerosol content is linked to emissions of  $CO_2$ .

Table 6 analyses some of the aspects of the 'alternative scenario' proposed by Hansen et al. [26]. The key features (in terms of radiative forcing to 2050) are:



Figure 21: Radiative forcing from  $CH_4$  in various scenarios. From [35: Appendix II]. Note that at 530 ppm  $CO_2$ , and additional 0.1 Wm<sup>-2</sup> corresponds to an additional 10 ppm  $CO_2$ -equiv.

- **carbon dioxide:** A growth rate of 1.5 ppm/yr to 2050, which was regarded as requiring a modest decrease in  $CO_2$  emission rates.
- **methane:** Reducing the radiative forcing from methane by 0.2 /Wm<sup>-2</sup>, implying a 30% reduction in methane sources, with a positive economic return due to avoiding the energy loss associated with various forms of methane emission.
- other long-lived greenhouse gases: Little net change with small decreases from halocarbons (mainly from CFCs) and small increase from N<sub>2</sub>O;
- **aerosols:** No change in aerosol forcing was assumed. However large uncertainties were noted, as was the need for improved monitoring. The possibility of making the aerosol contribution more negative than at present, by reducing the positive contribution from black carbon emissions, was noted but not included in the calculations.

Hansen proposed that by avoiding increases in  $CO_2$  emissions for several decades (and concentrating on methane reductions),  $CO_2$  reductions (which would later be needed) could commence around 2050. In order to explore the viability of this, we consider a pathway to  $CO_2$  stabilisation at 500 ppm (the dashed line from the 500 ppm case in Figure 16) and extend the Hansen et al. scenario using the second lowest of the stabilisation pathways shown. This has relatively little reduction before 2050 (and a small increase for a few years). However, by 2050 emissions need to be undergoing reductions that are sustained well beyond 2100.

The other difficulty with this approach is that stabilising  $CO_2$ -equivalent at double pre-industrial levels (560 ppm) implies only 0.6 Wm<sup>-2</sup> of non-CO<sub>2</sub> forcing. With the net negative contributions from aerosols expected to reduce greatly as  $CO_2$  emissions reduce, this implies the need

Year	$\mathrm{CO}_2$	$CH_4$	Other LLGHGs	All aerosol	Total
2000	1.4	0.7	0.8	-1.4	1.5
2050	2.4	0.5	0.8	-1.4	2.3
2050	2.65				
2150	3.1				3.7

for considerable reductions in the other greenhouse gases. This would require early action in most cases other than methane because of the long lifetimes.

Table 6: The radiative forcing (in  $Wm^{-2}$ ) in the 'alternative scenario' from Hansen et al. [26] (upper section). The lower section shows a comparable case, based on stabilising CO<sub>2</sub> at 500ppm and its possible extension beyond 2050 to CO<sub>2</sub>-equivalent of double pre-industrial CO<sub>2</sub>.

As noted in Section 4.3.2, atmospheric aerosol content has been closely linked to  $CO_2$  emissions and this relationship has been used in a number of modelling studies. This relationship may be less close in the future because of:

- Efforts to reduce to sulphur to CO<sub>2</sub> ratio in emissions on non-greenhouse environmental grounds. Such reductions are widespread in the developed world.
- The Hansen et al. scenario which notes the possibility of additional greenhouse mitigation, reducing the forcing below what is shown in Table 6 by selectively reducing the 'black carbon' component (believed to have positive radiative forcing).

However an analysis in which aerosol forcing is related to  $CO_2$  is still of value for several reasons:

- it provides a reference for comparison with earlier work;
- aerosol control measures are likely to reduce the aerosol to CO<sub>2</sub> emission ratio and so using 'present' ratios provides a plausible upper limit for future aerosol forcing.

Figure 22 provides an example of the relation. The curves shown represent the pairs of  $CO_2$  and  $CO_2$ -equivalent concentrations once aerosols are included. The steps in the calculation are:

- select a 'stabilisation' profile specifying concentrations,  $C_{CO2}(t)$ , as functions of time;
- calculate the emissions,  $E_{CO2}(t)$  corresponding to the profile;
- assume a radiative forcing of  $F = F(1990)E_{CO2}(t)/E_{CO2}(1990) \approx 0.5E_{CO2}(t)/8$  from aerosols (with F in Wm<sup>-2</sup> and E in GtC/yr), approximating the present net effect;
- calculate the CO<sub>2</sub>-equivalent of the combined 'CO<sub>2</sub> plus aerosol' forcing.



Figure 22: Equivalent  $CO_2$  allowing for aerosol forcing proportional to  $CO_2$  emissions. Solid lines show the  $CO_2$  concentration for the pathways to stabilisation at 450 ppm, 500 ppm and 550 ppm (the dashed curves in the respective cases on the left of Figure 16). The dashed curves here show the  $CO_2$ -equivalent from the  $CO_2$  concentrations, combined with aerosol forcing proportional to the  $CO_2$  emissions shown (again as dashed curves) on the right of Figure 16.

As expected from the emission trajectories, the difference between  $CO_2$  and  $CO_2$ -equivalent concentrations declines as the target concentration is approached and continues to decline as emissions reduce so as not to exceed the decreasing net uptake into the oceans and biosphere. Over the first half of the century, the consequent reductions in temperature and its growth rate do not differ greatly from those resulting from  $CO_2$  with the SRES B1 estimates of aerosol forcing (see Figure 20).

## 4.4 Applying the results

#### 4.4.1 Extensions

The results of this work feed into more detailed analysis of climate change in three ways. Firstly, the various emission pathways imply particular distributions of risks of various impacts. The emission pathways provide the forcing from which a detailed impact assessment can evaluate the relative risks of various choices. Secondly, the global pathways described here define totals relative to which national targets are set. Finally, the relative costs of alternative cases can be compared.

Expanding on these areas of subsequent analysis:

Impacts Studies of impacts need to be based on the level of detail of spatial and temporal

variability captured by General Circulation models (GCMs). CSIRO has implemented an impacts analysis system based on multiple archived GCM runs from groups world-wide, in order to be able to assess which features of model results should be regarded as robust [68: and references therein].

National targets Some of the issues involved in setting national targets are:

- Frameworks for differentiated commitments (as specified by the UNFCCC). This implies some concept of 'equity' (in general terms). Some of the frameworks that reflect this are 'Contraction and Convergence,' and the 'Brazilian Proposal' [16].
- Preliminary analysis suggests that the rate of convergence to 'equity' is a key parameter.
- The way in which these choices impact on the major emitters is likely to determine the shape of any future agreements.
- Convergence rates for Australia need to be determined in the context of global targets and constraints imposed by large emitters.
- Policies and measures for achieving emission targets need to be developed.

**Analysis of costs of alternative pathways** The key points in comparing alternative pathways to stabilisation are:

- Long-term stabilisation of climate involves steadily-decreasing emissions of CO<sub>2</sub> in the long term, in order to stabilise atmospheric CO<sub>2</sub> concentrations.
- In contrast, constant concentrations of other gases can be achieved by holding emissions constant.
- Emission-equivalence for stabilisation of the non-CO<sub>2</sub> gases can be defined in terms of the AGWP (see Table 4.3.3).
- Pathways to stabilisation can generally be adopted independently for each gas. The main functional linkage is between CO<sub>2</sub> emissions and aerosol levels.

## 4.4.2 Global decision criteria

In setting a global framework for avoiding dangerous climate change, some of the main choices to be made are:

- the target level of radiative forcing (i.e. level of equivalent CO<sub>2</sub>);
- the way in which this target is partitioned between the greenhouse gases, particularly the partitioning between CO<sub>2</sub> and other gases;
- the pathways to stabilisation (which can be different for each gas);
- the way in which emission targets are partitioned between nations.

In reality, targets and agreements will almost certainly be set in terms of relatively simple metrics.



Figure 23: Global average per capita  $CO_2$  emissions for selected pathways to 450, 500 and 550 ppm  $CO_2$  (solid curves), compared to per capita emissions from Australia for fossil emissions (1950 onwards, including cement production) and with emissions from land-use change included. Note that short-term irregularities arise from the combination of disparate data sources.

#### 4.4.3 Decision criteria for Australia

In going from the global targets to policy for Australia, there are two important questions (with consequent subsidiary questions):

- What form of global framework would be most desirable for Australia (and what might Australia do to promote such a choice)?
- What form (or range of forms) of global framework is likely to gain global acceptance (and how can Australia best adapt to such frameworks)?

The answers to the two main questions may well be distinctly different.

One form of global framework that has been proposed is known as 'Contraction and Convergence'. The 'contraction' aspect involves defining emission targets for stabilisation — as described above. The 'convergence' aspect envisages all nations moving towards equal per capita emissions. To illustrate the implications of this, Figure 23 expresses emission trajectories from each of the 450 ppm, 500 ppm and 550 ppm concentrations targets in terms of per capita emissions, assuming UN population projections to 9.1 billion in 2050 and constant thereafter. Also shown in per capita terms are Australian fossil emissions (initially from CDIAC and subsequently from national emissions inventories) and the combination of Australian fossil and land-use emissions (from the national inventory).

## 4.5 CO<sub>2</sub> overshoot



ppm after an initial 'overshoot'.

Due to uncertainties in climate sensitivity and in the impacts of climate change, it is possible that a 450 ppm  $CO_2$ -equiv target may be too high for avoiding dangerous climate change.

Since, in terms of LLGHGs a 450 ppm  $CO_2$ -equiv target has been exceeded, lower targets are going to imply a concentration 'overshoot'. Unlike the cases considered in section 5, the overshoot cannot be confined to the non- $CO_2$  gases, but will have to involve reductions in actual  $CO_2$  concentrations. Analysis of profiles with overshoot involves a more complex set of tradeoffs, and so a detailed analysis is beyond the scope of the present report.

Figures 24 and 25 present some examples for ultimate targets of 360, 380 and 400 ppm  $CO_2$ . It will be seen that, as with the 350 ppm target analysed in the 1994 IPCC study [20], each of these implies a need to extract  $CO_2$  from the atmosphere. The main mechanism that has been proposed has been termed 'biofuel energy capture and storage', involving the sequestration of  $CO_2$  emissions from biofuels.

For all but the lowest targets, there is the possibility of achieving a target concentration after an 'overshoot' without anthropogenic removal processes, but this will be at the expense of requiring longer times to achieve the target concentration.

A measure of the point at which an 'overshoot' case can only be achieved by active extraction of  $CO_2$  from the atmosphere can be obtained by considering the 'time-slice' analysis used by Enting [14] and others. This attributes concentrations (and temperature changes) to particular emission periods by calculating concentrations where emissions follow a particular scenario and are then set to zero at a specific times. Figure 26 partitions the concentrations from IS92a into 20-year emission bands. While the contribution from each 20-year slice declines, it does not approach zero. Each 20-year band of emissions leaves a residual concentration that remains in the atmosphere until geological processes (or active anthropogenic removal) intervene. It will be seen that once a particular concentration is reached, even zero emissions result in only small reductions in the final  $CO_2$  concentration.



Figure 25:  $CO_2$  emissions for the cases shown in Figure 24 for stabilisation at 360, 380 and 400 ppm after an initial 'concentration overshoot'.



Figure 26: A 'time-slice' analysis, from [14], attributing  $CO_2$  concentrations over time to the 20-year periods in which the emissions occurred. Thus the lowest band is for pre-1960 emissions, and successive bands are for emissions: 1960–79, 1980–99, 2000–19, 2020–39, 2040–59, 2060–79 and 2080–2099, assuming the IS92a emission scenario.

## 5 Case studies

This section describes in detail two cases representing stabilisation of radiative forcing at levels corresponding to  $450 \text{ ppm CO}_2$ -equiv and  $550 \text{ ppm CO}_2$ -equiv.

The distinction between  $CO_2$  concentration equivalence and  $CO_2$  emission equivalence creates a number of difficulties in defining a 'budget' for non- $CO_2$  gases. Consequently the analysis is presented in two variations:

- The first form is in terms of targets from radiative forcing. As such it can be immediately expressed as a specification of CO<sub>2</sub> concentration equivalence. It is described in Sections 5.1 and 5.2. It does not have a unique representation as a CO<sub>2</sub>-equivalent emission budget using the 'Kyoto' definition. It has been long-known that attempts to impose such an equivalence are conceptually unsound [61, 62] and can lead to significant errors [57, 43]. The temperatures obtained using this form were used by CSIRO for studies of regional impacts.
- The second form is an indicative budget that defines emissions broadly consistent with the long-term target of radiative forcing. It is intended as a starting point for analyses that explore, in economic terms, trade-offs between reductions of the various greenhouse gases. It is described in Sections 5.3 and 5.4. The aim is to produce a specification with reductions across a suite of gases, so that calculated trade-offs, based on 'Kyoto-equivalence' will be less erroneous than they would be if a 'CO<sub>2</sub>-only' specification was used as the starting point. Since economic trade-offs calculated in 'Kyoto-equivalent' terms will not lead to 'concentration-equivalence' we have not tried to make our 'starting point' concentration-equivalent to the radiative forcings that were used for the temperature analysis, but simply aim at the same stabilisation target.

## 5.1 Specifications

The modelling of carbon and temperature is described in Section 2.2 and generally follows the approach used in earlier CSIRO studies [18]. This uses a simple climate model to calculate the causal sequence from emissions to concentrations and then to radiative forcing and global mean warming.

As noted in Section 2.2, the temperature response is scaled to reflect the range from the recent IPCC Fourth Assessment Report. In order to match observed changes (and achieve about  $0.73^{\circ}$ C warming from anthropogenic emissions from pre-industrial times to the 1990s, and a  $0.173^{\circ}$ C increase from 1990 to 2000) scaling the climate sensitivity implied a need to re-scale the relation between aerosols and CO<sub>2</sub> emissions from a factor of 0.125 to a factor of 0.05. This reflects the considerations discussed in [1] and discussions (26/11/07) between Ian Enting and Roger Jones of CSIRO. (The correlation between aerosol forcing and climate sensitivity becomes particularly relevant for calculations spanning uncertainty in climate sensitivity).

- The choices by the Garnaut secretariat, expressed in terms of equivalent CO<sub>2</sub> concentrations, were thus equivalent to a specification of the forcing from long-lived greenhouse gases and ozone at stabilisation.
- For the purposes of modelling temperature changes, it was assumed that these levels are reached by 2100, i.e. constant radiative forcing from non-CO<sub>2</sub> gases applies thereafter with a linear decrease from 2000 to 2100.
- These specifications do not explicitly require a particular partitioning of emissions between the long-lived gases. As noted in Section 4.3.3, under stabilisation, equivalence can be achieved by substitution between the non-CO<sub>2</sub> gases in proportion to their infinitetime limits of AGWPs.
- In order to provide a specific case for analysis, the linear profile of radiative forcing was expressed using the SRES B scenario of the halocarbons and equal scaling of other gases to achieve the specified profile.
- **450 ppm CO<sub>2</sub>-equiv case** For stabilisation at 450 ppm CO<sub>2</sub>-equiv (2.54 Wm<sup>-2</sup>), the analysis was in terms of stabilising CO<sub>2</sub> at 420 ppm (2.17 Wm<sup>-2</sup>). The CO<sub>2</sub> profile for a case with relatively smooth changes in emissions is shown in Figure 27. For stabilisation at 450 ppm CO<sub>2</sub>-equiv, this implies a radiative forcing of 0.37 Wm<sup>-2</sup> from non-CO<sub>2</sub> gases.
- **550 ppm CO**<sub>2</sub>-equiv case For stabilisation at 550 ppm CO<sub>2</sub>-equiv (3.61 Wm<sup>-2</sup>) there is a range of possibilities. The case chosen for analysis (by the Garnaut Secretariat) was based on stabilising CO<sub>2</sub> at 500 ppm (3.10 Wm<sup>-2</sup>), with the specific trajectory being the mid-range case given as the dashed curve in the 500 ppm case on Fig 16 and in Figure 27. Thus, non-CO<sub>2</sub> gases contribute 0.51 Wm<sup>-2</sup>, Table 1.

## 5.2 Results

The main results of the case studies are the  $CO_2$  emissions shown in Figure 28 and the temperature increases shown in Figure 29. For the two cases, Tables 7 and 8 give the  $CO_2$  concentrations, warming,  $CO_2$  emissions, the net forcing (as  $CO_2$  equivalent, due to both gases and aerosols) and the  $CO_2$  concentration equivalent of the gases (i.e. excluding aerosols). Table 4 shows that the integrated  $CO_2$  emissions for the 420 and 500 ppm  $CO_2$  targets are 550 and 972 GtC, integrated from 2005 to 2150.

One particular point to note is that initially the temperatures are slightly higher for the case with the lower target. This reflects the very rapid emission reductions required for the 450 ppm  $CO_2$ -equiv target and our assumption that aerosol loading is proportional to  $CO_2$  emissions. This type of behaviour has been noted previously by Wigley et al. [70].



Figure 27: Profiles for cases stabilising at 450 and 550 ppm  $CO_2$ -equiv. The solid curves show the  $CO_2$ -equivalent forcing from greenhouse gases, the dashed curves show the concentrations of actual  $CO_2$ . The dotted curves show  $CO_2$ -equivalents of combined forcing of gases and aerosols (approximating aerosol loading as being proportional to  $CO_2$  emissions). Anomalies in recent years reflect inconsistencies between historical estimates and future scenarios and also the recent low growth in  $CH_4$  concentrations.



Figure 28: CO<sub>2</sub> emissions for the cases chosen for more detailed modelling.

Year	$CO_2$	Warming	Emissions	Forcing	Gas forcing
	ppm	°C	GtC/year	ppm CO <sub>2</sub> -equiv	ppm CO <sub>2</sub> -equiv
1990	350.81	0.667	7.4	367.9	438.0
1995	358.30	0.733	7.9	377.4	454.3
2000	366.90	0.793	8.8	383.5	472.4
2005	376.54	0.839	9.6	383.1	480.4
2010	386.40	0.872	9.9	387.2	488.5
2015	395.80	0.909	9.7	394.5	495.8
2020	404.09	0.958	9.1	404.8	501.5
2025	410.64	1.021	8.0	417.9	505.0
2030	415.12	1.096	6.9	430.4	505.8
2035	417.88	1.170	5.8	440.0	504.5
2040	419.34	1.237	4.9	446.5	501.7
2045	419.95	1.291	4.3	450.0	497.8
2050	420.13	1.329	3.8	450.6	493.4
2055	420.17	1.354	3.5	449.9	489.0
2060	420.13	1.369	3.3	448.6	484.5
2065	420.06	1.376	3.0	446.7	479.9
2070	420.00	1.378	2.9	444.3	475.5
2075	419.97	1.376	2.7	441.8	471.1
2080	419.97	1.372	2.6	439.2	466.8
2085	419.98	1.365	2.5	436.4	462.5
2090	420.00	1.358	2.3	433.8	458.3
2095	420.00	1.349	2.2	430.9	454.1
2100	420.00	1.339	2.1	428.0	449.9

Table 7: Results for 450 ppm CO<sub>2</sub>-equiv case.



Figure 29: Temperatures for the two cases (assuming three degree climate sensitivity).

Table 8: Results for 550 ppm CO <sub>2</sub> -equiv cas	se.

Year	$\mathrm{CO}_2$	Warming	Emissions	Forcing	Gas forcing
	ppm	°C	GtC/year	ppm CO <sub>2</sub> -equiv	ppm CO <sub>2</sub> -equiv
1990	350.81	0.667	7.4	367.9	438.0
1995	358.29	0.733	7.9	377.4	454.3
2000	366.87	0.794	8.8	383.6	472.4
2005	376.62	0.839	9.8	382.3	481.2
2010	387.15	0.866	10.4	383.7	490.7
2015	398.14	0.891	11.0	386.7	500.7
2020	409.37	0.918	11.3	391.3	510.8
2025	420.60	0.951	11.5	397.3	520.7
2030	431.57	0.992	11.5	404.6	530.1
2035	442.06	1.039	11.3	413.1	538.7
2040	451.81	1.094	10.9	422.8	546.2
2045	460.59	1.155	10.3	433.4	552.5
2050	468.26	1.221	9.6	444.0	557.3
2055	474.85	1.288	9.0	453.7	560.7
2060	480.46	1.352	8.3	462.5	562.9
2065	485.16	1.413	7.7	470.4	563.9
2070	489.04	1.469	7.1	477.3	564.0
2075	492.17	1.519	6.5	483.2	563.1
2080	494.63	1.564	5.9	488.1	561.5
2085	496.51	1.604	5.4	492.0	559.2
2090	497.89	1.638	5.0	495.0	556.4
2095	498.84	1.667	4.5	496.9	553.0
2100	499.45	1.691	4.2	498.0	549.4

#### 5.3 A budget-oriented specification

Because the case studies were designed to analyse stabilisation of the anthropogenic contribution to climate change, they are expressed in terms of targets for radiative forcing. This is equivalent to specifying targets in terms of equivalent  $CO_2$  concentrations.

For emissions, the concept of  $CO_2$ -equivalence can only be consistently defined within very specific contexts and the equivalence ratios between gases will depend on the context. This section addresses the issues involved in defining stabilisation in terms of emission targets. The following section describes our methodology and results.

A further complication occurs when comparing (or exchanging) emissions over time. For a gas with a simple proportional sink,  $\dot{M}$ , the rate of change of mass in the atmosphere, responds to emissions, E, as

$$M = E - M/\tau$$

where  $\tau$  is an atmospheric lifetime. Integrating this gives

$$\Delta M = \int E - \frac{1}{\tau} \int M$$

Thus one can relate integrated emission budgets to atmospheric changes when  $\int M/\tau$  is small This occurs when the time period considered is small compared to the lifetime,  $\tau$ . A special case arises for CO<sub>2</sub> where a specific lifetime cannot be defined. In this case one has an effective lifetime  $\tau_{\text{eff}}$ , often taken as of order 60 years under current conditions, but which becomes very long under conditions of stabilisation. Thus as well as using cumulative CO<sub>2</sub> emissions over short periods, as in the specification of the first Kyoto commitment, one can, to a good approximation, match a CO<sub>2</sub> concentration change, to an amount of cumulative CO<sub>2</sub> emissions when the time period extends to the point of stabilisation. As noted above, Table 4 shows that the integrated CO<sub>2</sub> emissions for the 420 and 500 ppm CO<sub>2</sub> targets are 550 and 972 GtC, integrated from 2005 to 2150. The table also confirms that the cumulative emissions are relatively insensitive to the specific pathway chosen.

The selection of these case studies has involved several specific choices:

- 1. the CO<sub>2</sub> equivalence of the target; (450 and 550 ppm CO<sub>2</sub>-equiv);
- 2. the partitioning of this target between CO<sub>2</sub> and non-CO<sub>2</sub> gases (using 420 and 500 ppm for the actual CO<sub>2</sub>);
- 3. the choice of time profile for the actual CO<sub>2</sub> (shown in Figure 27) as noted earlier, the profiles considered here generally imply less abrupt changes than those used as illustrations in the Stern report;
- 4. the choice of time profile for the radiative forcing from non-CO<sub>2</sub> gases, taken as a linear change between 2005 and 2100;
- 5. the choice of climate response, taken as a 3 degree climate sensitivity, with the transient response scaled to the HadCM3 model as in earlier CSIRO studies [18];

6. the representation of future aerosol loading, which was taken as scaled to  $CO_2$  emissions.

This level of specification has not given a partitioning between the non- $CO_2$  greenhouse gases, and indeed not even a partitioning between direct and indirect greenhouse gases.

A target expressed in terms of radiative forcing (or equivalent CO-2 concentration) can be decomposed as:

$$RF(target) = RF(CO_2) + RF(Non-CO_2 LLGHGs) + RF(O_3)$$

or subtracting CO<sub>2</sub>, and explicitly considering CH<sub>4</sub>, N<sub>2</sub>O and the Montreal gases (as a group)

$$RF(target non-CO_2) =$$

$$RF(CH_4) + RF(N_2O) + RF(Montreal) + RF(Other LLGHGs) + RF(O_3)$$

This is not a greenhouse gas budget of the type used in section 2.2, in the sense of being a balance between sources, sinks and accumulation. Thus it does not directly imply a set of emissions. However, at stabilisation, the various terms on the right (apart from ozone), imply constraints on the set of emissions. With emission equivalence defined in terms of the infinite-time limit of AGWPs, the form

 $RF(target non-CO_2)-RF(O_3) =$ RF(CH<sub>4</sub>) + RF(N<sub>2</sub>O) + RF(Montreal) + RF(Other LLHGH)

does correspond to a 'budget' for non- $CO_2$  emissions. As noted in section 4.3, using the infinitetime limit precludes comparisons with  $CO_2$ . As a compromise, we report our results as  $CO_2$ equivalent emissions using both 100 year and 500 year GWPs.

#### 5.4 Budget trade-offs

As noted earlier, we regard the concept of  $CO_2$ -equivalence as being a descriptive quantity rather than being suitable for calculations. In particular, the temperature stabilisation needed to be performed in terms of radiative forcing (implying concentration-equivalence) while the analysis of mitigation trade-offs requires some form of emission equivalence.

The study by Reilly et al. [57] has noted the problems with Kyoto-equivalence (based on the 100-year GWP). These problems are particularly severe in cases involving stabilisation — the Reilly et al. example (cases 2' and 3' in Fig 3a) has Kyoto-equivalent emissions giving warming (from 1990 to 2100) of 0.5 °C for a multi-gas reductions and 1.2 °C for CO<sub>2</sub>-only reductions.

In order to reduce this problem, our analysis has several stages:

• Our reference case is not a CO<sub>2</sub>-only case, i.e. for a 450 ppm CO<sub>2</sub>-equiv target, we do not use the Kyoto-equivalent of the CO<sub>2</sub> emissions for stabilisation at 450 ppm. Rather our

reference case uses a 420 ppm  $CO_2$  target (and 500 ppm  $CO_2$  for the 550 ppm  $CO_2$ -equiv target). While this is a somewhat arbitrary choice, it should at least reduce the distortions that would arise from starting with a 'CO<sub>2</sub>-only' reference case.

- We use a similar approach for the partitioning of the non-CO<sub>2</sub> components, using the SRES B1 scenario as a basis for making our reference case reflect plausible relations between emission reductions.
- In practice, our use of SRES B1 must also reflect an additional requirement of the modelling — a grouping of forcing agents into (a) those that are treated explicitly, (b) those that are treated as a group (c) those that are not considered — often this means the indirect greenhouse gases — those that affect tropospheric ozone. Economic models differ significantly in how they partition the gases between these different classes.
- Finally, we propose that a better approximation to concentration-equivalence can be achieved by using GWPs based on a longer time horizon we propose the use of 500-year GWPs, since these are readily available.

While we would expect that an 'economically-optimal' partitioning of greenhouse gases would have a forcing profile that is relatively close to our reference (and much closer than if we started from a ' $CO_2$ -only' reference), ultimately this expectation needs to be tested against the economic analysis.

Our key requirement is to achieve an amount of radiative forcing for the non-CO<sub>2</sub> gases which allows for stabilisation at 450 ppm CO<sub>2</sub>-equiv with 420 ppm CO<sub>2</sub>, and 550 ppm CO<sub>2</sub>-equiv with 500 ppm CO<sub>2</sub>. Using the formula for radiative forcing of CO<sub>2</sub>, as given in the TAR, of  $5.35 \ln((CO_2 \text{ conc.})/(CO_2 \text{ eqm conc.}))$  W/m<sup>2</sup>, with pre-industrial concentration of 280 ppm, one obtains that the additional allowed forcing is 0.37 Wm<sup>-2</sup> and 0.51 W/m<sup>2</sup> respectively.

We note here that our procedure in deriving a multi-gas scenario is ad hoc, and in particular is not derived from economic modelling of the cost of abatement of the various GHGs. Specifically, the choice of the split between  $CO_2$  and non- $CO_2$  is ad hoc, as is the split between the non- $CO_2$  gases. Ideally, economic modelling would be used to determine the most cost-effective split between gases for a given  $CO_2$ -equiv stabilisation level; indeed we expect that this initial approximation will be refined after a suitable economic analysis is performed.

## 5.4.1 Method

Our choice is not to achieve stabilisation of radiative forcing in 2100, but instead to achieve constant emissions in 2100 which will eventually lead to the stabilisation of radiative forcing from non-CO<sub>2</sub> gases. The long lifetime of N<sub>2</sub>O in particular (114 years) means that stabilisation of radiative forcing may not be achieved until well after 2200. This gives an overshoot in the amount of radiative forcing (i.e. CO<sub>2</sub>-equivalent concentration).

The key gases to consider apart from  $CO_2$  are  $CH_4$ ,  $N_2O$ , tropospheric ozone, ozone depleting gases controlled by the Montreal protocol, other long lived greenhouse gases such as HFCs,

PFCs, and  $SF_6$ , and aerosols. We now discuss how we treat each of these components in the derivation of our scenario.

- CH<sub>4</sub>, N<sub>2</sub>O and tropospheric ozone: We model mitigation of CH<sub>4</sub>, N<sub>2</sub>O and ozone precursors (NO<sub>x</sub>, CO, and VOC) by assuming that we can decrease them all in 2100 to the same fraction λ of emissions in 2000. After 2100 we assume that emissions of the gases are constant, and we choose λ to give the correct radiative forcing. i.e. if emissions of species x in the year 2000 are E<sub>x</sub>, then we fix emissions in 2100 to be λE<sub>x</sub>. For CH<sub>4</sub> and N<sub>2</sub>O we can use their known lifetimes to calculate the radiative forcing when emissions are held constant, while for tropospheric ozone we use the static value of CH<sub>4</sub>, and the emissions of NO<sub>x</sub>, CO, and VOC to determine the amount of radiative forcing.
- Other LLGHGs: For these gases (i.e. Kyoto gases other than CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O), we adopt the B1 scenario, and assume that radiative forcing due to these gases is instantly stabilised in 2100 at the value of 0.14 Wm<sup>-2</sup>. The B1 scenario for these gases gives a 'soft landing' radiative forcing is almost flat as we approach 2100. The principal difficulty in avoiding unrealistic assumptions in treating these gases are the long lifetimes of some of them, particularly SF<sub>6</sub>. In essence, due to the long lifetime of 3200 years, SF<sub>6</sub> is akin to CO<sub>2</sub> and we can only emit a finite amount over a period of centuries, as it just builds up in the atmosphere and could conceivably make a large contribution to anthropogenic radiative forcing.
- Montreal Protocol gases: We expect emissions of Montreal Protocol gases to decrease to 0, and hence don't need to consider their contribution to the stabilisation scenario. Principally due to the long life of CFC-12 (given as 100 years in AR4), the expected total radiative forcing of these gases is still quite high in 2100 at 0.10 Wm<sup>-2</sup>, but on the time scale of centuries it will become negligible.
- Aerosols: Aerosols remain in the atmosphere for only a short time, and we expect anthropogenic aerosols to diminish as CO<sub>2</sub> emissions decrease. Thus we take the long term concentration of anthropogenic aerosols to be zero, and don't need to consider aerosols directly in the derivation of the scenario. The temperature modelling uses the approximation of having aerosol forcing proportional to CO<sub>2</sub> emissions.

The SRES B1 scenario is SRES scenario which is closest in behaviour to a stabilisation scenario, even though mitigation is not explicitly included. It initially allows for some increase in emissions, with later decreases ensuring that emissions in 2100 are lower than those in 2000.

So, instead of choosing the highly unrealistic scenario of linearly decreasing emissions from 2000 to 2100 for CH<sub>4</sub>, N<sub>2</sub>O and ozone precursors, we adopt the  $B_1$  scenario as the base scenario, and subtract away a linear function which is 0 in the year 2000 (leaving the year 2000 emissions values unchanged), and which gives the correct value ( $\lambda E_x$ ) in 2100.

The only free parameter in the above method is  $\lambda$ , which we must tune to give 0.37-0.14 = 0.23 Wm<sup>-2</sup> for 450 ppm CO<sub>2</sub>-equiv stabilisation, and 0.51 - 0.14 = 0.37 Wm<sup>-2</sup> for 550 ppm CO<sub>2</sub>-equiv stabilisation.

#### 5.4.2 Results

The results are reported in tables 9, 10 and 11 and in figures 30 and 31.

The main points of the specifications are:

- We report our results in GtC-equiv units, with respect to a 1990 background CO<sub>2</sub> concentration of 350 ppm.
- We find  $\lambda = 0.16$  for 450 ppm stabilisation, and  $\lambda = 0.25$  for 550 ppm stabilisation. i.e. for long term stabilisation at 550 ppm CO<sub>2</sub>-equiv, with 500 ppm CO<sub>2</sub>, in this scenario emissions of CH<sub>4</sub>, N<sub>2</sub>O, and ozone precursors must eventually be decreased to 25.0% of their year 2000 value.
- The actual emissions of CO<sub>2</sub> are the same as for the respective cases defined in terms of profiles of radiative forcing. They are given, in GtC/year, in tables 7 and 8. Emissions of CH<sub>4</sub> and N<sub>2</sub>O are given in actual mass units (Tg/year and TgN/year) and also in 100-yr and 500-yr CO<sub>2</sub> equivalent emissions. Emissions in the 'other' category, which excludes aerosols or tropospheric ozone are given as 100-yr and 500-yr CO<sub>2</sub> equivalent emissions. Note that tropospheric ozone was considered in determining the split of radiative forcing between gases, even though it is not reported as part of an explicit partitioning of emissions.
- GWP values and atmospheric lifetimes are from AR4 WGI Table 2.14.
- The concentration dependence of radiative forcing by CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O is from Table 6.2 of the TAR. Pre-industrial concentrations taken to be 280 ppm for CO<sub>2</sub>, 700 ppb for CH<sub>4</sub>, and 270 ppb for N<sub>2</sub>O. (Note: direct effect only assumed for CH<sub>4</sub>, indirect effect of stratospheric H<sub>2</sub>O not included)
- Radiative forcing for tropospheric ozone taken from corrected formula in the footnote of Table 4.11 in the TAR. Note that this includes effects of CH<sub>4</sub> as well as ozone precursors NO<sub>x</sub>, CO, and VOC (volatile organic compounds).
- We take the mean estimate from the TAR for the radiative forcing of tropospheric ozone,  $1 \text{ DU} = 0.042 \text{ W/m}^2$ .

Particularly notable in these results is the slow approach to the target value of the radiative forcing. Ultimately, the low case converges to a total of 0.37 Wm<sup>-2</sup>, and the high will converge to 0.51 Wm<sup>-2</sup>. The 2200 value is much closer to this final stabilisation level for the high case, as there is less abatement of N<sub>2</sub>O emissions. Note that in each case the radiative forcing due to N<sub>2</sub>O will decay until it is a little bit under the radiative forcing due to CH<sub>4</sub> (about 10% under).

The radiative forcing associated with these reference budgets is plotted in Figures 30 and 31. Also included in these figures is the simple approximation (linear decline to 2100 and then constant there-after) used in the temperature modelling and impacts analysis.

			4			FF 4 -	1	
Year	$CH_4$ ,	$CH_4$	$CH_4$	$N_2O$	$NO_2$	$NO_2$	Other	Other
	Tg/yr	GtC(100)	GtC(500)	TgN/yr	GtC(100)	GtC(500)	GtC(100)	GtC(500)
2000	323.0	2.039	0.620	7.000	0.828	0.425	0.141	0.141
2010	330.6	2.087	0.635	7.043	0.833	0.428	0.221	0.172
2020	340.3	2.148	0.653	7.187	0.850	0.436	0.243	0.163
2030	329.9	2.083	0.633	6.830	0.808	0.415	0.293	0.186
2040	307.5	1.941	0.590	6.474	0.766	0.393	0.361	0.222
2050	267.2	1.687	0.513	6.017	0.712	0.365	0.456	0.266
2060	231.8	1.463	0.445	4.960	0.587	0.301	0.466	0.278
2070	195.4	1.234	0.375	4.204	0.497	0.255	0.453	0.264
2080	146.1	0.922	0.280	3.347	0.396	0.203	0.431	0.238
2090	100.7	0.636	0.193	2.291	0.271	0.139	0.417	0.233
2100	52.3	0.330	0.100	1.134	0.134	0.069	0.399	0.227

Table 9: Non-CO<sub>2</sub> emissions for the 450 ppm  $CO_2$ -equiv case.

Table 10: Non-CO<sub>2</sub> emissions for the 550 ppm CO<sub>2</sub>-equiv case.

			-			11 ~	1	
Year	$CH_4$ ,	$CH_4$	$CH_4$	$N_2O$	$NO_2$	$NO_2$	Other	Other
—	Tg/yr	GtC(100)	GtC(500)	TgN/yr	GtC(100)	GtC(500)	GtC(100)	GtC(500)
2000	323.0	2.039	0.620	7.000	0.828	0.425	0.141	0.141
2010	333.6	2.106	0.640	7.107	0.840	0.431	0.221	0.172
2020	346.1	2.185	0.664	7.314	0.865	0.444	0.243	0.163
2030	338.7	2.138	0.650	7.021	0.830	0.426	0.293	0.186
2040	319.3	2.016	0.613	6.728	0.796	0.408	0.361	0.222
2050	281.8	1.779	0.541	6.335	0.749	0.385	0.456	0.266
2060	249.4	1.574	0.479	5.342	0.632	0.324	0.466	0.278
2070	216.0	1.363	0.414	4.649	0.550	0.282	0.453	0.264
2080	169.5	1.070	0.325	3.856	0.456	0.234	0.431	0.238
2090	127.1	0.802	0.244	2.863	0.339	0.174	0.417	0.233
2100	81.7	0.515	0.157	1.770	0.209	0.107	0.399	0.227

Table 11: Radiative forcing contributions (in  $Wm^{-2}$ ) at stabilisation for the 450 ppm CO<sub>2</sub>-equiv and 550 ppm CO<sub>2</sub>-equiv targets. The zero for the Montreal gases is the notional long-term consequence of complete phase out.

	Radiative forcing Wm <sup>-2</sup>					
	450 ppm $CO_2$ -equiv 550 ppm $CO_2$ -					
Total	2.54	3.61				
$\mathrm{CO}_2$	2.17	3.10				
Total - $CO_2$	0.37	0.51				
$\mathrm{CH}_4$	0.10	0.15				
$N_2O$	0.09	0.14				
Tropospheric O <sub>3</sub>	0.05	0.09				
Montreal	0.00	0.00				



Figure 30: Partitioning of radiative forcing from non-CO<sub>2</sub> gases for the indicative emissions budget (see table 9) for 450 ppm CO<sub>2</sub>-equiv case. 'Other' refers to the Kyoto gases other than CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O. The horizontal dashed line shows the target radiative forcing of 0.37 Wm<sup>-2</sup>.



Figure 31: Partitioning of radiative forcing from non-CO<sub>2</sub> gases for the indicative emissions budget (see table 10) for 550 ppm CO<sub>2</sub>-equiv case. 'Other' refers to the Kyoto gases other than CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O. The horizontal dashed line shows the target radiative forcing of 0.51 Wm<sup>-2</sup>.

## 6 Summary

This report has focused on developing pathways of emissions reductions which lead to the stabilisation of greenhouse gases at levels of concentration which have been chosen in order to keep impacts below an agreed threshold.

#### The need to avoid 'dangerous climate change'

The project specification asked the authors to consider what threshold might be considered as the point beyond which the impacts would amount to 'dangerous climate change'. However, what constitutes 'dangerous climate change' begs the question of 'dangerous for whom or what?' Decisions about what constitutes 'dangerous climate change' will thus depend on value judgements about physical, biological and sociological impacts. They are social choices. But they will be best made if the consideration of available options is informed by good science.

While acknowledging that the choice of what should be considered 'dangerous' cannot be succinctly defined, one choice that has been widely discussed as a useful guide is a carbon dioxide equivalent concentration that results in an increase in global average surface air temperature of 2°C above pre-industrial times. Although such a rise will not be 'safe' for all human and natural systems, it is often argued that there is good evidence that warming above this threshold will lead to wide ranging and serious adverse impacts on many aspects of the Earth's environment.

Uncertainties in the science of the climate's response to rising concentrations of greenhouse gases mean that it is not possible to state a precise relation between a chosen temperature target and corresponding targets for atmospheric concentrations and emissions. Rather, the choice of mitigation targets needs to be made on the basis of consideration of reduction of risk.

# Stabilising $CO_2$ requires an initial rapid reduction and subsequent steady reduction of $CO_2$ emissions which must be continued over very long time frames (centuries to millennia).

Once a choice of a threshold concentration of greenhouse gas emissions has been made, it is necessary to devise a strategy for stabilising the concentration at this level. In discussing how to achieve such a stabilisation of  $CO_2$  it is important to distinguish between stabilising emissions to the atmosphere, and stabilising concentrations therein. Due to the facts that current emissions exceed the capacity of natural systems to absorb these emissions and that, under stabilisation, this natural uptake will decline as the oceans and biosphere come into balance with the atmosphere, emissions have to be reduced in order to stabilise the atmospheric levels.

The current concentration level of atmospheric GHGs and the continuing high emissions mean that it will be difficult to achieve stabilisation. Because emissions over recent years have been higher than expected the task of achieving stabilisation has become correspondingly more difficult. This is a legitimate basis for considerable concern. It suggests that the window of opportunity to take action is reducing, and urgent action is required before further, and perhaps irreversible, climate change occurs. Even if strong measures are implemented immediately to rapidly reduce emissions some further climate change is inevitable due to the effects of past actions and the resulting 'committed warming' which they have already set in motion.

#### Stabilising other gases can be achieved by stabilising emissions

As indicated above, the stabilisation of carbon dioxide is complicated by its interactions with the oceans and biosphere which can both have large transfers of  $CO_2$  to and from the atmosphere. Stabilisation involves reaching an equilibrium between these various processes, requiring a steady reduction in emissions. However, the other greenhouse gases (such as methane) behave in a much simpler fashion. For each of these GHGs, its residence time in the atmosphere reflects the average time that it takes for a molecule of that gas to break down into other chemicals. Thus for these gases, stabilisation of their concentrations in the atmosphere can be achieved by stabilising their emissions at appropriate levels. However, unless emissions are reduced to a level where they balance current sinks, there will be a time delay (several times the atmospheric lifetime) between stabilisation of emissions and stabilisation of concentrations during which concentrations will grow until the sinks balance the emissions. Thus for long-lived gases such as N<sub>2</sub>O, the slow approach to stabilisation levels will imply a significant 'overshoot' in its contribution to radiative forcing that may be very hard to balance by reductions of other gases.

In considering possibilities for future climate change it is important to distinguish between ranges of outcomes arising from different possible choices, and ranges that reflect scientific uncertainty in the prediction of outcomes from a particular choice.

As an example, it is important to distinguish between the range of different pathways of carbon dioxide emissions reductions leading to stabilisation of the carbon dioxide concentration at a target value, and the range of possible predicted values of the warming that might result. This report describes a range of pathways to stabilisation that is more comprehensive than the illustrative examples given in the Stern Report [63].

Choices about which GHG emissions should be reduced, at what rate, and in what order, require considerations of science, and also costs. Relevant costs include: the costs of mitigation action and the costs of adapting or failing to adapt to impacts associated with different rates of change of temperature.

The scientific considerations require us to find a means of comparing the role of the different GHGs. Because  $CO_2$  is both the most abundant of the GHGs, and has the most complicated behaviour due to its two-way interaction with the biosphere, much of our analysis of pathways to stabilisation have concentrated on  $CO_2$ .

Our approach to the treatment of GHGs is different to that in the Stern Report [63]. Stern provides a small number of illustrative examples characterised by indicative carbon budgets at particular times, while perhaps giving insufficient emphasis to the fact that these budgets are both changing in time and dependent on the emissions trajectory. In comparison to the illustrative examples given in the Stern Report, we have identified smoother pathways to stabilisation. These paths take account of broad interactions between carbon concentrations in the atmosphere and the behaviour of carbon flows into and out of the biosphere. One result of this is that the percentage reduction rate required in the 21st century to reach a stabilisation target is smaller than in the 'Stern' examples. However limitations in the concept of  $CO_2$ -equivalence preclude precise comparisons between the work developed here and the Stern examples.

For policy and planning purposes we identify that the key trade-offs (for any particular stabilisation level) are between the peak height (maximum greenhouse gases emitted) and reduction rate (rate at which emissions must be reduced to achieve the target). The selection of an emissions trajectory for a selected concentration target depends on these choices and the relative importance assigned to the present vs. future implications. Apart from the implications of how climate impacts depend on rate of warming, the primary issues in such choices are economic. For any given upper concentration limit, higher levels of emissions in the near future (i.e. the peak height) mean that a more aggressive reduction in emissions is required to achieve stabilisation for any particular future point in time. The speed with which mitigation can be applied and ability to make changes is largely an economic decision. The scientific analysis suggesting the need for relatively low concentration targets, implies that it is preferable to both move to contain greenhouse gas emissions growth immediately and follow with rapid reductions so that changes to the climate system and the consequent impacts are minimised.

## The various forms of $CO_2$ -equivalence are primarily descriptive statistics and of limited applicability in quantitative analysis.

The concept of carbon dioxide concentration equivalence is often used in attempts to analyse the overall impact of rising GHG concentrations. It gives a single figure to capture the equivalent warming effect of a mixture of greenhouse gases. However, there are a number of problems with this concept and these are discussed in this report (see Section 2.4). A particular problem in the use of the concept is the potential confusion between the distinct concepts of 'carbon dioxide emission equivalence' and 'carbon dioxide concentration equivalence'. The two forms of carbon dioxide equivalence are useful for descriptive purposes and summary statistics. But they are inappropriate for use in detailed analysis especially in comparisons where concentrations are changing. Due to the long atmospheric lifetime of carbon dioxide and its predominance, it is the gas that is of most significance and whose emissions have to be bought under control. Depending on the contribution of rate of temperature increase to climate impacts, there may be some short term benefit in reducing methane and nitrous oxide emissions if significant changes can be made quickly. It is more likely that a combined and intensive effort to reduce all GHGs is necessary, particularly in view of the current lack of success in achieving global emission reductions.

# The appropriateness of including or excluding aerosol effects in expressing $CO_2$ -equivalent concentrations depends on the context.

The issue of whether the cooling affect of aerosols ('global dimming') is included in the carbon dioxide equivalent concentration calculations has occasionally become contentious. Taking the current concentrations of LLGHGs results in a figure of 455 ppm CO<sub>2</sub>-equiv, which is above the target associated with 2°C warming (median value) and 'dangerous anthropogenic interference'.

The above warming effect is reduced by aerosols. However, the measures taken to reduce GHG emissions will probably also reduce the amount of aerosols in the atmosphere, since much of this arises from burning fossil fuels. As a result it will also reduce the cooling affect arising from aerosols. Thus including aerosols is appropriate when discussing the present situation, while considering only the long-lived gases is appropriate when discussing changes to which there is a long-term 'commitment'.

The main uncertainty in the analysis arises from uncertainties in the climate response, complicating comparisons of costs of impact vs mitigation.

There are a number of uncertainties associated with determining a target concentration for the stabilisation of atmospheric GHGs. Climate sensitivity (the amount of warming that results from increased atmospheric carbon dioxide concentrations) has a range of uncertainty associated with it. A generally accepted guide is that a doubling of  $CO_2$ -equivalent concentration will result in about a 3°C increase in global average surface temperature. The range of uncertainty for this figure is discussed in the report.

Another area of uncertainty is the extent to which feedbacks may result from global warming which create an increased risk of non-linear and even catastrophic events. One example relates to the ocean's capacity to absorb  $CO_2$ . To the extent that this declines due to increased atmospheric concentrations, atmospheric concentrations of  $CO_2$  will increase still further. At the lower concentration targets discussed in this report and/or low to mid-range climate response, uncertainties in feedbacks are less important than uncertainty in climate response.

Another example relates to methane. With warmer temperatures there is an increased likelihood of permafrost melting and consequent releases of trapped methane. If released, this methane will contribute to further warming and hence more permafrost melting, creating a positive feedback cycle. Whilst we query a recent claim that such feedbacks have already been detected as occurring much earlier than expected, we stress that it is difficult to predict the extent and timing of these types of problems developing, but any one of a number of such feedbacks could significantly affect an already difficult problem. Again, addressing such concerns needs to be considered in terms of reduction of risk, rather than certainty of outcome.

Analysis of national emissions and stabilisation targets requires analysis of how global targets are partitioned between nations.

This issue is outside the scope this report. However useful ground-work for such a study has been provided here.

The analysis in this report suggests that there is no reason for complacency in relation to setting stabilisation targets for greenhouse gases in the atmosphere, moving immediately to contain growth in the corresponding emissions, and then reducing those emissions along one of the available reduction paths towards those targets. The choices involved are ultimately decisions about risks to the environment and human societies. They are decisions about costs to be accepted to avoid financial and physical costs in the future. The science suggests that containment of these risks will be much easier to achieve by early and firm action.
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## Abbreviations

- AGBM Ad hoc Group on the Berlin Mandate. (Body set up under UNFCCC).
- AGWP Absolute Global Warming Potential.
- AGCM Atmospheric General Circulation Model.
- AOGCM Atmosphere-Ocean General Circulation Model.
- AGO Australian Greenhouse Office.
- **AR4** Fourth Assessment Report (of IPCC).
- ATSE Australian Academy of Technological Sciences and Engineering.
- **BaU** Business-as-Usual. A description of various scenarios.
- **BC** Black carbon. Class of aerosol.
- CASPI Climate Adaptation Science and Policy Initiative (The University of Melbourne).
- C&C Contraction and Convergence. Proposed framework for emission targets.
- **CDIAC** Carbon Dioxide Information and Analysis Center. (Oak Ridge National Laboratory, USA).
- CFC Chlorofluorocarbons.
- CMIP Coupled Model Intercomparison Project. (A study analysing AOGCM behaviour).
- CoP Conference of Parties. (Parties to the UNFCCC and Kyoto Protocol).
- **C4MIP** Coupled Carbon Cycle Climate Model Intercomparison Project. (A study analysing carbon-climate feedbacks).
- **CRU** Climate Research Unit (University of East Anglia, UK).
- **CSIRO** Commonwealth Scientific and Industrial Research Organisation (Australia).
- **DU** Dobson units. A measure of atmospheric ozone content. Defined as the vertically integrated amount that would be a layer  $10^{-5}$  m (i.e. 1 cm) thick, at a pressure of 1013 hPa and 0°C.
- EPA Environmental Protection Agency (USA).
- EU European Union.
- FCCC Framework Convention on Climate Change (also UNFCCC).
- GCM General Circulation Model.

- **GISS** Goddard Institute for Space Studies.
- **GHG** Greenhouse Gas(es).
- Gt Gigatonnes. ( $10^9$  tonnes.) The correct SI unit for this quantity is petagrams (Pg,  $10^{15}$  grams).
- **GtC** Gigatonnes of carbon. Unit often used in carbon budgets describing exchange of carbon with other reservoirs where carbon is not in the form of CO<sub>2</sub>. Sometimes the technically correct SI equivalent, PgC, is used.
- $GtCO_2$  Measure of mass of  $CO_2$  in (or added to) the atmosphere. One  $GtC = 3.67 GtCO_2$ .
- **GWP** Global Warming Potential. A measure of the relative impact of different greenhouse gases.
- HCFC Hydrochlorofluorocarbons.
- HFC Hydrofluorocarbons.
- **IPCC** Intergovernmental Panel on Climate Change.
- K Kelvin. SI unit for temperature.
- **LLGHG** Long-Lived Greenhouse Gas(es).
- LUCF Land-use change and Forestry. (emission sector).
- MASCOS ARC Centre of Excellence for Mathematics and Statistics of Complex Systems.
- **MATCH** Modelling and Assessment of Contributions to Climate Change. A working group analysing the Brazilian Proposal.
- MIT Massachusetts Institute of Technology.
- NASA National Aeronautic and Space Administration (USA).
- NCDC National Climate Data Center (NOAA, USA).
- **NPP** Net Primary Production. A measure of net photosynthetic activity.
- NOAA National Oceanic and Atmospheric Administration (USA).
- **OC** Organic carbon. Class of aerosol.
- **ODS** Ozone depleting substances.
- **PDF** Probability distribution function.
- **PFC** Perfluorocarbons
- **ppb** Parts per billion. Proportion of a gas (as number of molecules) in the atmosphere (see also ppm). Note that billion refers to US (not British) usage, as 1 billion = 1000 million.

- **ppm** Parts per million. Proportion of a gas (as number of molecules) in the atmosphere. Essentially equivalent to proportion by volume and so ppmv is sometimes used. Proportion by mass (or weight) will be different because molecular weights of molecules differ).
- **ppt** Parts per trillion. Again, US usage, thus 1ppt is 1 part in  $10^{12}$ .
- **RIVM** Rijksinstituut voor Volksgezundheit en Millieu. (National Institute for Public Health and the Environment, Netherlands).
- SAR Second Assessment Report (of IPCC).
- SBSTA Subsidiary Body for Scientific and Technical Advice. (i.e. advice for the UNFCCC).
- SCEP Study of Critical Environmental Problems. A 1970 MIT-based study.
- **SCM** Simple Climate Model. See [33].
- SPM Summary for Policy Makers. In IPCC reports.
- **SRES** Special Report on Emission Scenarios (IPCC report) [34]. SRES also refers to the set of scenarios defined in that report.
- TAR Third Assessment Report (of IPCC).
- **TS** Technical Summary. In IPCC reports.
- WCRP World Climate Research Program.
- WG I, WG II, WG III Working Groups I, II and III of the IPCC.
- WMO World Meteorological Organization.
- **WRE** Wigley, Edmonds, Reichles. A group of stabilisation profiles (Named for the authors of the paper describing them [70]).

## Glossary

Single quotes in definitions denote other glossary items.

- **absolute global warming potential (AGWP)** A measure of the cumulative effect (over a specified 'time horizon') of a unit emission of a greenhouse gas. AGWP is defined as the radiative forcing integrated over the specified time horizon, taking into account the loss rate for the gas. The usual units are  $Wm^{-2}/kg$ , noting that for CO<sub>2</sub>, the mass of CO<sub>2</sub> (rather than the mass of carbon) is used.
- **airborne fraction** This represents the proportion of  $CO_2$  that remains in the atmosphere, i.e. the atmospheric growth rate divided by emissions (assuming consistent units such as GtC/yr). Oeschger et al. [53] noted what they termed the "apparent airborne fraction" which is the ratio of atmospheric growth rate to fossil  $CO_2$  emissions. While this apparent airborne fraction is easier to determine (since the poorly-known land-use change emissions are excluded), this apparent airborne fraction has no particular significance for carbon cycle dynamics [53, 15]. In spite of the clear distinction introduced by Oeschger et al. much subsequent usage has applied the term 'airborne fraction' to what Oeschger et al. termed the "apparent airborne fraction".
- **Berlin Mandate** A decision by CoP-1 (the first Conference of the Parties to the FCCC) [FCCC/CP/1995/7/Add.1] noting the inadequacy of the specific targets in the FCCC and initiating the negotiations that led to the 'Kyoto Protocol', beginning:

The conference of parties, at its first session, having reviewed Article 4, paragraph 2(a) and (b) of the United Nations Framework Convention on Climate Change, and Having concluded that these subparagraphs are not adequate, agrees to begin a process to enable it to take appropriate action for the period beyond 2000, including strengthening of commitments of the Parties included in Annex I to the Convention (Annex I Parties) in Article 4 paragraph 2(a) and (b) through the adoption of a protocol or another legal instrument.

- **Brazilian Proposal** A proposal, put forward during the negotiations leading to the Kyoto Protocol, that emission reduction targets for developed nations should be in proportion to their relative responsibility for the greenhouse effect.
- **Bern model** A lumped-reservior carbon cycle model developed by the Bern group. An early version appears as model J (see [20: appendix C]) in the 1994 stabilisation studies. The linearised  $CO_2$  response of the Bern model formally defines a GWP of 1.
- **Bern-CC model** An extension of the Bern model, developed to consider feedbacks coupling the carbon cycle and climate change.
- **carbon budget** This is the 'greenhouse gas budget' for  $CO_2$ . Unlike other gases which are mostly expressed in terms of total mass, the budget for  $CO_2$  is usually expressed in terms of carbon mass. (Note that for 'global warming potentials', and thus for much discussion

of  $CO_2$ -equivalent emissions,  $CO_2$  mass is used). As noted below, carbon budgets are often expressed as the budget of net anthropogenic changes, i.e. after subtracting a balanced (zero atmospheric change) pre-industrial budget. Figure 18 shows an example of how the carbon budget evolves over time for a particular case of stabilisation at 550 ppm.

- **climate sensitivity** A measure of the amount of climate change expected from a given degree of radiative forcing. It is defined as the equilibrium temperature increase arising from a doubling of  $CO_2$  concentration.
- **C4MIP** Coupled Carbon Cycle Climate Model Intercomparison Project. An 'intercomparison' of models that address the feedbacks between climate and carbon dioxide concentration.
- $CO_2$ -fertilisation The effect of increased photosynthesis resulting from higher  $CO_2$  concentrations.
- **committed warming** Also termed 'warming commitment' or 'climate change commitment'. The amount of unavoidable warming still to come. Usually taken as the amount of warming still to come if concentrations were held constant, and termed more specifically the "constant concentration temperature commitment" [39: Annex 1, p945]. Occasionally defined as the amount of warming still to come if greenhouse gas emissions ceased.
- **earth sciences** Traditionally the sciences of the lithosphere—geology, geophysics, seismology etc. Increasingly used for what is defined below as 'earth system science'.
- earth system science The science of the combined atmosphere-hydrosphere-biospherelithosphere system — planetary science for the planet Earth.
- emission scenario A 'scenario' that specifies future emissions of greenhouse gases. The IPCC has produced the 'IS92' and 'SRES' scenarios.
- equivalent carbon dioxide concentration The IPCC AR4 definition [39: annex 1, p945] is "The concentration of carbon dioxide that causes the same amount of radiative forcing as a given mixture of carbon dioxide and other greenhouse gases." Note that this defines 'CO<sub>2</sub> equivalent concentration' as a property of a **mixture** and does not define CO<sub>2</sub> equivalence for the individual gases in the mixture.
- **equivalent carbon dioxide emission** The IPCC AR4 definition [*39: annex 1, p945*] begins "The amount of carbon dioxide emission that would give the same integrated radiative forcing over a given time horizon." and concludes "Equivalent carbon dioxide emission is a standard and useful metric for comparing emissions of different greenhouse gases but does not imply exact equivalence of the corresponding climate change responses".
- **exponential** A mathematical relation between two quantities where a fixed additional change in one gives a fixed multiplicative change in the second: e.g. compound interest giving (at constant rates) the same proportional increase each year.
- **feedback** A characteristics of a system where the output affects the input. Positive feedbacks are when the output augments the input, amplifying the effect. Negative feedbacks are when the output suppresses the input, thus reducing the effect.

- **general circulation model (GCM)** A numerical model that calculates the global-scale timeevolution of the atmosphere and the oceans from the equations of motion (Newton's Laws in the appropriate numerical representation) and thermodynamics. In practice, there are limitations to this direct derivation from the physics, mainly due to non-linear processes acting on multiple scales, so that the effects of the smaller scales need to be represented through a 'parameterisation'. For the atmosphere, processes requiring such parameterisation include the representation of water and clouds and radiation, small-scale eddies and small-scale ice processes. The representation of the boundary interactions between the atmosphere and the land and ocean surfaces also require parameterisation.
- **global warming potential (GWP)** A quantification of the relative importance of emissions of different greenhouse gases, taking into account differences in the radiative effects and differences in the rates of loss of the gases from the atmosphere. GWP is a relative measure (defined relative to  $CO_2$ ) and for a particular gas is the ratio of the 'absolute global warming potential' for that gas, to the absolute global warming potential of  $CO_2$ .
- **greenhouse gas budget** This is a specification of the balance between sources, sinks and atmospheric accumulation of a greenhouse gas. Notionally a budget is instantaneous, and usually expressed in units of rate of change of mass. In practice budgets represent an average, with the averaging time being multiple years so as to average out seasonal variations. Longer averaging times can average out other variations such as El Niño effects in sinks, short-term economic effects on sources, that may be irrelevant to analysis of long-term global change. Implicit in this form of specification is that the averaging time is sufficiently short to ensure that the average dynamics approximates the actual dynamics (i.e. the time scales are short enough to be able to ignore non-linear variations). Sometimes (commonly for  $CO_2$ , and occasionally for other gases) budgets are expressed as net anthropogenic contributions, obtained by subtracting an estimated pre-industrial budget. Greenhouse budgets are presented with various degrees of aggregation, where sources and sinks may be partitioned according to process, sector, region etc.
- halocarbons A generic term for compounds analogous to hydrocarbons in having a skeleton of one or more carbon atoms, but which have various halogen atoms (fluorine, chlorine, bromine, iodine) attached to this skeleton. All the halocarbons will absorb in the infrared. Some of the main groups include CFCs (regulated under the Montreal Protocol), HCFCs (CFC replacements), and PFCS.
- **indirect greenhouse gas** A gas that does not directly affect the radiative balance of the Earth, but which, usually through chemical interactions, affects the amount of one or more gases that do absorb infra-red radiation. The most important of the indirect greenhouse gases are those that affect tropospheric ozone.
- **intercomparison** Term used in the earth systems science community for a comparison of models run under standard conditions.
- **IPCC** Intergovernmental Panel on Climate Change. A body set up the the United Nations Environment Program and the World Meteorological Organisation. Its primary task is to produce assessments of the science of climate change and related issues.

- **IS92** A set of greenhouse gas 'emission scenarios', IS92a, IS92b, IS92c, IS92d, IS92e, IS92f, produced by the IPCC in 1992.
- **Kyoto Protocol** An agreement under the FCCC, whereby developed nations parties restrict greenhouse gas emissions to a specified percentage of 1990 emissions. The Kyoto Protocol came into effect in February 2005, following ratification by the requisite number of countries.
- **logarithmic** A mathematical relation between two quantities where a fixed multiplicative change in one gives a fixed additive change in the second.
- **Magic-C** (a Model for the Assessment of Greenhouse Gas Induced Climate Change). A simple climate model developed by Wigley and collaborators at the Climate Research Unit, University of East Anglia. Used in many IPCC studies. The carbon component of an early version is described as Model W in [20: Appendix C].
- mitigation Action to reduce the human impact on climate.
- **Montreal Protocol** The Montreal Protocol on Substances that Deplete the Ozone Layer was adopted in Montreal in 1987, and subsequently adjusted and amended in London (1990), Copenhagen (1992), Vienna (1995), Montreal (1997) and Beijing (1999). It controls the consumption and production of chlorine- and bromine-containing chemicals that destroy stratospheric ozone, such as CFCs, methyl chloroform, carbon tetrachloride, and many others.
- **ozone** A molecular form of oxygen,  $O_3$ . Although ozone is a minor constituent of the atmosphere, and a harmful pollutant in the lower atmosphere, ozone is of great importance because it absorbs most incoming ultra-violet radiation. It has a slight cooling effect. Tropospheric ozone acts as a greenhouse gas with a warming effect.
- **parameterisation** The representation of a complex process in simple terms, with the representation being adjusted (i.e. parameters tuned) by methods such as comparison of behaviour with observations and/or the behaviour of a more realistic model.
- **pattern scaling** This is a technique for relating details of climate change to global scale change [51]. It approximates the changes in small-scale features as a multiple of global mean temperature change. The scaling factor is derived from one or more 'general circulation models' (GCMs). Pattern scaling provides a way of estimating climate impacts by the use of simple climate models. The significance is that the combination of using a simple climate model, followed by pattern scaling can be performed much more quickly than GCM integrations and so many more cases can be explored.
- projections Conditional predictions, especially those conditional on assuming a 'scenario'.
- **radiative forcing** A global-scale quantification of the change in the balance of the Earth's radiative energy transfer due to some perturbing influence. Usually defined in terms of balance at the tropopause and on time-scales where the stratosphere has achieved radiative equilibrium. It is a concept appropriate for simple climate models. General circulation models calculate the radiative changes more directly and at the model resolution.

- **saturation** A characteristic of absorption of radiation. Absorption of radiation at some frequency is saturated once all radiation (at that frequency) is being absorbed.
- **scenario** A proposed future, generally taken as requiring some degree of internal consistency. Scenarios provide input into 'projections' of the future. See 'emission scenarios' and particular cases 'IS92' and 'SRES'.
- **simple climate model** These are models that provide simple parameterised representation of the causal sequence from emissions to concentrations to radiative forcing to global warming. The structure and use of simple climate models is described in an IPCC Technical Paper [*33*]. Generally the behaviour of these models is tuned so that the simple model matches the behaviour of a more complicated model (i.e. a GCM). The benefit of this is that simple climate models can be use to explore (approximately) the large-scale behaviour of a range of different GCMs, e.g. with a range of equilibrium and/or transient climate sensitivities. The difficulty that this creates is that when comparing the results from simple climate models, it is essential to know which model parameters have been used. Examples of simple climate models include 'MAGIC-C'. Additional features may be included in order to give more details, e.g. land-ocean and/or north-south differences. Simple climate models are often embedded in a more comprehensive model, including components such as emissions modelling and impacts (e.g. via some form of pattern scaling). The term integrated assessment model is sometimes used for such models, e.g. the IMAGE model from RIVM, Netherlands.
- **SRES** A report by the IPCC describing 'emission scenarios' [34]. Also, the scenarios described in that report, termed (for example) SRES-A1, SRES-B2 ....
- **thermohaline circulation** The large-scale vertical circulation of the oceans, driven by density differences due to differences in temperature and salinity.
- **time horizon** The period over which the integrated radiative forcing is calculated in order to determine 'global warming potentials' (GWP). The 'Kyoto Protocol' uses GWPs with a 100-year time horizon to define 'equivalent carbon dioxide emissions'.
- **tipping point** A point at which a system ceases to respond smoothly to changes, making an abrupt jump to a new state.
- **transient warming** Changes in radiative forcing create an energy imbalance that lead to changes in the Earth's temperature. Due to the large heat capacity of the oceans there is a time delay before the Earth reaches balance at a new higher equilibrium temperature. Thus, under conditions of changing radiative forcing, the amount of temperature change lags behind the equilibrium change associated with the radiative forcing. The transient warming refers to that actual amount of warming over time. The slower, the change in radiative forcing, the closer the transient warming will be to equilibrium warming.
- **transient climate response** Usually defined as the 'transient' warming' associated with doubling of  $CO_2$  concentrations (or  $CO_2$ -equivalent concentrations). This will depend on how rapidly the  $CO_2$  is increasing. A 'standard' study, following protocol of the CMIP intercomparison, used a 1% per annum  $CO_2$  increase. Results reported at a special IPCC

workshop [38: fig 3, p6] suggest that this transient response is close to 50% of the equilibrium response. More extensive results in AR4 [39: fig 10.25] show a comparable ratio, but rather more scatter. For rates of increase, slower than 1% per annum, ratios larger than 50% are expected for the ratio of transient response to equilibrium response. For the cases considered here, approximately 2/3 of the equilibrium warming has taken place by that concentrations stabilise. This is comparable to other results.

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