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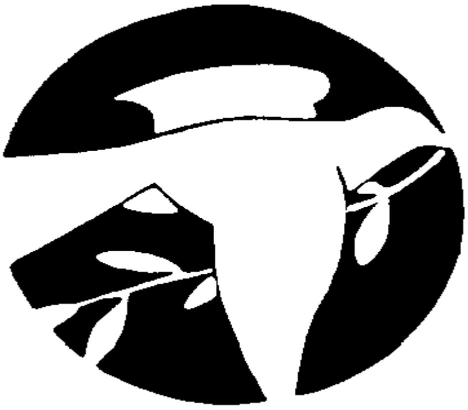
Fossil Fuels and Climate Protection:

The Carbon Logic



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Fossil Fuels and Climate Protection - The Carbon Logic

Abstract

Preventing dangerous climate change will involve limiting both the rate and magnitude of climate change over the next century to levels that natural and human systems can tolerate without significant damage. This report shows the implications for overall fossil fuel use, in the form of a 'carbon budget', over the next century if the global community is to prevent dangerous climate change.

It is demonstrated that it is only possible to burn a small fraction of the total oil, coal and gas that has already been discovered, if such dangerous changes are to be avoided. Even the reserves of fossil fuels that are considered economic to recover now, with no advances in technology, are far greater than the total allowable 'carbon budget'.

This conclusion is shown to be robust to a wide range of assumptions about how sensitive the climate is to human interference, and the levels of change that might be considered unacceptable or dangerous.

Comparison of the 'carbon budget' with projections of possible future energy sources nevertheless suggests that such a target is both technically and economically feasible.

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Executive Summary

Introduction

This paper calculates a carbon budget for a given set of ecological constraints on climate change over the next century. The carbon budget concept has the capacity to shed significant light on the implications of current fossil fuel policy for long term climate policy objectives. It can also provide some novel insight into the debate over whether or not the world is facing an oil shortage, by comparing an allowed carbon budget against estimates of available oil.

In the international policy context the idea of carbon budget makes clear the choices that developed and developing countries face in the current round of climate negotiations. The more fossil fuel that developed countries use now (i.e. the slower they reduce emissions) the less may be left over for developing countries if climate goals are to be met.

Carbon dioxide emissions and fossil fuels

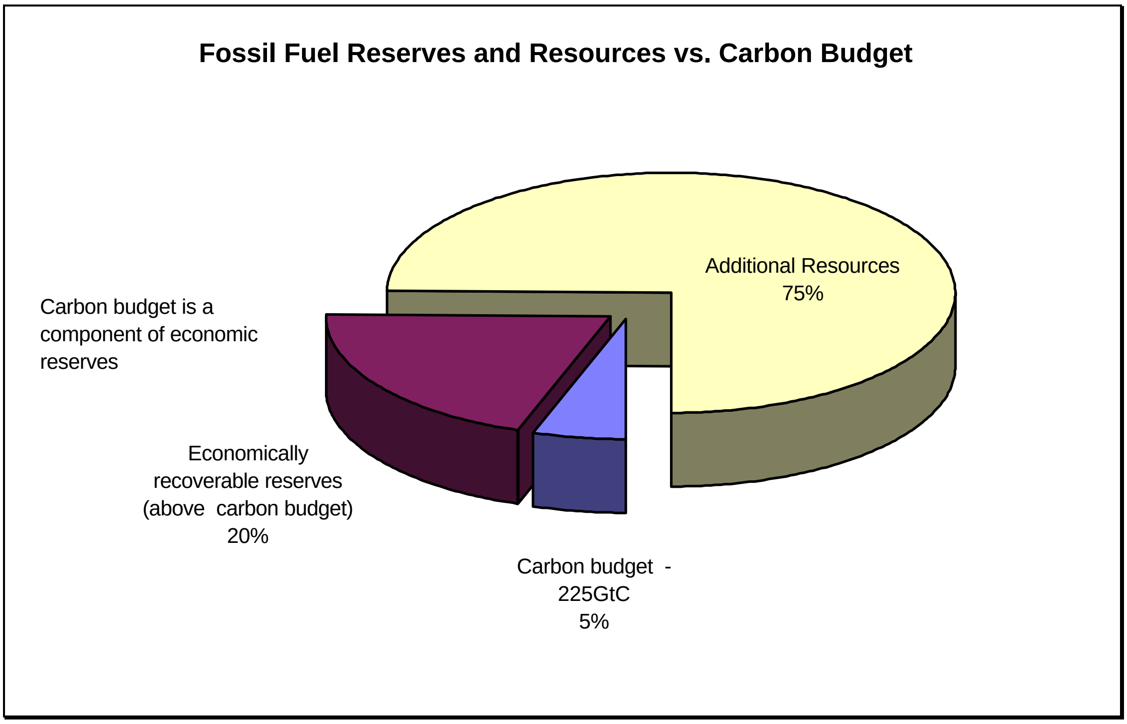
Each year the world releases approximately 6 billion tonnes of carbon (gigatonnes or GtC) in the form of carbon dioxide (CO_2) from the burning of fossil fuels - coal, oil and gas. These emissions have increased at around 2% per year over the past several decades. CO_2 is the major greenhouse gas and its significance is likely to grow over the next century. Fossil fuel use was responsible for nearly 60% of greenhouse gas emissions in 1990.

In the absence of action to reduce CO_2 emissions, around 1,500 GtC are likely to be emitted over the next century. Deforestation may contribute 30-95 GtC of this, with the rest being from the use of coal, oil and gas. Over the next century human activities are likely to add some 4-10 times more fossil carbon to the atmosphere than has been added since the industrial era began.

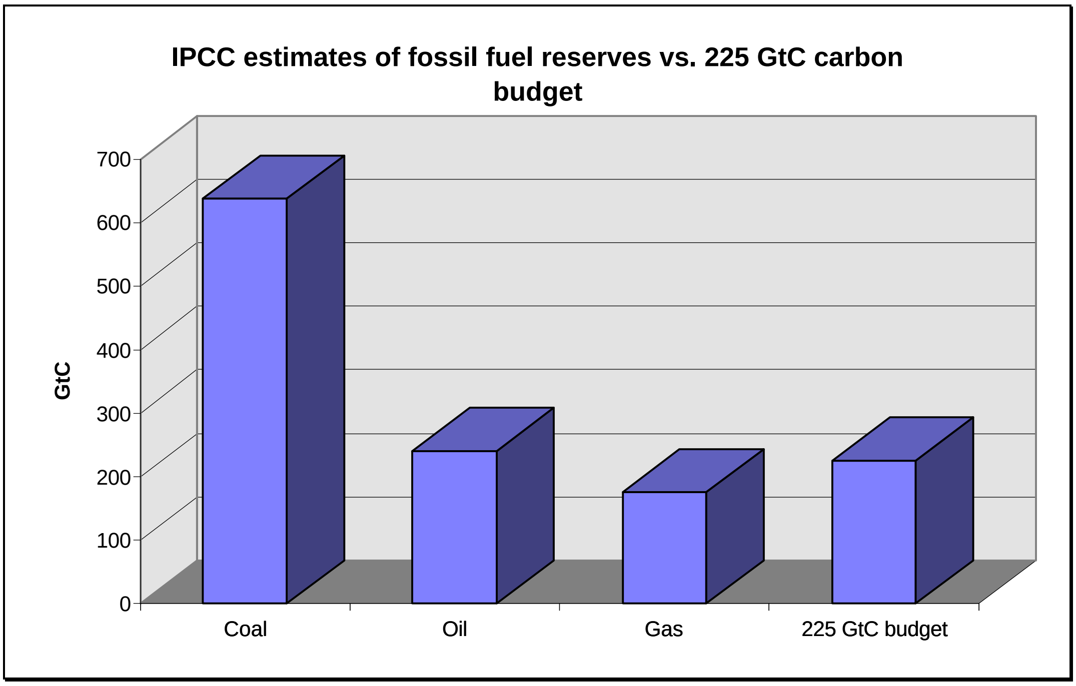
In broad terms, reserves of oil, gas and coal identified as “economically recoverable” total over 1,000 GtC. Economically recoverable “reserves” are expanding due to oil, coal and gas exploration and technical development. The “resource base” that could be ultimately brought into reserves is well over 4,000 GtC.

Estimates of economically recoverable reserves of fossil fuels range from 829 GtC to 1,501 GtC. Coal predominates in the reserve estimates, totalling 638-1,034 GtC. Conventional oil and gas reserves are much smaller by comparison, but still total 182-205 GtC. Unconventional reserves of oil and gas, which are likely to be economically recoverable, total a further 133-262 GtC.

At present, if one compares fossil fuel reserve estimates with future CO_2 emission scenarios in the absence of climate policies to the year 2100 then only at the upper end of these estimates are there ‘enough’ economically recoverable reserves of fossil fuels. This does not tell the full story however as there are over 4,000 GtC of fossil fuel resources, which with ongoing technical advances are likely, over time, to become economically recoverable.



It seems clear that if productivity gains in the fossil fuel industry continue at historical rates in the future, there is unlikely to be a shortage of fossil fuels - coal, oil or gas - over the next century. The analysis in this report shows that environmental considerations will have to limit the use of fossil fuels well before technical scarcity becomes a limiting factor.



The more investment that occurs in the exploration and technical development of resources (or of marginal reserves) the more of these will be converted to reserves (i.e. classified as economically recoverable). Investment in further exploration and development of oil, for example, will be conditioned by market expectations of the future demand. If markets expect increasing demand in the future then investments are likely to be made in "expanding" the reserves available. If, as is concluded in this report known, economically reserves of fossil fuels already exceed ecological limits then such investments by the market would be unnecessary and unwise.

One of the policy implications of this situation is that governments need to act urgently to curtail market expectations of increasing use of fossil fuels. Government encouragement of fossil fuel use through direct and indirect subsidies and the issuing of exploration licenses will only lead to more exploration and development of fossil fuel reserves. Failure by governments to act now to curtail market expectations of future fossil fuel demand can only impose higher political and economic costs on future generations' attempts to constrain the amounts of fossil fuels exploited in order to protect the climate system.

Ecological limits

The 1992 UN Framework Convention on Climate Change makes staying within ecological limits its central objective. Its ultimate objective is to stabilize greenhouse gas concentrations at a level that would prevent dangerous human interference with the climate. And further, it requires that this be done fast enough so that ecosystems can adapt naturally to climate change and food production is not threatened.

In 1990 a United Nations Advisory Group on Greenhouse Gases recommended global targets for the maximum rates and total amounts of temperature and sea-level rise as a consequence of the emissions of greenhouse gases. In other words, what level of change nature can tolerate, or "ecological limits". Temperature increases above 1.0^{o}C above pre-industrial levels could bring about rapid and unpredictable changes to ecosystems, leading to large damages. In addition, the rate of increase of global mean temperature was found to be a major determinant of damage. A rate of increase above 0.1^{o}C/decade could lead to major ecosystem damage as well as an increasing risk of climate instabilities.

A sea-level rise of 20 centimetres (cm) above 1990 levels was found to be a threshold of significant damage. Further, it was found that whilst a 50 cm sea-level rise limit above 1990 levels may possibly prevent the complete destruction of many island nations it would lead to large increases in the damage caused by storms.

Limits confirmed by recent scientific assessments

The findings of the Intergovernmental Panel on Climate Change (IPCC) and other scientific developments over the past seven years have tended to reinforce the validity of the global targets for climate change described by the UN Advisory Group on Greenhouse Gases.

An equivalent doubling of CO_2 over pre-industrial levels, which could occur between 2030 and 2040, is likely to cause dangerous climate changes.[1] The projected damages include significant loss of human life from the direct and indirect effects of climate change, a loss of biodiversity and, under highly optimistic assumptions, a further 60-350 million more people placed at risk of hunger, predominantly in developing countries. For a 50 cm increase in sea-level, which is projected over the next century, there could be a dramatic increase in the number of people at risk of flooding, loss of small island countries and significant impacts on rice production in Asia.

In the very long term (i.e. several centuries) an equivalent doubling of CO_2 is estimated to raise sea-level by over a metre and probably increase the global mean temperature by around 3.5^oC (using the estimate for climate sensitivity to greenhouse gases adopted in this report).

For increases in greenhouse gas concentrations lower than doubling large damages are still predicted. One study has shown that stabilizing CO_2 at 450 ppmv would lead to a temperature increase of 1.7^oC above pre-industrial levels and a sea-level rise of 29 cm by 2100. About one quarter of natural vegetation would be threatened and there is likely to be significant impacts on agricultural production in many regions.

Major changes in the earth's forests are projected for only a 1^oC increase in global mean temperature, leading to very large changes and the possible disappearance of entire forest types.

It has been shown that many of the projected impacts of future emissions are only avoidable if action is taken early. A "safe emissions corridor" analysis has shown that large emissions reductions are needed to avoid ecologically dangerous climate changes.

Uncertainties add to risk of climate instabilities and feedbacks

The rapidity of the current increase in greenhouse gas concentrations could lead to major climate instabilities. A permanent shut down of the ocean thermohaline circulation (of which the Gulf stream is a part) has been projected as possibility. A weakening (or shutdown) of the thermohaline circulation would lead to CO_2 concentrations increasing faster than expected and would lead to some very significant regional climate changes.

Projected climate change, if not controlled, could lead to some major feedbacks (i.e. amplifications of changes) which would make it difficult if not impossible to prevent dangerous climate change. Large amounts of carbon, relative to human emissions, may be released into the atmosphere from forests in response to changing climate. The response of the oceans could also have a big impact on future CO_2 concentrations, leading to atmospheric CO_2 concentration being higher than the IPCC has estimated.

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[1] Equivalent doubling of CO_2 means an increase of all the greenhouse gases - CO_2, methane, nitrous oxides - to a concentration equivalent to a doubling of CO_2 (about 560 ppmv). This would obviously mean a lower level of actual CO_2

Overall the likely effect of feedbacks from the terrestrial biosphere (e.g. forests) and oceans over the next century may be to amplify human induced climate change and reduce the amount of fossil carbon (and hence the carbon budget) that can be emitted for any given set of climate targets.

Climate sensitivity and precautionary climate policy

Since 1990 the IPCC has adopted a ‘best-estimate’ of the warming that would occur if CO_2 concentration is doubled and the climate allowed to stabilize (i.e. the climate sensitivity) of 2.5°C, with a range of 1.5-4.5°C. Scientific evidence is increasingly pointing towards a higher sensitivity than the IPCC ‘best-estimate’.

A climate sensitivity in the range of 3-4°C appears to better fit observations than 2.5°C when the combined effects of greenhouse gas concentration increases, sulphur aerosols and solar irradiance changes are taken into account. The most advanced climate models reviewed in the IPCC Second Assessment Report have climate sensitivities in the range 2.1-4.6°C with the median of the models being around 3.7°C.

A higher climate sensitivity magnifies the risk created by an increase in greenhouse gas concentrations and also reduces the ‘carbon budget’ for any given set of global climate targets.

From a precautionary policy perspective it would be prudent to base climate policy on a higher climate sensitivity than that adopted by the IPCC as its ‘best-estimate’. For this reason, throughout this work 3.5°C will be used as the central estimate for policy purposes.

Sea-level rise risk underestimated

Scientific uncertainties in relation to the explanation of sea-level rise observed over the past century have grown in the past decade rather than narrowed. The direction of these uncertainties is sufficient to raise serious concern that the risks of large, long term, irreversible sea-level rise as a consequence of the effects of greenhouse warming on the West Antarctic Ice Sheet, and to a lesser extent the Greenland Ice Sheet, have been underestimated.

Projected climate changes exceed ecological limits

Projected climate change over the next century will almost certainly breach the ecological limits described above if action is not taken to reduce emissions. In 1995 the Intergovernmental Panel on Climate Change (IPCC) found that global mean temperature has already risen 0.3-0.6°C above pre-industrial levels. Projected rates of increase of global temperature due to existing and forecast emissions are expected to be 0.2-0.3°C per decade over the next few decades. The rates of change over the next century are likely to exceed any in the last 10,000 years. In the absence of action to reduce emissions global temperature is likely to increase by about 2.4°C and sea-level by approximately 50 cm above 1990 levels by 2100, based on IPCC best-estimates of climate science. With the climate sensitivity adopted in this work the warming is likely to be more than 3.0 °C above the pre-industrial global mean temperature and sea-level rise 55-60 cm above 1990 levels.

These projected changes are well above the levels identified as likely to lead to significant ecosystem damage and are likely to lead to damages to food production in the most vulnerable parts of the world. There is also likely to be a significant loss of human life from the indirect health effects of climate change.

Global ecological targets

Given this situation Greenpeace believes that the overall goals for global climate protection should be to:

- Limit the long term committed increase of temperature to less than 1°C above pre-industrial global average temperature.

- Bring the rate of change to below 0.1°C per decade as fast as possible - i.e. within a few decades.

- Limit the long term sea-level rise to less than 20 cm above 1990 levels

- Limit the rate of sea-level rise to below a maximum of 20mm/decade

Greenpeace recognises that any attempt to quantify future climate change impacts is fraught with uncertainties. However, this cannot be used to justify inaction, but instead means that the precautionary principle must be urgently applied. The extent of human interference with the climate system means that potential catastrophic changes beyond those considered here are always possible and will become more likely the longer action is delayed.

The carbon budget

A ‘carbon budget’ - i.e. the total emissions to the atmosphere of carbon dioxide (taking into account the mix of greenhouse gases of which CO_2 is most important) - can be calculated on the basis of the ecological targets. What actually happens to the climate can only be significantly affected by changes (i.e. major reductions) in emissions of greenhouse gases, both in total (for example taking “long term” as being up to 2100) and in terms of the “pathway” or trajectory that emissions take, e.g. how much is emitted sooner, or later. Calculating the ‘carbon budget’ requires assumptions to be made about several factors including how sensitive the climate is to human interference, the role of other greenhouse gases and what level of damage is acceptable.

Taking the climate sensitivity to be 3.5°C, with a limit of a 1°C increase in global mean surface temperature above pre-industrial levels and assuming that other greenhouse gases contribute about one quarter of the effect of CO_2 alone in the long term, the ‘carbon budget’ over the next century can be estimated in terms of billions of tonnes of carbon (GtC). With these assumptions, the ‘carbon budget’ is:

- 145 GtC - With no action to stop current trends of deforestation (as forests release carbon when destroyed), with 80 GtC emitted from this source over the next century.

- 225 GtC - With major action to halt deforestation, stabilising the role of forests at current levels, which would involve a significant global reafforestation programme next century.

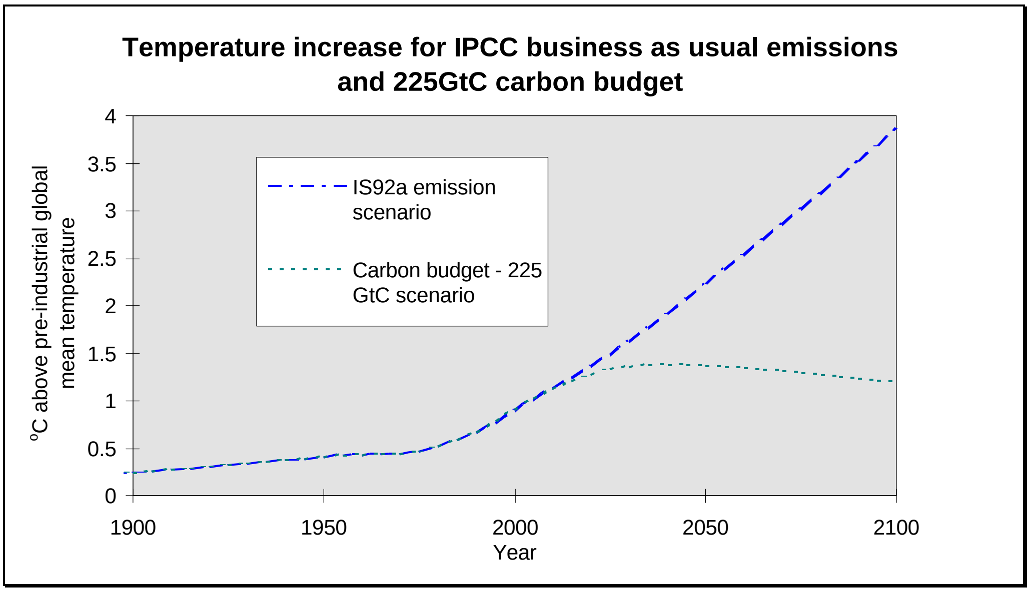
- 265 GtC - With major action to halt deforestation and a major global afforestation programme to sequester (take up) an extra 40 GtC.

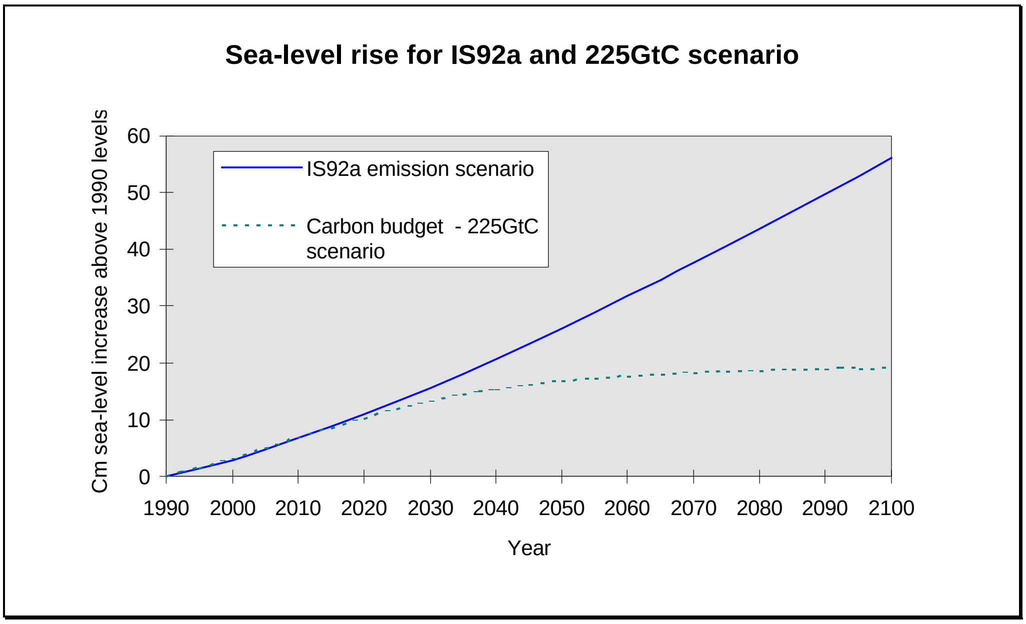
There is an uncertainty of around 50% associated with these budgets deriving from uncertainties in the climate sensitivity, the role of other greenhouse gases, in the carbon cycle models and other factors.

It should be noted that limiting the long term temperature rise may mean getting back below a 1.0°C increase above pre-industrial levels as it may not be possible to avoid a rise of 1.0°C. Because of the lag between temperature rise in the air and the thermal expansion of the sea, it is still possible to avoid breaking the limit for sea-level rise if fast enough action is taken.

The central estimate of the ‘carbon budget’ of 225 GtC is only about a quarter of existing reserves and is a very small fraction (5%) of the estimated resource base of oil, coal and gas.

The climate effects of this budget, based on the climate sensitivity adopted in this report, are such that the global mean temperature is calculated to peak at 1.4°C above pre-industrial levels and then decline reaching around an increase of 1.2°C by 2100. In the absence of climatic surprises the temperature would continue to decline slowly and fall below the long term limit of 1°C in the 22nd century. Sea-level would rise by about 20 cm by 2100 (based on IPCC best estimates of sea-level rise parameters).





See main body of report for description of assumptions. The climate sensitivity used throughout this report is 3.5°C.

Sensitivity of the carbon budget to assumptions

Greenpeace advocates a precautionary approach to environmental protection. However, it is worth exploring the effect on the ‘carbon budget’ of different assumptions about the sensitivity of the climate system, and different views on the limits that should be set to climate change.

The European Union has proposed that global temperatures should not be allowed to exceed a 2°C increase above pre-industrial levels. With a 3.5°C climate sensitivity and with the deforestation assumption used in the central estimate this would require that total fossil fuel emissions be below 410 GtC over the next century. However, a 2 °C warming was identified by the Advisory Group on Greenhouse gases as an upper limit beyond which the risks of grave damage to ecosystems increases rapidly. Yet the carbon budget for this limit is less than 40% of known economically recoverable reserves of fossil fuels - oil, coal and gas is less than 10% of the resource base.

Avoiding an equivalent doubling of CO_2 concentration, with the same assumption as above would require the total fossil fuel emissions over the next century to be less than 720 GtC. This is about 70% of economically recoverable reserves of oil, coal and gas and less than one fifth of the total fossil fuel resource base. Further, it is only one half of what the world is likely to burn in the absence of action on climate change in the next century. Allowing a doubling of CO_2 would lead to major damages including significant loss of human life from the indirect and direct health effects of rapid climate change, increasing hunger and famine in several parts of the world and major damage to ecosystems. Furthermore, economic losses from climate impacts would increase from an increase in extreme weather events such as floods, droughts and forest fires.

If all the currently estimated fossil fuel reserves were burnt over the next century this could lead to a long term increase in global mean temperature of over 5°C above pre-industrial levels when the effects of other greenhouse gases are taken into account[2].

The central IPCC business as usual scenario for fossil fuel use over the next century projects the release of approximately 1,415 GtC into the atmosphere by 2100. This would lead to a global average increase of around 2.5-2.9°C above pre-industrial temperatures by 2100 (with 2.5 °C climate sensitivity). The longer term (equilibrium) increase in global mean temperature corresponding to the greenhouse gas concentrations in 2100 resulting from this scenario, would be over 4 °C or 5.6 °C with a 3.5°C climate sensitivity.

Even if more 'optimistic' scenarios are used, the logic of an immediate start to a fossil fuel phase out remains. For example, to keep to the 1.0°C limit, a 225 GtC budget results from assuming a 3.5°C climate sensitivity. A 295 GtC budget results from assuming a 2.5°C climate sensitivity. This is still far less than fossil fuel reserves. The EU's global objective of keeping the global average increase in temperature below 2.0°C above pre-industrial levels implies a 'carbon budget' of 410 GtC with a 3.5°C climate sensitivity and 585 GtC with a 2.5°C climate sensitivity.

The carbon logic - fossil fuel phase out

The estimated carbon budgets are vastly exceeded by known fossil fuel reserves, and are even exceeded by known oil and gas reserves. A phase out of fossil fuels therefore logically follows.

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[2] Assuming the climate sensitivity is 3.5°C, the radiative forcing of other greenhouse gases adds 23% to that of CO_2 alone and atmospheric concentrations of greenhouse gases remain constant at the level reached when this volume of carbon is emitted to the atmosphere. Setting the climate sensitivity to 2.5°C would reduce the long term warming to around 3.6°C with the same assumptions.

An urgent start is required for several reasons:

- To meet ecological targets for rates of sea-level and temperature rise.

- At current rates of fossil fuel use a 225 GtC budget will be exceeded in about 30 years globally (2025).

- At historic rates of increase in fossil fuel emissions (about 2%/yr.) a 225 GtC budget would be exceeded by around 2020.

- Energy planning and infrastructure is long term and major change is required (switching to renewable energy and energy efficient technologies).

- Industrialised countries will be required to give a lead to other countries and begin a phase out sooner.

- Climate change may proceed faster as a result of "surprise" positive feedbacks not included in models. The longer action is delayed, the more likely climate catastrophes are to occur. these could include, for example, a shift in the ocean currents that presently warm Europe; a collapse of part of the Antarctic ice sheet causing a massive rise in sea-levels; a shift in the monsoon having major impacts on agriculture in Asia. Such catastrophes, once triggered, are effectively irreversible.

Some of the key implications for policy flowing from the limited 'carbon budget' are:

- Coal use needs to be phased out as rapidly as possible as it has the highest carbon intensity of the conventional fossil fuels and the largest reserves. Only a small fraction of the economically recoverable reserves can ever be used.

- There should be no further exploration and/or technical development of unconventional oil and gas reserves. Estimated economically recoverable volumes of gas and oil in this category are sufficient alone to breach the 'carbon budget'.

- There will need to be immediate and significant constraints placed on the technical development and exploration of known oil and gas reserves. Volumes in these reserves, particularly when taking into account the process of reserve appreciation following technical developments, are sufficient already to breach the 'carbon budget'.

This is the carbon logic. The inescapable conclusion, and Greenpeace's immediate call for action is for national governments in industrialized countries to:

- Adopt legally binding obligations to reduce their CO_2 emissions by 20% on 1990 levels by 2005 at the Third Conference of the parties of the Framework Convention on Climate Change in Kyoto in December 1997.

- Adopt national policies to substantially reduce emissions of CO_2 and other greenhouse gases.

- Stop plans to allow the expansion of exploration for oil and gas reserves.

- Stop all technical and other developments that would facilitate the exploitation of unconventional oil and gas reserves.

- Begin the phase out of coal power stations and coal mining.

Further exploration and development of fossil fuel resources by industrial nations should be halted immediately, as it makes the problem worse and more difficult to solve and is a waste of money that should be invested in clean energy.

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Bill Hare, Amsterdam
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Fossil Fuels and Climate Protection - The Carbon Logic

1. Introduction

The UN Framework Convention on Climate Change (UNFCCC), signed at Rio in 1992, makes staying within ecological limits its ultimate objective. This treaty requires that the global community takes action to prevent dangerous human interference with the climate.

Preventing dangerous climate change will involve limiting both the rate and magnitude of climate change over the next century to levels that natural and human systems can tolerate without significant damage. The focus of this report is to calculate the cumulative Carbon Dioxide (CO_2) emissions to the year 2100 which would be consistent with limiting the magnitude of global warming to within defined ecological limits. This calculation can be seen as a global 'carbon budget', which if exceeded would most likely mean that ecological limits would be breached.

Scientific knowledge of climate change has improved considerably since the First Assessment Report of the Intergovernmental Panel On Climate Change (IPCC) in 1990. Most notably the 1995 IPCC Second Assessment Science Report[3] has taken the first tentative steps towards finding that human induced global warming can now be detected:

> *"the balance of evidence suggests a discernible human influence on global climate".*

In describing this conclusion the 1995 IPCC Science report[4] cites three key pieces of evidence:

- The 20th Century mean temperature is "at least as high" as the mean temperature in any other century since 1400 A.D.
- Statistical assessments of the significance of the 0.3-0.6^{o}C global warming since 1860 have found that "the observed warming trend is unlikely to be entirely natural in origin".
- Comparison of the observed pattern of climate changes with the expected pattern of effects from the combined influence of greenhouse gases and sulphate aerosols with the most advanced computer models of the climate. Pattern-based studies are those in which the modelled climate response to combined forcing by greenhouse gases and anthropogenic sulphate aerosols is compared with observed geological, seasonal and vertical patterns of atmospheric temperature change. These studies show that observed changes in

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[3] IPCC SAR WGI: J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (ed.'s) (1996), *Climate Change 1995 - The Science of Climate Change.* Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

[4] IPCC SAR WGI Summary for Policy Makers, *op.cit.* p. 4.

> global temperature increasing match the expected response of the combined affects of greenhouse gases and anthropogenic sulphate aerosols. As a consequence the IPCC found that the "probability is very low" that the correlation between the expected and observed patterns of temperature change "could occur by chance due to natural variability"

As the science of human induced climate change has become clearer, attention has focused more intensively on the principal causes.

Fossil fuel production, distribution and combustion is recognised as the major human source of greenhouse gas emissions. Whilst the principle greenhouse gas from fossil fuel use is carbon dioxide (CO_2), emissions from this source also include methane (i.e. coal mining, natural gas production) and nitrous oxide (i.e. catalytic converters in cars). The relative importance of CO_2 from fossil fuel combustion is expected to grow, in the absence of policy intervention, over the next century. In 1990 fossil fuels accounted for around 58% of global greenhouse gas emissions (on a global warming potential weighted basis). Coal and oil were each responsible for 23%, gas for 12%, agriculture 18%, deforestation 17%, industrial halocarbons etc. 4% and waste disposal 3% (Table 1).

In its Second Assessment Report the IPCC emphasized the growing significance of CO_2:

> *"The importance of the contribution of CO_2 to climate forcing, relative to that of the other greenhouse gases, increases with time in all of the IS92 emission scenarios*[5] *(a to f). For example, in the IS92a scenario, the CO_2 contribution increases from the present 60% to about 75% by the year 2100. During the same period, methane and nitrous oxide forcings increase in absolute terms by a factor that ranges between two and three."*[6]

Two scientific issues of direct policy relevance to the question of stabilization of atmospheric CO_2 concentrations are the scale of emission reductions required to achieve this and the inertia of the climate system itself.

Stabilizing atmospheric CO_2 concentration requires large emission reductions owing to the long time required for the oceans and the biosphere to take up CO_2 from the atmosphere[7]. Stabilization of emissions is not sufficient as this would lead to CO_2 concentration continuing to increase for several centuries, approaching 500 parts per million by volume (ppmv) by 2100 and rising thereafter. Immediate stabilization of CO_2 concentration would require an immediate reduction of 50-70% in emissions and continuing further reductions[8].

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[5] The term IS92 refers to the greenhouse gas emissions scenarios developed by the IPCC in 1992. The scenarios are categorized a,b,.,f with IS92a being considered informally as the median scenario.

[6] IPCC Synthesis Report, Par. 4.16 (IPCC Second Assessment Synthesis of Scientific-Technical Information Relevant to Interpreting Article 2 of the UN Framework Convention on Climate Change, IPCC, Geneva , Switzerland)

[7] IPCC WGI SAR Chapter 1 *op.cit*. See pp. 85-86 for a discussion of the take up of CO_2 by the ocean and biosphere.

[8] IPCC Synthesis Report, par. 4.6.

Table 1 Contribution to 1990 Greenhouse Gas Emissions by Source Category

Total Fossil fuel combustion: electricity, transport, industrial energy and fuel use of which each fuel contributes:	58%
Coal	23%
Oil	23%
Gas	12%
Industrial sources: cement production, adipic acid production (exc. PFCs, HFCs, CFCs and HCFCs)	4%
Agriculture: enteric fermentation, rice paddies. animal waste, cattle and feedlots, cultivated Soils	18%
Deforestation and land use changes	17%
Waste: Domestic and industrial waste, sewage, landfill	3%
	100%

This table shows the estimated source of greenhouse gas emissions on a 100 year global warming potential (GWP) weighted basis. Global warming potential is defined as the cumulative radiative forcing over a fixed period of time caused by a unit mass of a greenhouse gas relative to a reference gas, usually CO_2. GWP is hence an index used to compare the relative effects of mass units greenhouse gas emissions. Methane (CH_4) has a 100 year GWP of 21 and Nitrous Oxide (N_20) having a GWP of 310. The HFCs, PFCs etc. have very high GWPs. Emissions are from data reported by the IPCC in 1994[9] and GWPs are from the IPCC in 1995[10].

It is known that the climate system takes a long time to respond to the stabilization of greenhouse gas concentrations and that sea-level would continue to rise for many centuries after atmospheric stabilization. This led the IPCC to warn policy makers that:

> *"The long time scales involved in the climate system (e.g., the long residence time of greenhouse gases in the atmosphere) and in the time for replacement of infrastructure, and the lag by many decades to centuries between stabilization of concentrations and stabilization of temperature and mean sea level, indicate the importance for timely decision-making."*[11]

In this urgent context the international climate policy debate is now entering a crucial stage.

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[9] IPCC 1994. J.T. Houghton, L.G. Meira Filho, J. Bruce, Hoesung Lee, B.A. Calander, E. Haites, N. Harris and K. Maskell (eds.); Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios. Reports of Working Groups I and III of the Intergovernmental Panel on Climate Change, forming part of the IPCC Special Report to the First Session of the Conference of the Parties to the UN Framework Convention on Climate Change, published for the Intergovernmental Panel on Climate Change, Cambridge, Cambridge University Press, 1995

[10] IPCC WGI SAR Chapter 1, Table 2.9: D. Schimel, D. Alves, I. Enting, M. Heimann, F.Joos, D. Raynaud, T. Wigley, M. Prather, R. Derwent, D. Erhalt, P. Fraser, E. Sanhueza, X. Zhou, P. Jonas, R. Charlson, H. Rodhe, S.Sadasivan, K.P Shine. Y. Fouquart, V.Ramaswamy, S. Solomon, J.Srinivasan, D. Albritton, R. Derwent, I. Isaksen, M.Lal, D. Wuebbles (1996). Radiative forcing of climate change. Chapter 2, pp. 65-131 of IPCC SAR WGI

[11] IPCC Synthesis Report, par. 1.1.

It is apparent that most of the wealthy OECD[12] countries are failing the meet their legally soft obligation in the United Nations Framework Convention on Climate Change to "aim" to bring their greenhouse gas emissions back to 1990 levels by the year 2000. As a consequence of the failure of the Climate Convention to motivate real action by the industrialized countries, international attention is now focused on negotiating legally binding emission reduction obligations. Two and a half years of intense international negotiations are scheduled to conclude at a Ministerial level segment of the Third Conference of the Parties to the Climate Convention (COP-3) in Kyoto, Japan 1-10 December, with the adoption of a set legally binding obligations for industrialized countries to reduce their emissions by target dates in 2005 and 2010.

By mid 1997 a range of emission reduction targets were on the table for negotiation in Kyoto. These include the European Union's proposed greenhouse gas reduction target of at least 7.5% by 2005 and 15% by 2010, from 1990 levels, for industrialized countries and the Alliance of Small Island States 1994 proposal for a target for industrialized countries of a CO_2 reduction of 20% by 2005 relative to 1990 levels. Both the USA and Japan see these targets as too aggressive and appear unwilling to approach the EU proposal.

Within the international negotiations on climate change there has been much discussion over short term emission targets. There has however been very little discussion over the overall scale emissions that must be made in the next century and still avoid dangerous levels of climate change. Such a discussion is vital for informing the negotiations over short term emission targets which must be agreed in Kyoto. It is in this context that a 'carbon budget' linked to ecological objectives is a very useful concept for climate policy purposes. Minimizing the rate of climate change is a fundamental aspect of climate policy and this constraint plays a major role in defining the time path of emission reductions, and hence on the rate at which a 'carbon budget' is consumed.

The 'carbon budget' concept has the capacity to shed significant light on the implications of current fossil fuel policy for long term climate policy objectives. It can also provide some novel insight into the debate over whether or not the world is facing an oil shortage, by comparing an allowed 'carbon budget' against estimates of available oil. In the international policy context the idea of 'carbon budget' makes clear the choices that developed and developing countries face in the current round of climate negotiations. The more fossil fuel that developed countries use now (i.e. the slower they reduce emissions) the less would be left over for developing countries.

As will be seen, there is a strong relationship between cumulative carbon emissions and climate change and the juxtaposition of this with the need to prevent dangerous interference with the climate system leads to a certain inexorable logic - the carbon logic. The carbon logic shows that we simply cannot burn more than a small fraction of fossil fuel resources.

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[12] Mexico and South Korea, although part of the OECD are not in Annex I of the Climate Convention and hence do not have binding emission obligations under Article 4.2(a) and (b) of that convention.

2. Carbon Dioxide Emissions and Fossil Fuel Resources

2.1 Historic

The atmospheric load of CO_2 is now over 765 billion tonnes of carbon (GtC)[13], an increase of around 175 GtC over pre-industrial levels. By 1997 CO_2 concentration was over 360 ppmv, about 30% above the pre-industrial level of 280 ppmv which is believed to have prevailed for the past several thousand years, and is growing at around 1.5 ppmv/yr.

Around half of the approximately 450 GtC of CO_2 emitted up until 1995 over the past two centuries remains in the atmosphere.

Coal dominates historic fossil CO_2 emissions, comprising 60% of the estimated 218 GtC of fossil carbon emitted from 1860-1990 (Table 2 and Figure 2) Oil comprises 28% and gas 12% of this volume of carbon. Deforestation is estimated to have contributed a total of around 150 GtC, from pre-industrial times until 1990. Annually industrial CO_2 emissions have been significantly higher than deforestation emissions since the early decades of this century. Cumulative emissions from fossil fuel use exceed those from deforestation now by a significant and growing margin (Figure 3).

Whilst historically coal has dominated emissions from fossil fuel use, from the late 1960's to mid 1980's oil was the dominant global source of CO_2 emissions from fossil fuels. Since the mid 1980s coal and oil combustion have emitted comparable amounts of CO_2 (see Figure 4). For the decade 1983-1992, oil and coal emitted about the same volume of CO_2 (Table 2) and by the mid 1990s emissions of CO_2 from oil were slightly higher than from coal. Gas contributed around 17% to fossil CO_2 emissions in the 1990's.

Table 2 CO_2 Emissions from Fossil Fuels 1860-1992

	Consumption 1860-1990 GtC	%	Consumption 1990	%	Consumption 1983-1992	%
Gas	26	11.9%	1.1	19.3%	9.7	17.3%
Oil	61	28.0%	2.3	40.4%	23.4	41.9%
Coal	131	60.1%	2.3	40.4%	22.9	40.8%
Total	**218**	**100.0%**	**5.7**	**100.0%**	**56.0**	**100.0%**

Source: IPCC SAR WGII Tables B.3 and B.4 in Sect B.3.3.1 and Gregg Marland, Oak Ridge National Laboratory.

Of the fossil fuels coal is the most carbon intensive[14] with natural gas having the lowest carbon intensity (Table 3).

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[13] By convention CO_2 is reported here in tonnes of carbon: 3. 7 tonnes of CO_2 contains 1 tonne of carbon. The mass units used here are gigatonnes of carbon (GtC). A Gigatonne = 10^9 tonne or 1 billion tonnes.

[14] Carbon intensity refers to the amount of CO_2 emitted per unit of primary energy.

Table 3 Carbon intensity of fossil fuels

Fuel Source	MtC/EJ	Ratio to Natural Gas
Natural Gas	14.4	100%
Crude Oil	19.9	138%
Coal (Bituminous)	25.4	177%

The emission factors here are gross emissions only and do not include emissions from production processes[15]. MtC refers to million tonnes of carbon and EJ refers to Exajoules of primary energy, which is 10^{18} joules. Total commercial primary energy use globally in 1991 was around 330 EJ.

2.2 Projected Emissions

In 1992 the IPCC generated six scenarios (IS92a-f) of future greenhouse gas and sulphur emissions, in the absence of climate change policies over the period 1990-2100[16]. All of these scenarios show large cumulative CO_2 emissions over this period. Table 4 summarises the assumptions made in these scenarios, as well as their overall carbon emissions.

The mid-range IPCC scenario (IS92a) projects total emissions of 1,500 GtC over the next century, from 1990 to 2100. The lowest IPCC scenarios would emit around 770-980 of carbon and the highest around 2,190 GtC with deforestation is projected to result in emissions of in the range of 30-95 GtC. Scenario IS92c is the lowest IPCC scenario projecting around 680 GtC of fossil CO_2 emissions, however the population projection for 2100 used in this scenario (and IS92d) is only 6.4 billion. This factor, along with a very low assumed economic growth rate, led the 1994 IPCC WGIII report on emission scenarios to state "users of the IPCC scenarios are cautioned, however, that the lowest (IS92c) has emission levels and some input assumptions that are more characteristic of a policy, rather than a reference scenario."[17] Because of their low population assumptions the two lowest IPCC scenarios are not considered here to be realistic. In the absence of climate policy action fossil fuel emissions over the next century are likely to be close to 1,500 GtC.

The full range of the IS92 scenarios shows that cumulative emissions over the next century are likely to add some 4-10 times more fossil carbon to the atmosphere than has been added since the industrial era began. Annual CO_2 emissions in the IS92 scenarios grow considerably over the period to 2100 (see Figure 1), with the exception of the IS92c scenario. In the IS92a case annual emissions are projected to be nearly 3 times 1990 levels in 2100.

One of the features shared by all of the IPCC scenarios is that oil and gas are in limited supply and coal becomes the predominant fossil fuel over the longer term (Table 5). It is assumed that conventional oil and gas resources will be used up over the next

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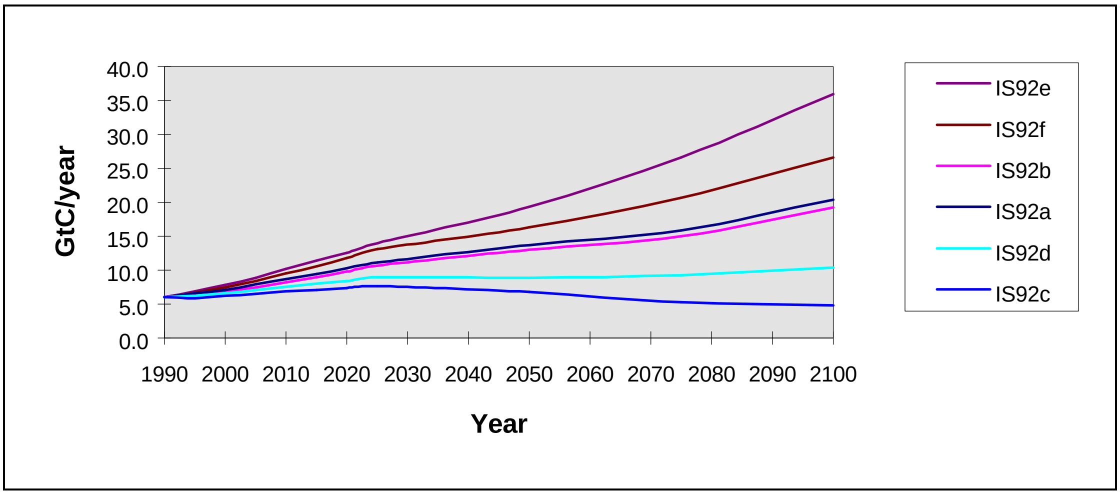
[15] Lazarus, M (1993), Towards a Fossil Free Energy Future: A Technical Analysis for Greenpeace International, Stockholm Environment Institute, Boston Center, Table 4.6, p. 37.

[16] Legett, J., W.J. Pepper, R.J. Swart (1992) Emission Scenarios for the IPCC: An Update Chapter A3 in Houghton, J.T., B.A. Callander and S.K. Varney (ed.'s), *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, Published for the Intergovernmental Panel on Climate Change, Cambridge University Press, 1992.

[17] IPCC 1994 op.cit. p. 258.

century, requiring a shift to a coal intensive energy system. The relationship of the IPCC scenarios to estimates of fossil fuel resources will be examined in the next section.

Figure 1 IPCC IS92 fossil fuel CO_2 emission scenarios



Note that the IS92c scenario (the lowest) has both very low population estimates and low economic growth assumptions which mean that it is unlikely to characterise a "no climate policy" scenario. IS92d also has very low population assumptions.

Despite this long term trend towards coal in the IPCC scenarios, estimates of which fuel will dominate emissions over the next few decades vary. In the short to mid-term the International Energy Agency projects that CO_2 emissions from oil will accelerate faster than those from coal combustion to 2010 (Table 6). On the other hand both the IPCC scenarios and the World Energy Council project that, in the absence of policy action, coal use will accelerate faster, particularly in the longer term. In the IPCC business as usual scenario by 2050 coal emits over 60% of CO_2 emissions, with oil having a 20% share (Table 7).

Table 4 IPCC 1992 Emissions Scenarios: Assumptions and cumulative carbon emissions[18].

Scenario	*Population*	*Economic Growth*	*Energy Supplies*	*Cumulative emissions 1990-2100 GtC*
IS92a	World Bank 1991	1990-2025: 2.9%	12,000 EJ conventional oil	1,500
	11.3 billion by 2100	1990-2100: 2.3%	13,000 EJ natural gas	
			Solar costs fall to $0.075/kWh	
			191 EJ of biofuels available at $70/barrel*	
IS92b	as above	as above	as above	1430
IS92c	UN Medium-Low Case	1990-2025: 2.0%	8,000 EJ conventional oil	770
	6.4 billion by 2100	1990-2100: 1.2%	7,300 EJ natural gas	
			Nuclear costs decline by 0.4% annually	
IS92d	UN Medium-Low Case	1990-2025: 2.7%	Oil and gas same as IS92c	980
	6.4 billion by 2100	1990-2100: 2.0%	Solar costs fall to $0.065/kWh	
			272 EJ of biofuels available at $50/barrel	
IS92e	World Bank 1991	1990-2025: 3.5%	18,400 EJ conventional oil	2,190
	11.3 billion by 2100	1990-2100: 3.0%	Gas same as IS92a,b	
			Phase out nuclear by 2075	
IS92f	UN Medium-High Case	1990-2025: 2.9%	Oil and gas same as IS92e	1,830
	17.6 billion by 2100	1990-2100: 2.3%	Solar costs fall to $0.083/kWh	
			Nuclear costs increase to $0.09/kWh	

This table shows in summary form the assumptions behind the IPCC 1992 (IS92) scenarios. Note that both IS92c and d have very low population estimates for 2100. Some elements of the IS92 scenarios relating to emissions of halocarbons and other greenhouse gases were modified in the IPCC Second Assessment Report, however these changes do not affect the fossil fuel emissions.

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[18] IPCC SAR WGII Summary for Policymakers, p. 3 in R. T Watson, M. C. Zinyowera, R. H. Moss, D. J. Dokken (ed.'s) (1996), *Climate Change 1995 - Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis,* Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Table 5 IPCC IS92 Scenarios: Cumulative carbon emissions 1990-2100

Scenario	Coal GtC	Oil GtC	Gas GtC	Total Fossil carbon GtC	Deforestation GtC	Total carbon GtC
IS92a	989	239	187	1,415	85	1,500
IS92b	919	239	187	1,345	85	1,430
IS92c	425	159	105	690	80	770
IS92d	685	159	105	950	30	980
IS92e	1,551	367	187	2,105	85	2,190
IS92f	1,181	367	187	1,735	95	1,830

This table shows the cumulative carbon emissions over the period to 2100 for the six IPCC 1992 scenarios as a total and by source. The carbon emissions from oil and gas have been estimated using the emission factors in Table 3 and coal is a residual of the total for the period.

Table 6 International Energy Agency (IEA) Projections of CO_2 emissions by source

	IEA 1993 GtC/yr.		IEA 2000 GtC/yr.	%	IEA 2010 GtC/yr.	%
Gas	1.0	16.6%	1.2	17.3%	1.7	18.7%
Oil	2.7	44.0%	3.2	44.3%	3.9	43.3%
Coal	2.4	39.4%	2.7	38.4%	3.4	38.0%
Total	6.2	100.0%	7.1	100.0%	9.0	100.0%

The IEA projections[19] show an anticipated predominance of oil in the first decade of next century. This is in contrast to the IPCC scenarios which generally show coal being the major source of CO_2 from early in the next century.

Table 7 IPCC IS92a Scenario: CO_2 emissions by source

	2010 GtC/yr.	%	2020 GtC/yr.	%	2050 GtC/yr.	%
Gas	1.9	22.9%	2.2	22.7%	2.2	16.7%
Oil	2.8	33.7%	3	30.9%	2.7	20.5%
Coal	3.6	43.4%	4.5	46.4%	8.3	62.9%
Total	8.3	100.0%	9.7	100.0%	13.2	100.0%

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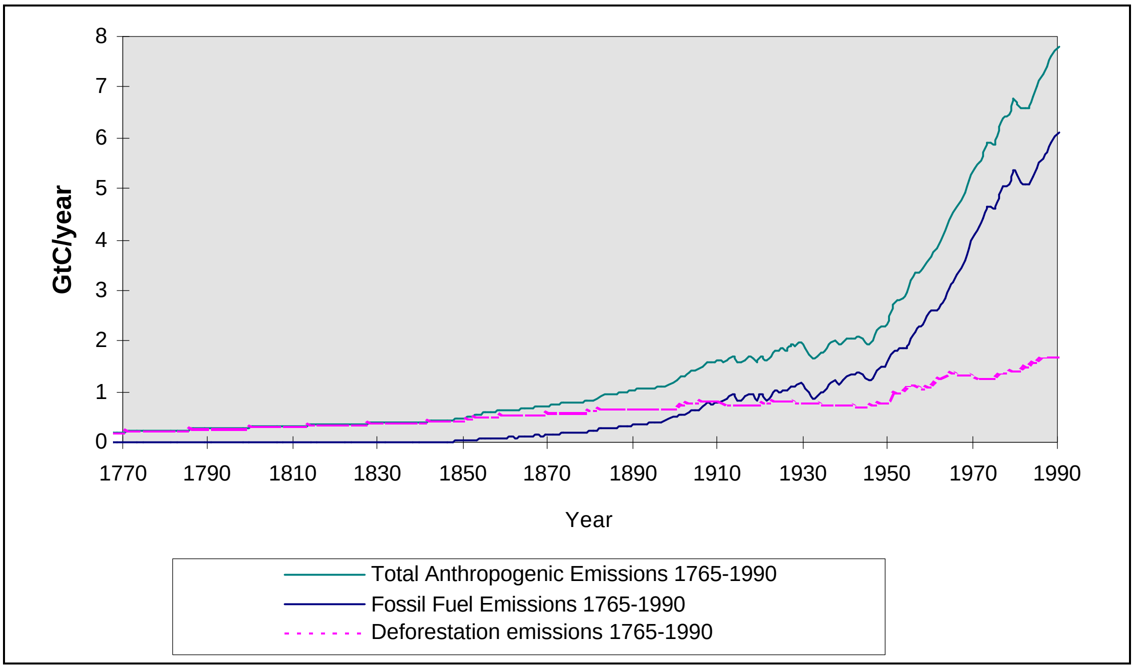
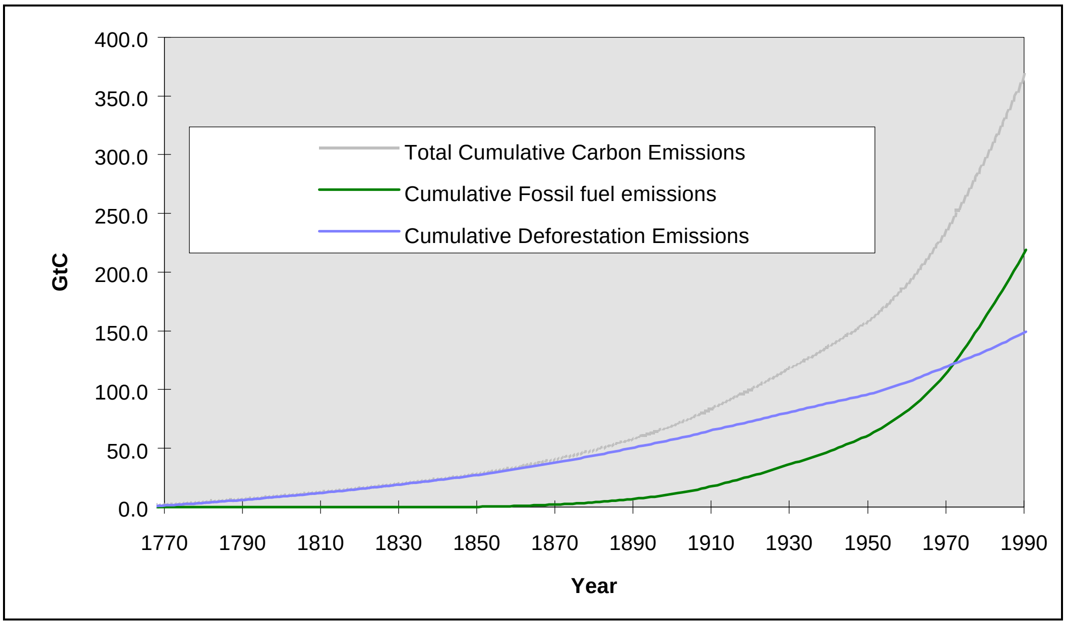
[19] IEA (1996), World Energy Outlook 1996, International Energy Agency, Paris

Figure 2 Carbon Emissions by Source 1765-1990



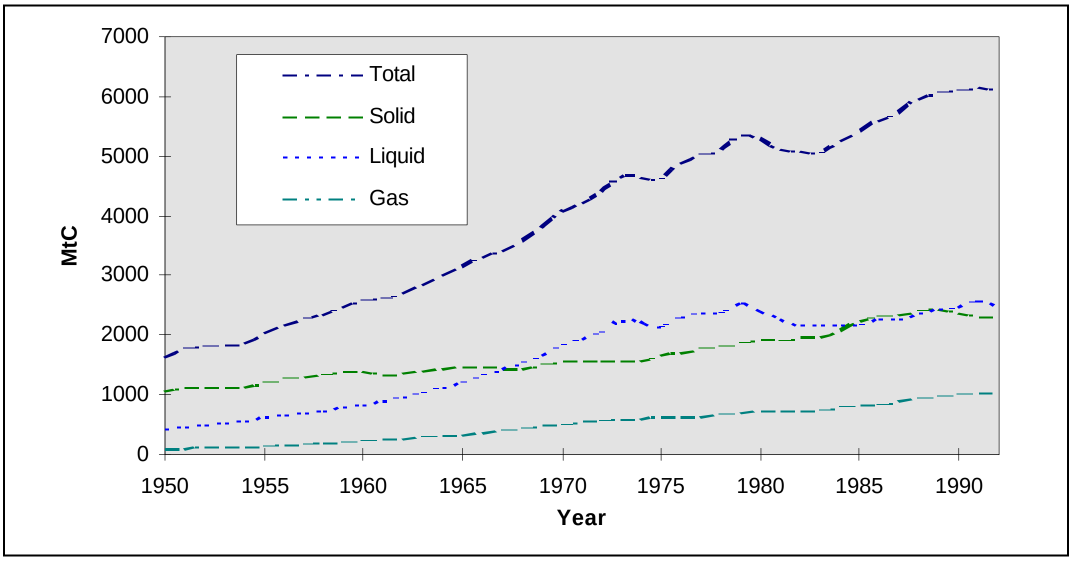
This figure shows the annual deforestation and fossil carbon emissions estimated from pre-industrial times to the present. Annual fossil fuel emissions significantly exceeded deforestation emissions from the 1920's. Source: CSIRO.

Figure 3 Cumulative Carbon Emissions by Source



This figure shows the cumulative contribution to emissions since pre-industrial times. Cumulative fossil fuel emissions overtook deforestation emissions around 1970 although annual fossil fuel emissions exceeded deforestation emissions from 1910 onwards. The fact that cumulative emissions from fossil fuel emissions took so long to exceed deforestation is because of the long period of steady deforestation starting in the 18th century and extending into the 20th

Figure 4 Fossil Fuel Emissions by Source 1950-1992



This figure shows the relative contribution of the different sources of fossil fuels in the period 1950-1992. Oil became the dominant fossil fuel source of CO_2 from the late 1960's onwards. Coal use however rose steadily across this period and once again rivalled oil in the late 1980's and early 1990's. Source: Gregg Marland, Oak Ridge National Laboratory.

2.3 Fossil Fuel Reserves and Resources

The question that naturally arises, given the large volumes of fossil fuels projected to be burnt over the next century, is whether or not sufficient resources exist in an economically recoverable state. Some have argued that oil and gas are scarce resources and hence their contribution to future climate change is necessarily limited. Before reviewing the estimates for fossil fuel resources it is useful to briefly review some terms:

> Fossil fuel reserves are those defined as economically recoverable with known technology and within a price range close to the present or reasonably foreseeable.
>
> Resources are theoretical maximum potentials based on geological information, including reserves defined above.

The economically recoverable reserves are those most likely to be burnt in the short to medium term. Table 8 shows recent IPCC, World Energy Council (WEC), International Institute for Applied Systems Analysis (IIASA) estimates of reserves and resources for the various fossil fuels. The distinction between conventional and unconventional fuels is quite blurred in the literature and here we follow the approach of the IPCC and WEC. Unconventional gas includes coal bed methane, ultradeep gas reserves and gas in aquifers. Gas hydrates, principally as methane clathrates, are vast[20] and are not included in this analysis. Unconventional oil includes oil shales, tar sands and heavy crude oil. Such oils are much more carbon intensive than conventional oils.

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[20] Estimates range up to 18,000 GtC.

The overall estimates of reserves of fossil fuels presented in Table 8 range from 829 GtC to 1,501 GtC. If one compares fossil fuel reserve estimates with the IPCC emissions scenarios to 2100, then only at the upper end are there enough fossil fuels to supply the mid-range (IS92a) scenario. The volume of carbon in the WEC reserve estimates, for example, are only 65% of the cumulative emissions projected from IS92a. However, as will be seen below such a comparison does not take account of ongoing technical advances which continue to "convert" fossil fuel resources to economically recoverable reserves.

Coal predominates in the reserve estimates, totalling 638-1,034 GtC. Conventional oil and gas reserves are much smaller by comparison, but still total 182-205 GtC. Unconventional reserves of oil and gas total a further 133-262 GtC.

Beyond the reserves the total resource base is much higher again, lying in the range 4,166-4,678 GtC. The total oil resource base exceeds 650 GtC and the gas resource is over 500 GtC.

Table 8 Fossil Fuels: Economic Reserves and Resource Base

	IPCC 1995 Reserves Identified /Potentials by 2020-2025 GtC	WEC 1993 Conventional reserves GtC	IIASA 1997 Reserves GtC	IPCC 1995 Resource Base Maximum Potentials GtC	WEC 1993 Resource Base Maximum Potentials GtC	IIASA 1997 Resource Base GtC
Gas - conventional	72	69	81	138	133	243
Unconventional gas	103		111	403		260
Oil - conventional	110	114	124	156	167	243
Unconventional oil	130		151	296	497	427
Coal	638	646	1,034	3,173	3,622	3,505
Total	**1,053**	**829**	**1,501**	**4,166**	**4,419**	**4,678**

This table shows the 1995 IPCC, 1993 World Energy Council[21] (WEC) and 1997 IIASA[22] fossil fuel reserves and resources estimates in GtC. The WEC does not show unconventional gas separately. Reserves are defined as economically recoverable and resources include reserves plus geologically inferred resources.

It is clear from the above estimates that to meet the IPCC scenarios for future oil and gas use, a large amount of the oil and gas currently identified as unconventional, or that is currently defined as not economically recoverable (the difference between the resource base and reserves in Table 8), will need to be 'moved' into the resource category.

Oil use in the IPCC emission scenarios spans 159-367 GtC with the mid-range scenario consuming 239 GtC, which is much higher than conventional reserves identified in

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[21] World Energy Council (1993), Energy for Tomorrow's World - The realities, the real options and the agenda for achievement, St. Martin's Press/Kogan Page, London.

[22] Rogner, Hans-Holger (1997) Climate Change Assessments: Technology Learning and Fossil Fuels - How Much Carbon Can Be Mobilized?, Paper presented to International Energy Agency Workshop on Climate Change Damages and the Benefits of Mitigation, 26-28 February 1997, International Institute for Applied Systems Analysis (IIASA).

Table 8, but of the same order as the sum of conventional and unconventional reserves. Recent oil industry estimates span the range of those estimated by the IPCC and WEC (Table 9).

For gas use, the IPCC scenarios span 105-187 GtC. Known conventional reserves are considerably below these volumes. However estimates of natural gas reserves have been increasing in recent years. The International Gas Union has recently estimated that proven reserves stand at 77 GtC[23] with "additional reserves" totalling 136 GtC bringing the total resource to 213 GtC. Additional reserves are defined as being of foreseeable economic interest and include conventional and unconventional gas. The IGU has reported that the increase in reserves is due to technological advances, particularly in exploration in offshore areas, which is changing the economics of gas extraction quite rapidly.

From a policy perspective one of the lessons from the recent expansion of gas reserves is the ongoing role of technological change, even in circumstances where prices have remained relatively low.

2.4 Oil Reserves

The size of oil reserves and their ultimate extent is an area of significant and indeed polarized policy debate. A common perception is that there might not be enough oil to meet growing demand. On the other hand, from an environmental perspective, it is logical to question whether there is too much oil ever to be used.

Of the few certain data in this area it is known that approximately 800 billion barrels (Gb) of oil have been produced to date and that production is currently at around 25 Gb/day. Production has grown at about 1.25%/yr. over the period 1987-1996[24]. Oil reserves, defined as that which has been discovered and remains unused, are estimated, at the end of 1995, to lie between 746 and 1056 Gb[25], with the consensus being around 1,000 Gb. In other words 1,000 Gb of oil, or about 115 GtC of emissions, can be produced at current prices with current technology.

Of the known reserves of oil, Odell estimates that scientific and technological developments may well add a further 400 Gb (46 GtC) to the volume of ultimately recoverable oil in existing reserves. The US Geological Survey estimates that there may be a further 600 Gb (70 GtC) of oil in conventional reserves which remain to discovered. Odell considers this estimate to be conservative. Taken together with the known reserves of 1,000 Gb, these two estimates point to the total unexploited reserve volume being approximately 2,000 Gb, which is equivalent to about 230 GtC[26]. This latter figure is quite close to the resource base estimated by IIASA (Table 8).

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[23] IGU (1997) World Gas Prospects, Strategies and Economics, International Gas Union, 20th World Gas Conference Proceedings, Copenhagen, June 1997. Units originally in Exajoules (EJ) and converted at the rate of 14.4 MtC/EJ.

[24] Odell (1997) *op.cit.* p. 1.

[25] Odell (1997) *op.cit.* p. 6.

[26] Odell (1997) *op.cit.* p. 17.

Table 9 Recent industry estimates of oil reserves[27]

	Oil and Gas Journal: Estimated Proven Reserves at January 96.	**World Oil** Estimated Proven Reserves at December 95.	**Petro Consultants** Assessed Reserves, 1995.	**US Geological Survey**
Regions	GtC	GtC	GtC	GtC
North America	8.9	8.9	7.4	11.9
South America	9.0	9.9	5.9	8.6
Europe	1.9	3.6	3.5	4.3
FSU	6.8	22.1	8.8	14.0
Africa	8.5	9.2	6.1	8.3
Middle East	76.5	68.4	50.9	67.6
Far East	4.9	5.9	4.4	7.2
Australasia	0.2	0.5	0.3	0.5
Total	116.7	128.3	86.5	122.4

Original data are in billions of barrels of oil and have been converted to GtC using the factor of 0.116 GtC/Gb (billion barrels) based on emission factors in Table 3 and the conversion of 5.815 GJ/barrel of crude oil[28]. The emissions factor implied in the IPCC estimates is approximately 10% lower than those used here whereas the IIASA factors are within a few percent of those used in this work.

Unconventional oil includes tar-sands, heavy oils and oil shales and resources and reserves of these are very large compared to conventional supplies. The estimates in Table 8 indicate reserves are of the order of 1,200 Gb (130 GtC) and resources in the range 3,000-4,500 Gb.

On the surface this appears to be a "healthy" supply of oil compared to demand. However neither these numbers, nor the analysis underpinning them, are undisputed. Essentially there are two quite divergent views of the future of oil reserves. These views have quite different policy implications from a conventional oil supply security perspective.

The "oil scarcity" viewpoint is held by oil companies and many petroleum geologists who believe that the volume of oil and the rate at which it can be recovered are inherently and physically limited by the nature of the geological origin of oil. In this view oil is in scarce supply and global production will peak within a few decades and afterwards the world will face a permanent situation of scarce and declining oil availability[29]. Hatfield, for example, argues that the consequence of this situation is that soon this issue may override other environmental concerns:

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[27] Odell, P. (1997) A Guide to Oil Reserves and Resources: Report to Greenpeace, Energy Advice Ltd, 1997, London.

[28] Lazarus (1993) op.cit. p.v. A gigajoule (GJ) is 10^9 joules.

[29] C.J. Campbell (1997), "Better Understanding Urged for Rapidly Depleting Reserves" in Oil &Gas Journal, OGJ Special, 7 April 1997; pp. 51-52,54.

> *"Despite the intensive, intergovernmental debates on the environmental effects of energy policies, geological constraints on the amount of inexpensive fluid fuel that can be produced will soon override governments decisions about the future rate of fossil fuel burning"* [30]

Contrasted against this point of view is the "economic" view. Dusseault, for example, argues that the idea of oil being limited is "an incorrect and insidious myth" and that technological change and market pressures will bring other resources into the market:

> *"Limitations on oil use are [therefore] logically related to environmental issues such as global warming and air pollution; resource limits do not for practical purposes exist. Oil shortages are actually short-term shortfalls in cheap conventional crude oil supplies, and have little to do with actual-long term hydrocarbon supplies"*[31]

Figure 5 shows that total oil reserves increased over the past twenty five years and are now 70% higher than in 1973. Over this time the reserve size to production ratio has increased from 25 years to nearly 45 years[32]. On the face of it this figure appears to support the "economic" point of view. It shows that the addition to oil reserves over time has outweighed by a wide margin the annual consumption of oil.

However, proponents of the "oil scarcity" view argue that the increasing reserve size shown in Figure 5 is not an accurate picture of the supply balance for oil. Hatfield, argues that much of the increase over the 1973-1995 period results from "political" adjustments in the reserves held by key OPEC countries rather than new discoveries.

In 1988 and 1989 Venezuela, Iran, Iraq, Abu Dhabi and Saudi Arabia revised their oil reserves upward by a total of 277 billion barrels and this accounted for nearly all of the growth in global reserves between 1987 and 1990[33]. Whilst some have suggested that these reserve revisions were essentially political[34] Campbell (a scarcity advocate) suggests that the main policy point about this revision is that nothing new was discovered - the change were just in reporting[35]. In other words there have been no new major oil discoveries since the 1960's.

From the "oil scarcity" point of view, growing oil demand essentially means that if there were no new discoveries (and assuming the rate of production could increase until the reserves are depleted) the 1,000 Gb of conventional resources would be used

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30 Hatfield, C. B. (1997), "Oil Back on the Global Agenda" in Nature, vol. 387, 8 May 1997; pp. 121.

[31] Dusseault, M. B. (1997), "Flawed Reasoning about Oil and Gas" in Nature, vol. 386, 6 March 1997; pp. 12.

[32] Note that the reserve to production ratio (R/P), whilst widely used in the industry is an extremely poor indicator of supply availability, particularly once supply has peaked and is dropping from an oil reservoir. The R/P ratio can be maintained under this circumstance, event though the rate of production is falling. The ratio has the units of years where the reserve size is the total volume in reserves and the production is a rate of volume of oil produced per year.

[33] Hatfield, *op.cit.*

[34] Hatfield, *op.cit.*

[35] Campbell, *op.cit,* p. 54.

up before 2030 (or before 2025 if demand were to grow at 2% per year). Even large additions to this reserve size would delay the extinction of the resource by only a few years. Further, as it is known that the production rate from oil reservoirs peaks and then declines at some point near the mid-point in their production cycle, some geologists consider it unlikely that with the currently estimated reserves (or even large additions) that current or projected production rates could be maintained much beyond 2010-2015.

Viewing the same history, Odell, a proponent of the "economic" view point, argues that the oil industry has in fact demonstrated a "high degree of success ... even through a period of great disturbances in its organisation, structure and commercial fortunes, in maintaining and generally increasing the shelf-stock of reserves at a more than adequate level over a very long period."[36] Whilst a significant portion of the additions to reserves has come from the appreciation of existing reserves there have also been quite significant additions from new discoveries. In relation to the future, Odell argues that there are likely to be large additions to reserves possible through the appreciation of existing reserves and the discovery of new oil reservoirs (see above).
Even if the rate of addition of conventional oil to reserves slows and production begins to decline, from the second "economic" point of view the existence of large volume of unconventional oil, combined with technological change and rising prices, will ensure that these resources will come on stream in large volumes in the future[37].

Technological development, often subsidised by governments, has meant that the cost of extracting oil from unconventional sources such as heavy oil has declined. Dusseault gives the example of heavy oil production in Canada whose cost has more than halved from the late 1980's to 1996. He points out that heavy oil resources are much larger than conventional oil and if only 20% of Canadian heavy oil is economically recoverable this would supply the USA and Canada with oil for the next 100 years or more[38]. Further, he argues, a large increase in the production cost of oil could be sustained without significant increases of the price of fuel on the market in Europe if governments are prepared to shift the tax burden from fuel in the future.

An indication of the relative volume of near term substitutes for conventional oil available from technical developments can be gained from Table 10. This shows that relatively large volumes of alternatives to conventional oil may be available. These come from enhanced and improved recovery from existing fields, natural gas liquids and from heavy oil and shales. Over the time frame of 10-20 years this could add nearly 50% to current reserves.

2.5 Conclusions

It seems clear, not withstanding the arguments of the "oil scarcity" advocates, that technological change and the price mechanism will, as it has in the past, constantly enlarge the boundaries of conventional reserves and further move resources into

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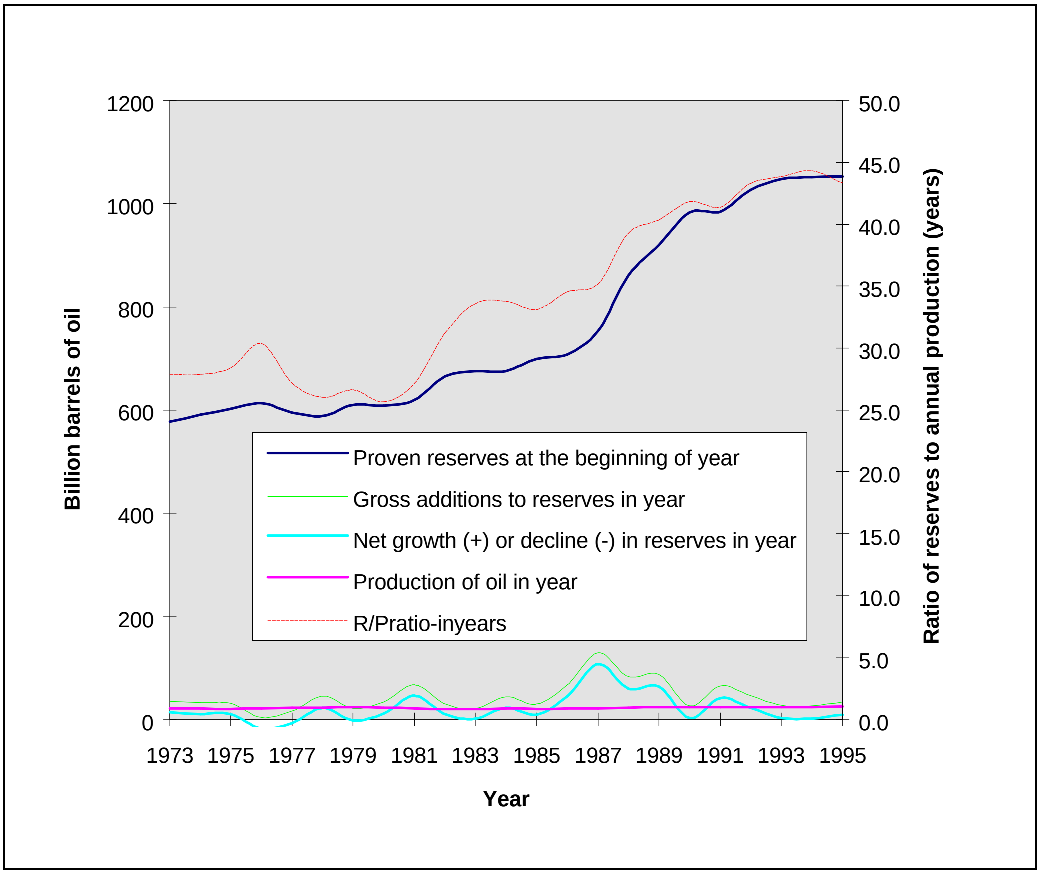
[36] Odell (1997) op.cit. p. 10.
[37] Odell (1997) op.cit. p. 22 and Dusseault (1997) op.cit. p. 12.
[38] Dusseault (1997) op.cit. p. 12.

reserves. A recent IIASA-World Energy Council analysis of available fossil fuel resources has attempted to evaluate an economic supply curve for fossil fuel resources taking into account technological change. Unlike previous analyses the assessment estimated technology productivity gains in fossil fuel exploration and extraction over time based on historical experience in order to generate a quantity cost curve for each major fossil fuel type. The results of this work are shown schematically in Figure 6 and Figure 7.

Figure 5 Oil reserves and production 1973-1995[39]



Over the period 1973-1995 the gross additions to oil reserves exceeded production for most years in the period leading to a sizeable net increase in proven reserves over the period. The jump in gross additions in the period 1987-89 reflects revisions to reserve estimates in several major OPEC countries.

Some of the inferences from the curves in Figure 6 include: 300 GtC of carbon is available at under $US 10/boe (barrel of oil equivalent),[40] 600 GtC at under $US 20/boe, 900 GtC at under $US 30/boe;. around 300 GtC of oil and gas is available at around $US15-16/boe and around 400 GtC at or below $US20/boe (in 1990 prices). In other words if productivity gains in the fossil fuel industry proceed at historical rates then "mankind is well positioned to substantially increase climate destabilizing and local air quality emissions" and "this can be done quite cheaply"[41]. As a consequence

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[39] Odell (1997) op.cit.

[40] A barrel of oil equivalent is defined here as 5.815 GJ (gigajoules).

[41] Rogner, Hans-Holger (1996) An Assessment of World Hydrocarbon Resources, IIASA Working Paper WP-96-56, May 1996, p. 39.

one of the key conclusions of the IIASA assessment of world fossil fuel resources is that “environmental considerations may constrain fossil fuel use to below present-day levels long before global resource scarcity becomes the limiting factor”[42].

From a policy perspective the relationship between resources and reserves is quite fluid. The more investment that occurs in exploration and development of resources the more of these will be converted to reserves (i.e. classified as economically recoverable). Investment in further exploration and development of oil, for example, will be conditioned by market expectations of the future demand. If markets expect increasing demand in the future then investment is likely to be made in “expanding” the reserves available. One of the implications of this is that if the volume of reserves already exceeds some ecological limit (as is found in this report) then further investment in resource development is unnecessary and unwise. Ultimately this would impose higher political and economic costs on future generation’s attempts to constrain the amount of fossil fuels exploited.

Table 10 Potential liquid fuel substitutes for conventional oil

Category	Sub-category	Present reserves		Potential reserves	
		Gb	GtC	Gb	GtC
Heavy oil and bitumens		64	7	740	86
Oil shales		160	19	500	58
Non-heavy					
	> 200 m water depth	25	3	75	9
	Hostile (polar)	0	-	30	3
	Small and very small (< 10 Mb)	10	1	30	3
	Infill	0	-	50	6
	Sub-total:	35	4	185	21
Enhanced recovery		45	5	60	7
Improved recovery		45	5	60	7
Natural Gas Liquids -	Condensate	65	8	100	12
	By-processing	130	15	200	23
Total		500	58	2000	232

This table of date was provided in discussion notes by R.W. Bentley, University of Reading as a basis for discussion at a workshop in the future of oil[43]. The values in it should be seen as indicative only of the order of magnitude of potential alternatives to conventional oil.

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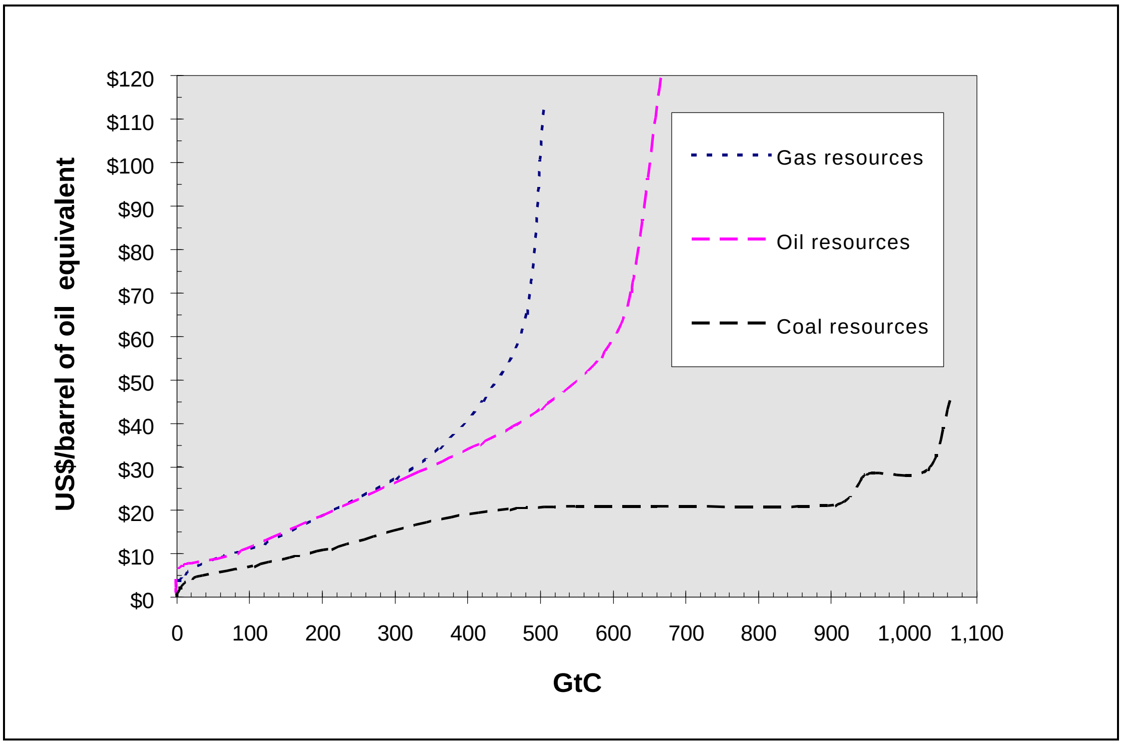
[42] Rogner op.cit. p. 38.

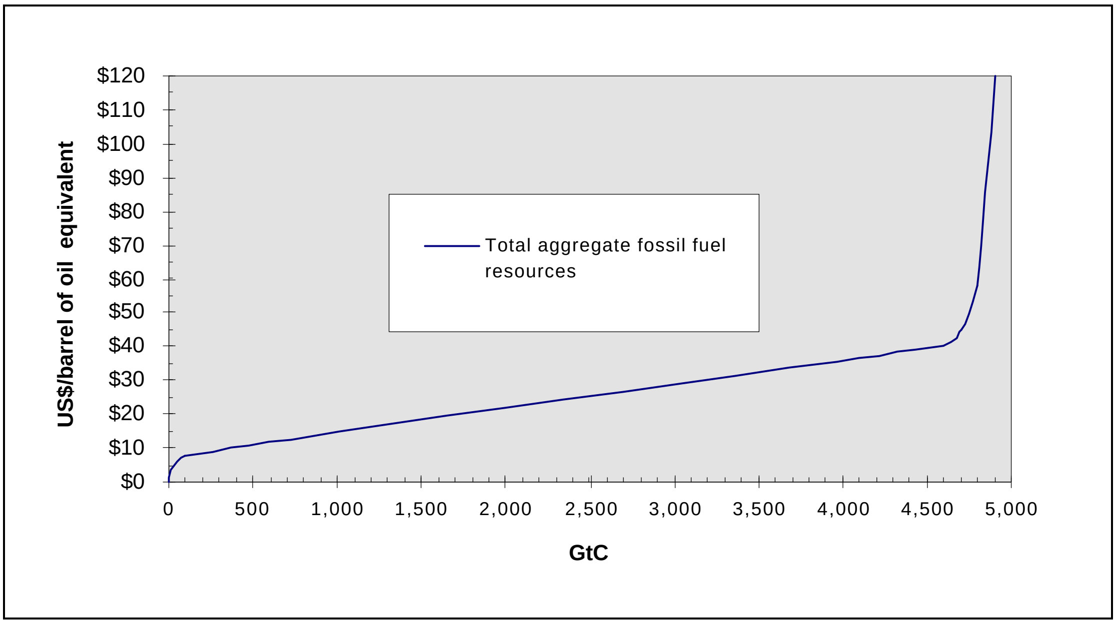
[43] Bentley, R.W. (1997) Briefing Notes for Workshop on ‘The Future of Oil’, Black Horse House, The University of Reading. Friday, June 13th 1997.

Figure 6 IIASA quantity-cost curve for gas, oil and gas resources



These curves are estimated from the curves presented in Rogner (1996) (see footnote 41) and are schematic only.

Figure 7 IIASA quantity-cost curve for total fossil fuel resource base



These curves are redrawn from the curves presented in Rogner (1996) (see footnote 41) and are schematic only.

3. Ecological Limits

The UN Framework Convention on Climate Change[44] (UNFCCC) signed at Rio in 1992 makes staying within ecological limits its "ultimate objective"[45] with greenhouse gas concentrations to be stabilized "at a level that would prevent dangerous anthropogenic [human made] interference with the climate system". This is objective is to be achieved "within a timeframe 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". Further, the climate convention also requires Parties to "take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects" and that "Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost."[46]

These elements of the Convention are the essential policy context for an examination of ecological limits that should guide international policy on climate change. Both the rate and the magnitude of climate change need to be addressed if the objectives of the climate convention are to be met. This point is made clear by two of the key findings of the IPCC Second Assessment Report:

> *"In all cases the average rate of warming would probably be greater than any seen in the last 10,000 years..."* [47]
>
> *"Most systems are sensitive to climate change. Natural ecological systems, socio-economic systems, and human health are all sensitive to both the magnitude and the rate of climate change."*[48]

It is clear from a review of the entire IPCC Second Assessment Report that climate change poses a significant threat to sustainable development , particularly for developing countries who are likely to be much more adversely affected than developed countries by the climate change projected for an equivalent doubling of CO_2[49].

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[44] United Nations Framework Convention on Climate Change (UNFCCC), Adopted by the Intergovernmental Negotiating Committee 9 May 1992, Opened for Signature at Rio de Janeiro 4 June 1992. Entered into force 21 March 1995. U. N. Doc. A/AC.237/18 (Part II) (Add 1).

[45] Article 2 of the UNFCCC.

[46] Article 3.3 of the UNFCCC

[47] IPCC SAR WGI *op.cit.* Summary for Policy Makers, p. 6.

[48] IPCC SAR WGII *op.cit.* Summary for Policy Makers, p. 9.

[49] It is important to note the difference between CO_2 equivalent and actual CO_2 concentrations. Equivalent CO_2 refers to the greenhouse effect of both the actual CO_2 concentration and the other greenhouse gases combined and converted to a CO_2 equivalent concentration. Stabilizing actual CO_2 concentrations at for, example, 450 ppmv means equivalent CO_2 concentrations of around 530 ppmv owing to the effects of the other gases. The climate difference between stabilizing at 450 ppmv actual CO_2 and 450 ppmv equivalent is significant i.e. 0.6^oC - 0.8^oC depending on the climate sensitivity parameter and the role of other greenhouse gases.

Whilst the IPCC found that "existing studies show ... global agricultural production could be maintained relative to baseline production in the face of climate change projected under doubled equivalent CO_2 equilibrium conditions", it also warned that:

> *"there may be increased risk of hunger and famine in some locations; many of the world's poorest people - particularly those living in subtropical and tropical areas and dependent on isolated agricultural systems in semi-arid and arid regions - are most at risk of increased hunger"*[50]

The major areas at risk were found by the IPCC to be in subtropical and tropical areas "home to many of the world's poorest people" and in particular the populations most at risk are those "dependent on isolated agricultural systems in semi-arid and arid regions face the greatest risk of increased hunger due to climate change". Regions particularly at risk included sub-Saharan Africa; South, East, and Southeast Asia; and tropical areas of Latin America, as well as some Pacific island nations[51]. Rosenzweig and Parry calculated, under highly optimistic assumptions that 60-350 million more people could be at risk of hunger as a consequence of climate change and that these would be predominantly in developing countries[52]. It is clear, on the basis of the evidence reviewed in the IPCC Second Assessment Report, that there is a dangerous threat to food production in a number of developing countries.

In this section we review the background behind the issue of ecological limits and advances in scientific understanding of how these limits may be applied to international climate policy.

3.1 Targets and Indicators of Climate Change

In 1990, on the basis of scientific knowledge available before the IPCC First Assessment Report was concluded, the WMO/ICSU/UNEP Advisory Group on Greenhouse Gases (AGGG) produced an analysis of "targets and indicators" for climate change[53]. This work focused on developing quantitative targets for long term risk management which could be used as the basis for short term emission targets[54]. The purposes of these indicators was to set limits to rates and total amounts of temperature rise and sea-level rise, on the basis of known behaviour of ecosystems as a guide to policy in order to protect both human and natural ecosystems.

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[50] IPCC Synthesis Report, op.cit. Par. 3.13

[51] Watson, R.T, M.C. Zinyowera and R. H. Moss (1996) IPCC WGII Technical Summary: Impacts, Adaptation and Mitigation Options in IPCC SAR WGII *op.cit.*

[52] Rosenzweig C. and M. Parry, "Potential impact of climate change on world food supply", Nature, v.367, p.133-138, 13 January 1994

53 Rijsberman, F.J and R.J. Swart (eds.) (1990), Targets and Indicators of Climate Change, Stockholm Environment Institute. The World Meteorological Organization/International Council of Scientific Unions/United Nations Environment Programme (WMO/ICSU/UNEP) Advisory Group on Greenhouse Gases (AGGG) set up three working groups in 1988 one of which was to examine targets and indicators of climate change. This group was under the Chairmanship of P. Vellinga and P.H. Gleick.

[54] Rijsberman, F.J and R.J. Swart (eds.) (1990) op.cit. p.iv

The indicators of climate change identified by this group were sea-level rise, committed (or equilibrium) global mean temperature and CO_2 concentrations. Targets were identified for the climate change indicators that incorporated different levels of risk.

Temperature and sea-level rise targets for the lowest level of risk were:

- Maximum 1.0° increase above pre-industrial levels. Increases beyond this "may elicit rapid, unpredictable and non-linear responses that could lead to extensive ecosystem damage"[55].

- Maximum rate of warming of 0.1°C/decade. The rate of warming needs to be below this to ensure that most ecosystems can adapt. This would lead to some damage, however higher levels would lead to rapidly rising risk.

- Maximum rate of sea-level rise of 20mm/decade. This "would permit the vast majority of vulnerable ecosystems, such as natural wetlands and coral reefs to adapt with rates beyond this leading to rapidly rising ecosystem damage".

Targets for the higher levels of risk were:

- 2.0°C increase above pre-industrial levels. This is "an upper limit beyond which the risks of grave damage to ecosystems, and of non-linear responses, are expected to increase rapidly".

- Maximum 50 cm sea-level increase above 1990 global mean sea-level. This could "prevent the complete destruction of island nations, but would entail large increases in the societal and ecological damage caused by storms".

At this high level of risk Vellinga and Swart argue that there will be large impacts on many regions and that there is a high risk of climate instabilities and of strong feedbacks:

> *"We must expect that in many places in the world there will be a crisis in the world food supply and ecosystems and the corresponding disruption of socio-economic systems and a loss of several islands"*[56].

Several important points need to be borne in mind when considering these targets and the different levels of risk associated with them:

(i) Long term climate commitments. The maximum sea-level and global mean temperature commitments are not limited to a specific time horizon i.e. 2100. This indicates that climate policy should be set with long term changes in mind. Once a change in sea-level rise is actually observed it may be irreversible for practical purposes and will almost certainly be associated with much larger change in the longer term.

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[55] Rijsberman, F.J and R.J. Swart (eds.) (1990) op.cit. p.viii

[56] Vellinga, P. and R. Swart (1990), "The Greenhouse Marallion: Proposal for a Global Strategy", pp. 129-134 in J. Jager and H.L.Ferguson(Ed's) (1990), Climate Change: Science, Impacts and Policy", Proceedings of the Second World Climate Conference, World Meteorological Organisation. Cambridge University Press.

(ii) Risk of large, local impacts and increase in the frequency of extreme events. The targets are for global mean changes. Regional changes of temperature and sea-level may be quite different. Mountain ecosystems and boreal forests, for example, are likely to experience more rapid change than the global average. In higher latitudes projected temperature changes are likely to be much higher than the global mean average. Global mean averages do not capture the effect of changes in the frequency or character of extreme events (i.e. storm, droughts, floods) or in seasonality patterns. Thus global mean averages are therefore only crude surrogates for indicators of damage in the most vulnerable places.

(iii) Precautionary principle and equity. Policy needs to be based on the precautionary principle and on equity. A 20 cm sea-level rise, for example, may not be problem for some countries but may be disastrous for others. Targets therefore need to be chosen that can guide policies to prevent dangerous climate change in the most vulnerable places.

Scientific work published since 1990 tends to support the lowest risk targets identified by the WMO/ICSU/UNEP Advisory Group. Whilst it is not possible here to fully review this work some examples are given below.

In 1995 the UK Meteorological Office Hadley Centre noted:

> *"The global mean rate of change is predicted to be a little above 0.2.C/decade in the early part of the next century; approximately twice the rate of change that many of the more sensitive ecosystems are thought to be capable of surviving"*[57]

It further pointed out that such rates:

> *"are likely to exceed the adaptive capacity of many ecosystems. Indeed the IPCC concluded that 0.1°C/decade was probably the maximum that many ecosystems could tolerate."*

The IPCC has confirmed that ecosystems and species are vulnerable to both the rate and extent of climate change and that rapid climate change is likely to lead to loss of biodiversity:

> "*Ecosystems contain the Earth's entire reservoir of genetic and species diversity and provide many goods and services critical to individuals and societies"*
>
> *"These systems and the functions they provide are sensitive to the rate and extent of changes in climate."....*
>
> *"there will likely be reductions in biodiversity and in the goods and service that ecosystems provide society"*[58]

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[57] Hadley Centre (1995), "Modelling Climate Change 1860 – 2050", UK Meteorological Office.

[58] IPCC SAR WGII *op.cit*., Summary for Policy Makers p. 5.

Quantitatively, the IPCC also found major changes in the earth's forests are projected for only a 1°C increase in global mean temperature leading to very large changes and the possible disappearance of entire forest types:

> *"Models project that a sustained increase of 1°C in global mean temperature is sufficient to cause changes in regional climates that will affect the growth and regeneration capacity of forests in many regions"*
>
> *"A substantial fraction (a global average of one-third, varying by region from one-seventh to two-thirds) of the existing forested area of the world will undergo major changes in broad vegetation types with the greatest changes occurring in high latitudes and the least in the tropics."*
>
> *"Climate change is expected to occur at a rapid rate relative to the speed at which forest species grow, reproduce, and reestablish themselves. ... Therefore, the species composition of forests is likely to change; entire forest types may disappear, while new assemblages of species and hence new ecosystems may be established."*[59]

A sea-level rise of the order of 50 cm would lead to major impacts on many small islands. Other impacts include a dramatic increase in the number of people at risk of flooding and significant impacts on rice production in Asia:

> *"The present number of people at risk will double if sea level rises 50 cm (92 million people/year) and almost triple if it rises 1 meter (118 million people/year).*
>
> *"Approximately 85% of the world's rice production takes place in South, Southeast, and East Asia. About 10% of this production is located in areas that are considered to be vulnerable to sea-level rise, thereby endangering the food supply of more than 200 million people."*[60]

In relation to the potential for rapid climate change to lead to climate instabilities recent work by Stocker and Schmittner[61] has shown that the rate of increase of greenhouse gas concentrations could have a major impact on the thermohaline circulation system of the North Atlantic ocean. They have found that the thermohaline circulation is sensitive not only to the final concentration of CO_2 in the atmosphere but also to its rate of change. Using climate model with a climate sensitivity of 3.7°C it is found that an increase in CO_2 of 1% per year to over 700 ppmv equivalent could lead to a permanent shut down of the thermohaline circulation. A slower increase to the same level slows down the thermohaline circulation.

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[59] IPCC SAR WGII *op.cit*., Summary for Policy Makers p. 5,6.

[60] IPCC SAR WGII *op.cit*, Chapter 9, p. 311.

[61] Stocker, T.F. and A. Schmittner (1997) "Influence of CO_2 emission rates on the stability of the thermohaline circulation", Nature Vol. 388, pp. 862-865

A 1% per year increase in CO_2 concentration approximates the rate increase of CO_2 equivalent greenhouse gas concentration projected over the next century and would produce a rate of increase in temperature of 0.2°C/decade[62].

The existence and strength of the thermohaline system contributes to the mild climates of north-west Europe. It also plays a significant role in the global carbon cycle - a strong thermohaline circulation carries large amounts of CO_2 to the deep oceans. A weakening of the thermohaline circulation would lead to CO_2 concentrations increasing faster and would lead to some very significant regional climate changes. (See discussion below in section 3.5.5). A shutdown in the thermohaline circulation could have quite dramatic and adverse effects on the climate of Europe in particular.

Overall assessments of the impacts of climate change point towards a high level of vulnerability for many natural and some human systems to rapid climate change. The most vulnerable systems are likely to be irreversibly damaged by sustained rates of temperature increase at or above 0.1°C/decade. Further there is a significant risk of feedbacks amplifying the changes and the potential for major climate instabilities

3.2 Projected impacts of IPCC emission scenarios

In considering the application of indicators and targets for climate change the question of how these compare with the projected effects of the IPCC emission scenarios arises.

Using the IPCC's central estimate of emissions (IS92a) over the next century, assuming the IPCC's 'best-estimate' value of climate sensitivity and including the effects of future increases in aerosol (see below), global mean surface temperature relative to 1990 is projected to increase 2.0°C by 2100. With aerosol concentration held constant at 1990 levels the best estimate is 2.4°C by 2100. In other words, by 2100 the IPCC best-estimate is for a global mean temperature increase of 2.5-2.9°C above pre-industrial levels. Further, temperatures would continue to increase for some time even if atmospheric CO_2 levels were stabilized in 2100. Rates of temperature increase over the next century would be in the range 0.2-0.3°C/decade.

The IPCC's 'best-estimate' of sea-level rise from 1990 to 2100 based on the IS92a scenario with constant aerosol emissions (see below) over this period is 55 cm (with increasing aerosol emissions it is 49 cm). The full range of uncertainty in the IPCC estimates for constant aerosol emissions is 23-96 cm. Sea-level would not stop rising in 2100, even if concentrations were stabilized. Owing to the inertia of the climate system and oceans in particular, it would "continue at a scarcely unabated rate for many centuries after concentration stabilization."[63]

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[62] The rate of increase of CO_2 alone in the 1990's is approximately 0.4-0.5%/yr, with the effects of other greenhouse gas emissions bring the total rate of increase to around 0.6-0.7%/yr. in CO_2 equivalent terms. The IS92a scenario projects an increase in equivalent CO_2 concentration of 0.7-0.8%/yr. compound over the next century.

[63] IPCC SAR WGI Chapter 7 p. 388: Warrick R. A., C. Le Provost, M.F. Meier, J. Oerlemans, P.Ll. Woodworth. (1996) Changes in sea level Chapter 7 pp. 259-405 of IPCC SAR WGI *op.cit.*

Using the same emission assumptions but with a climate sensitivity of 3.5 °C the projected mean global temperature increase would be in the range of 3.1-3.6 °C above the pre-industrial global mean temperature and the sea-level rise would be 54-60 cm above 1990 levels.

Table 11 shows the long term equilibrium warming commitment that would result for the IS92 scenarios ranges from 3.3°C to 8.4°C depending on the assumptions made.

In terms of the greenhouse gas concentration over the next century the IS92a scenario projects a doubling in CO_2 equivalent terms above pre-industrial levels in the decade 2030-2040. If aerosol effects are accounted for (see section 3.5.3 below) then this CO_2 equivalent doubling occurs in the decade 2050-2060, depending on the assumptions made. CO_2 actual levels would double around 2060. From a policy perspective based on the precautionary principle, the effective CO_2 doubling, not counting aerosol effects, by 2030-2040 is the most salient point (see section 3.5.3 below).

Projections of the transient effects over the next century of a scenario similar to the IS92a scenario using the IMAGE integrated assessment model, which has a climate sensitivity of 2.4°C for CO_2 doubling, show large damages[64]. The IMAGE baseline scenario emits 1691 GtC in the period 1990-2100, resulting in a CO_2 concentration in 2100 of 737 ppmv more than double the 1990 level. Some of the major results include:

- The rate of increase of impacts on vegetation and agriculture could be larger in the first half of the next century than in the second half.

- By 2100 the global average surface temperature would increase by around 2.8°C from 1990 levels, an increase above pre-industrial levels of around 3.3°C. Temperature increases would be higher in higher latitudes at around 4°C.

- 32% of the area currently used for maize production is projected to experience decreasing yield (Note that 15% of this area is projected to experience increasing yield).

- The area of natural vegetation under threat is very large. By 2100 climate change will threaten terrestrial vegetation type over 41% of the land surface area.

- Sea-level rise would be around 42 cm across the same time period - and would still be rising exponentially at the end of the century.

It is clear from these results that both the rate and magnitude of temperature and sea-level rise will exceed even the highest indicators described above. If the indicators are accurate then the projected emissions of greenhouse gases over the next century risk causing grave

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[64] Alcamo, Joseph and Eric Kreileman (1996) “Emission scenarios and global climate protection”, Global Environmental Change; Human Policy and Dimensions, Vol.6, Number 4, September 1996; pp. 305-334.

damage to ecosystems and forcing non-linear climate responses. In other words the environmental consequences of the IS92 scenarios would be enormous.

Table 11 Effects of IPCC IS92 emission scenarios

	Zero aerosol Emission in 2100			High aerosol emissions and effects in 2100			Sea-level and temperature in 2100	
Scenario	CO_2 equiv. conc. ppmv	Total Radiative Forcing to 1765-2100 W/m^2	Equilibrium warming commitment ^oC	CO_2 equiv. conc. ppmv	Total Radiative Forcing to 1765-2100 W/m^2	Equilibrium warming commitment ^oC	Sea-level rise 1990-2100 cm	Global mean temperature increase in 2100 ^oC
IS92a	1051	8.4	6.7	770	6.42	5.1	64	2.5
IS92b	1017	8.2	6.5	751	6.26	5.0	63	2.4
IS92c	632	5.2	4.1	534	4.11	3.3	48	1.3
IS92d	729	6.1	4.9	604	4.89	3.9	52	1.6
IS92e	1477	10.5	8.4	980	7.94	6.4	74	2.2
IS92f	1294	9.7	7.8	910	7.47	6.0	70	2.0

The equilibrium warming commitment is calculated using a climate sensitivity of 3.5°C. The zero aerosol emissions case shows the radiative forcing if all aerosol emissions ceased. The high aerosol emissions case is the high indirect sulphate case of the IPCC used to calculate projections of future temperature and sea-level rise, but with the radiative forcing computed from 1765. The sea-level and temperature projections for 2100 are for a climate sensitivity of 2.5°C and for zero aerosol emission changes from 1990 (i.e. constant aerosol emissions). See Table A.4 and A.5 of Raper et al (1996)[65].

3.3 Efficacy of concentration stabilization targets

As part of the 1994 IPCC Special Report a carbon cycle model intercomparison process was conducted using standardized atmospheric CO_2 stabilization scenarios. Based on standard concentration profiles over time (Figure 8) the carbon cycle models were used to calculate backwards (inverse modelling) to arrive at emission profiles that corresponded to the atmospheric stabilization profile[66]. Five levels of CO_2 stabilization were chosen - 350, 450, 550, 650 and 750 ppmv with the year of stabilization varying for each scenario ranging from 2100 for 450 ppmv to 2250 for 750 ppmv. The carbon cycle calculations were reviewed in the IPCC's Second Assessment Report in 1995, with the addition of further level at 1,000 ppmv.

Partly as a consequence of the IPCC exercise, and in the context of the climate convention negotiations, some countries have raised the idea of a long term concentration target rather than ecological targets as described above. Governments such as France and the USA have talked, formally or informally, of 550 ppmv for example as a long term target. Similarly many economic modelling exercises have focussed on 550 ppmv of CO_2.

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[65] Raper, S.C.B.; T.M.L. Wigley and R.A. Warrick (1996) "Global Sea-level Rise: Past and Future", Chapter 1 in John D, Milliman, Bilal U. Haq (eds.) Sea-Level Rise and Coastal Subsidence: Causes, Consequences, and Strategies, Dordrecht, Boston, London, Kluwer Academic Publishers, 1996

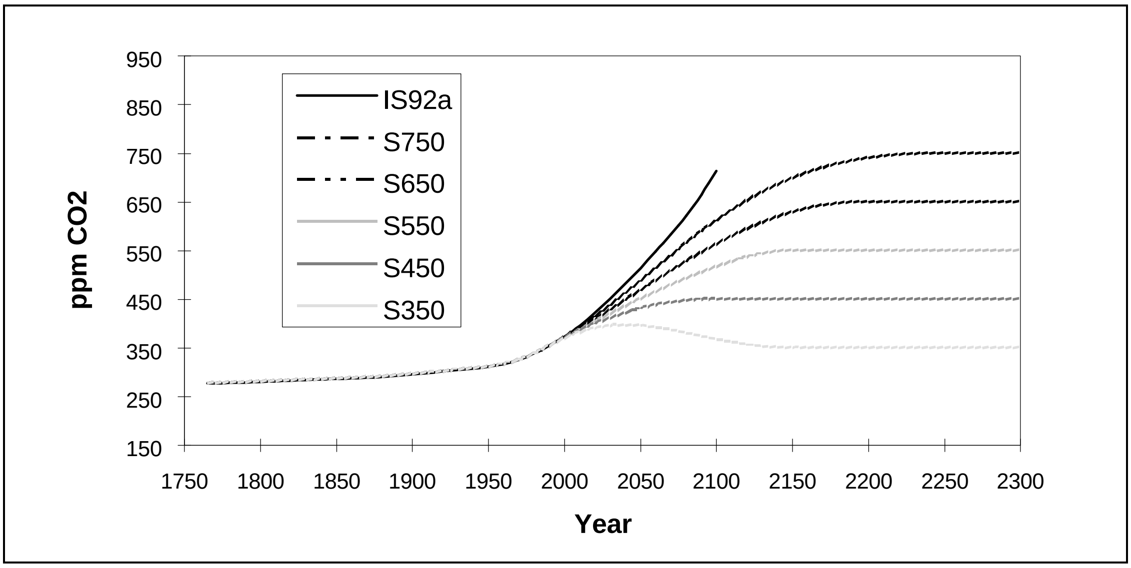
[66] Enting, I.G.; T.M.L. Wigley and M. Heimann (1994), Future Emissions and Concentrations of carbon dioxide, Technical Paper No. 31, CSIRO Division of Atmospheric Research, Mordialloc, Australia.

There is a sense then in which the IPCC stabilization levels may have been perceived as bracketing an acceptable range with those in the middle, 550 or 650 ppmv, becoming by default the compromise[67]. This tendency has been reinforced to some degree by the omission of the 350 ppmv scenario from the IPCC WGI SAR and the inclusion of a 1,000 ppmv scenario[68]. This is not however what the IPCC intended at all.

In this context then it is useful to review the efficacy of concentration targets as tools for climate policy and in particular the meeting of ecological objectives.

In the absence of policy action CO_2 levels would approach 650-750 ppmv by 2100, with equivalent CO_2 levels being much higher, over 1,000 ppmv[69]. Table 12 shows the calculated long term implications of these CO_2 stabilization scenarios for global average temperature and sea-level rise. It should be noted that the sea-level continues to rise well after the point at which atmospheric CO_2 is stabilized. Figure 14 shows the corresponding emissions calculated by the mid-range of the carbon cycle models for each of the concentration stabilization profiles for the same time period. For comparative purposes the IS92a scenario is shown.

Figure 8 IPCC CO_2 concentration stabilization scenarios



This figure shows the prescribed CO_2 concentration profile assumed in order to calculate the emissions profiles and hence the 'carbon budget' calculations over the period to 2300 for the IPCC stabilization scenarios. The S350 scenario stabilized CO_2 at 350 ppmv in 2150, S450 at 450 ppmv in 2100, S550 at 550 ppmv in 2150, S650 at 650 ppmv in 2200 and S750 at 750 ppmv in 2250. source: CSIRO

Figure 9 shows the calculated rates of global average temperature change for CO_2 stabilization scenarios ranging from 350 to 550 ppmv. This graph demonstrates that

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[67] Christian Azar and Henning Rodhe, "Targets for Stabilization of Atmospheric CO_2" in Science, vol. 276, 20 June 1997; pp. 1818.

[68] This scenario was included to show the emission consequences of higher stabilization levels. The authors note however that whilst the environmental consequences have not been assessed "they are certain to be very large". IPCC SAR Chapter 1, op.cit p. 83.

[69] See Table 11. This refers to the radiative forcing without consideration of aerosol effects. Inclusion of full aerosol effects would mean the equivalent CO_2 range is 750-1,000 ppmv.

the emissions corresponding to the achievement of the lower concentration stabilization level lower the warming rate the most rapidly.

Alcamo and Kreileman[70] have calculated, using the IMAGE model, the effects of stabilizing at 350, 450, 550, 650 ppmv of CO_2. Their calculations include other greenhouse gases, which means that the equivalent CO_2 level is higher than the nominal CO_2 stabilization levels. They find that stabilization above 450 ppmv will have large impacts. Below this level impacts will be significantly lower, however there will still be some residual effects. For stabilization at 450 ppmv or higher global temperatures are steadily increasing, as are impacts on natural vegetation and crop production, up to at least 2100. Sea-level rise continues to increase after 2100 in all cases. For stabilization below 450 ppmv (i.e. 350 ppmv) the impacts on natural vegetation and crop production stabilize before the middle of the century, although sea-level continues to rise. In summary the results of these scenarios are:

- Under the 350 ppmv scenario sea-level rise is 24 cm in 2100 and the temperature increase is 0.7^{o}C (1.2^{o}C above pre-industrial levels). The area of current maize production with decreasing yield is 16% in 2100 and area of natural vegetation threatened by climate change is 15%.

- For the 450 ppmv scenario the temperature increase is 1.7^{o}C above pre-industrial levels, sea-level rise is 29 cm, the threat to natural vegetation 23% and area of current maize production with decreasing yield is 21%.

- For the 550 ppmv scenario the temperature increase is 2.2^{o}C above pre-industrial levels, sea-level rise is 33 cm, the threat to natural vegetation 28% and area of current maize production with decreasing yield is 25%.

- For the 650 ppmv scenario the temperature increase is 2.5^{o}C above pre-industrial levels, sea-level rise is 36 cm, the threat to natural vegetation 31% and area of current maize production with decreasing yield is 26%.

The long term sea-level rise in each case would be some 2-3 times the increase to 2100.

One of the key results from this work is the finding that with each of the stabilization scenarios there is a much more rapid increase in temperature and of some climate impacts <u>in the first half of the next century</u> than before or after[71]. This implies that many of the projected impacts of future emissions are only avoidable of action is taken early. From a policy perspective this reinforces the urgency of early emission reductions to slow the rate of warming.

The work of Alcamo and Kreileman also sheds light on the question of the efficacy of concentration targets to meet the ultimate objective of the climate convention. Overall, they find that “stabilizing greenhouse gases in the atmosphere does not necessarily provide a high level of climate protection”. This conclusion is linked in

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[70] Alcamo and Kreileman (1997) *op.cit.* p. 315-314
[71] Alcamo and Kreileman (1997) *op.cit.* p. 317

part to the fact that the concentration targets do not explicitly include an objective of limiting the rate of change.

Table 12 Temperature and Sea-level rise implications of IPCC CO_2 Stabilization Scenarios.

IPCC CO_2 scenario	Year of CO_2 stabilization	Temperature increase above 1990[72] °C		Sea-Level Rise[73] (cm) Above 1990 levels	
(ppmv)		Year	Year	Year	Year
		2100	2500	2100	2500
350	2150	1.1	0.7	20 (15)	38 (21)
450	2100	1.6	1.8	29 (25)	84 (59)
550	2150	2.0	2.6	34 (32)	117 (87)
650	2200	2.2	3.3	37 (35)	142 (109)
750	2250	2.4	3.7	41 (40)	163 (123)

This table is a compilation of results and shows the effects of the CO_2 stabilization levels on global average temperature and sea-level in the longer term. The temperature increase incorporates the effects of other greenhouse gases by assuming that their post 1990 radiative forcing increase is 23% (see below) of that due to CO_2. It includes the offsetting effects of the pre-1990 aerosol forcing. The sea-level rise calculations are from a more recent source and correspond to the “best- estimate” climate and sea-level rise parameters in the 1995 IPCC Second Assessment Report. It is to be noted that unlike the temperature estimates above they do not include post-1990 changes in non-CO_2 greenhouse gas forcing. Despite this the sea-level rise estimates reported here are higher than those previously calculated using earlier (1990, 1992) IPCC best-estimate assumptions for sea-level rise. These former estimates are included in brackets.

3.4 “Safe Emissions Corridor” Approach

The timing and level of emission reductions needs to be driven by the precautionary principle and scientific considerations. Because of the complexity of the climate system and its inertia (slowness to react to increases or reductions in greenhouse gas emissions) emission reduction pathways need to take account simultaneously of several climate protection goals, which together have a chance of avoiding extensive ecosystem damage. This idea is reflected, for example in the proposal of the Alliance of Small Island States that the “guiding objective” of the Kyoto Protocol shall be to:

> *“ensure that global mean sea-level rise resulting from climate change does not exceed 20 centimetres and that the global average temperature does not exceed 2 degrees Celsius above the pre-industrial level”*[74].

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[72] Wigley, T.M.L (1995), “Global Mean Temperature and Sea-Level Consequence of Greenhouse Gas Concentration Stabilization”, Geophysical Research Letters, 22(1), 45-48.

[73] Raper et al (1996) op.cit.

Apart from minimizing the rate of climate change, the design of emission reduction pathways needs to avoid imposing very large emission reduction rates on future generations (which would be the result if action to reduce emissions is not begun immediately). Also, the risk of "surprises" and catastrophes should be reduced by taking action early.

The implications of a set of multiple climate constraints can be calculated using the "safe emissions corridor" concept developed by the Dutch IMAGE Climate Modeling team[75]. In essence this approach attempts to provide a tool for answering questions directly relevant to the climate negotiations:

- Which short term emission limits (to 2010) would be needed for the world to stay within both short and long term ecological limits of climate change throughout the next century provided no unforeseen catastrophes occurred?

- What are the allowable emissions from Annex I countries between now and 2010 and still enable future generations to meet the defined ecological and economic limits, without imposing very large rates of economic adjustment rates on future generations?

The size of the safe "emissions corridor" in the period to 2010 depends on the assumed climate constraints. The more stringent the constraints the lower is the top of the corridor. The bottom of the corridor is determined by the assumed maximum rate of emission reductions.

Of quite fundamental concern to policy is the implications of the location in the emission corridor in the period to 2010 for allowed emissions <u>after</u> 2010. If emissions are at the top of a corridor in 2010, then it is likely that the band of allowable emissions after 2010 will be very small. In other words, high emissions in the period to 2010 reduce the flexibility for policy post-2010. This fact would tend to place emphasis on emissions being no higher than around the middle of a corridor in order to protect options for future generations.

Four key limits were chosen - three ecological and one economic. The ecological limits are similar to those defined by the WMO/ICSU/UNEP AGGG - total temperature change to 2100, the decadal average rate of global temperature change and sea-level rise to 2100[76]. The economic limit chosen was a maximum annual rate of reduction of CO_2, reflecting possible economic constraints.

In addition, the assumption was made that developing country emissions would not be constrained by international climate policy over the period to 2010, by which time their total emissions would be in the range 5.5-7.0 GtC/year (CO_2 equivalent). This is consistent with the Berlin Mandate under which negotiations are occurring aimed at

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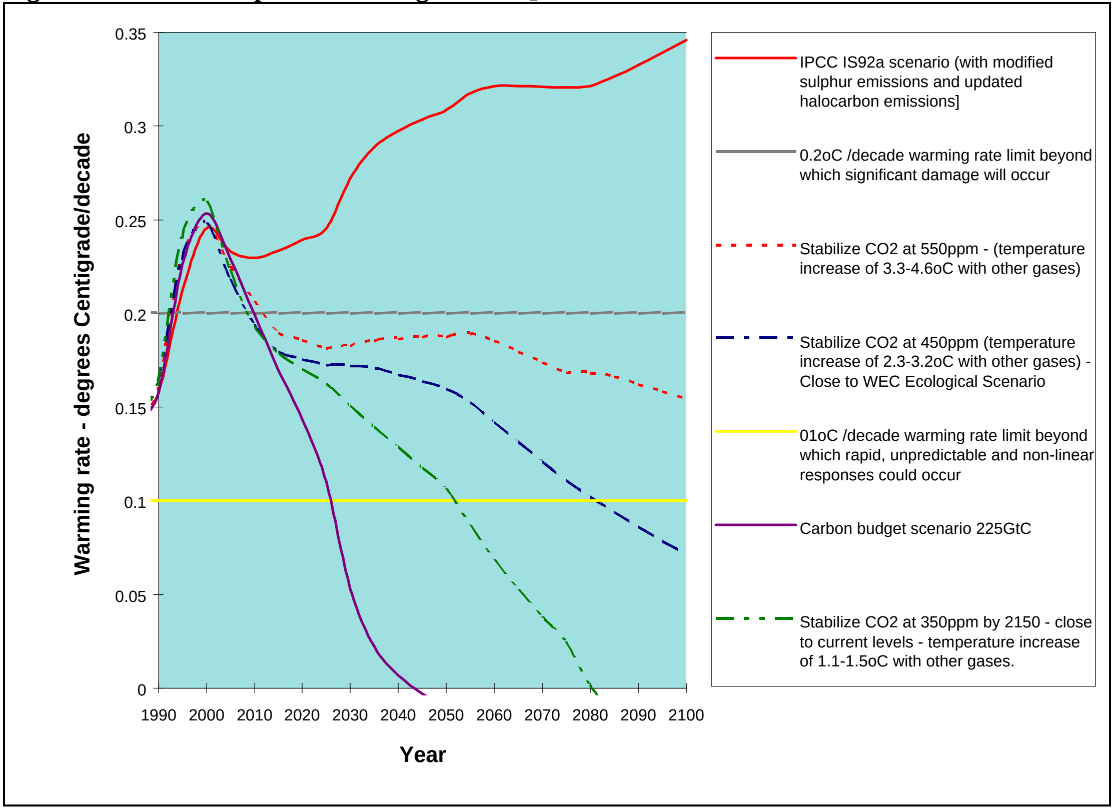
[74] FCCC/AGBM/1997/MISC.1/Add.2

[75] Alcamo and Kreileman (1996) <u>*op.cit.*</u>

[76] Alcamo and Kreileman (1996) <u>*op.cit*</u> p. .317. The temperature limits were set with respect to 1990 global average surface temperature, rather than pre-industrial levels.

securing legally binding emission reductions for industrialized countries at the Third Conference of the Parties to the Climate Convention (COP-3)[77]. For comparison, greenhouse gas emissions in 1990 totalled around 6 GtC (CO_2 equivalent).

Figure 9 Rates of temperature change for CO_2 scenarios



The calculations were made with a climate sensitivity of 3.5°C[78]. In these calculations the radiative forcing of the non-CO_2 gases (taking into account aerosols) in 2100 was 47% for the 350 ppmv scenario, 20% for the 450 ppmv scenario, 13% for the 550 ppmv scenario and 14% for the IS92a scenario. For the 350, 450 and 550 scenarios CH_4 and N_2O emissions were assumed to be approximately constant at 1990 levels. Fluorocarbon emissions were phased out in the 350 and 450 ppmv scenarios and continued at 500kt/yr. in 550 case. Sulphur emissions were correlated with fossil carbon emissions. The IS92a scenario was modified by lowering its sulphur intensity and modifying the halocarbon emissions to account for controls on CFCs and HCFCs. See section 4.2.2 for a discussion of the ‘carbon budget’ scenario.

The most stringent ecological limits studied were for a maximum rate of temperature increase of 0.1°C per decade, a maximum temperature increase and sea-level rise by 2100 of 1°C and 20 cm (respectively) above 1990 levels. Such limits may enable many, but not all, ecosystems to adapt, and may limit to some degree the danger from sea-level rise over the next century. In this scenario the allowed maximum rate of

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[77] The Berlin Mandate (Decision 1/CP.1) paragraph 2(b) specifically states that it will “not introduce any new commitments for Parties not included in Annex I (i.e. developing countries), but reaffirm existing commitments in Article 4.1 and continue to advance the implementation of these commitments in order to achieve sustainable development”. FCCC/CP/1995/7/Add.1 24 May 1995

[78] The MAGICC model was used for these calculations. See Wigley, T.M.L. (1994) MAGICC Model for the Assessment of Greenhouse Gas Induced Climate Change, Users Guide and Scientific Reference Manual, Climate Research Unit, University of East Anglia and NCAR, Boulder Colorado, October 1994

emission reductions after 2010 was assumed to be 2% per year. In this case, to keep emissions below the top of the safe emissions corridor, Annex I emissions must be cut by 48-62% from their 1990 levels by 2010[79].

Table 13 below shows the implications for industrialized country (Annex 1 countries)[80] greenhouse gas emissions relative to 1990 levels of these constraints for two developing country emission growth scenarios, one medium high and the other relatively low. Emissions in 2005 need to be some 23-27% below 1990 levels in 2005 and some 45-54% below in 2010. It should be noted that a sea-level rise to 2100 of 20 cm implies a longer term sea-level rise of some 2-3 times this level.

In one of the least stringent cases studied by the IMAGE team a maximum rate of temperature increase of 0.2°C per decade, a maximum temperature increase and sea-level rise by 2100 of 2°C and 40 cm respectively, were applied to the climate system. Breaching these limits would have a high risk of leading to irreversible ecological damage and major problems from sea-level rise. The allowed maximum rate of emission reductions after 2010 was assumed to be 4% per year. To reach the middle of this corridor, Annex I emissions must be cut by 19-46% from their 1990 levels by 2010.

The maximum permissible emissions limits over the period to 2010 that would allow for the possibility of meeting strong climate protection targets in the future whilst ensuring CO_2 emissions do not have to be reduced at more than 2% per year, amount to a reduction by Annex 1 countries of at least 37% from 1990 levels by the year 2010. Emissions in this range would be at the top of the strong target and in the middle of the weakest climate target studied. Being at the top of the “safe emissions corridor” however would provide relatively few options for future generations.

If such reductions are not met, then it may still be possible to meet ecological limits however this would require much more rapid global reductions of emissions. Whilst being more difficult to achieve it could create major problems for developing countries in the next century. Such problems would be a direct consequence of insufficient early action by Annex 1 countries

The “safe emissions corridor” analysis has significant implications for climate policy. Parties will have to agree on emission reductions of this magnitude if they are to avoid both exceeding ecological limits of climate change and imposing very large emission reduction rates on future generations.

A simplified analysis of this can be seen in Figure 10 which shows the allowed Annex 1 emissions to 2010 assuming that non-Annex 1 (developing countries) emissions grow without restraint during this period[81] for CO_2 stabilization scenarios. Superimposed on

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[79] Alcamo and Kreileman (1996) *op.cit.* pp. 327-328. The smaller reduction refers to the top of the corridor and the larger to the middle.

[80] This refers to Annex 1 of the Climate Convention which is the list of industrialized countries, including central and eastern Europe and countries of the former Soviet Union which are subject to legally binding controls on greenhouse gas emissions.

[81] Approximately the IPCC business as usual (IS92a) scenario for non-Annex I countries.

this is the emission profile corresponding to the top of the safe emissions corridor for the ecological limits calculated by the IMAGE model.

It is clear from the IMAGE analyses that if strong ecological goals are to be met the minimum and urgent first step required to move the world toward protecting the climate is a cut in industrialized country CO_2 emissions of at least 20 per cent below 1990 levels by the year 2005. The European Environment Agency has found, based on the IMAGE safe emissions corridor analysis, that, depending on action to stop deforestation globally and on the transfer of clean and renewable technologies to developing countries, a reduction in emission of around 30-55 per cent by 2010 for industrialized countries will be needed to avoid ecologically dangerous climate changes.

Table 13 IMAGE "Safe Emissions Corridor" - Annex I emission reductions for 20 cm sea-level rise target[82]

Annex I emission reductions relative to 1990 levels for the top of a "safe emissions corridor" for a 20 cm sea-level rise target.	2005	2010
Medium to high growth in developing countries (IPCC scenario IS92a)	27%	54%
Low growth in developing countries (IPCC scenario IS92d)	23%	45%

The fundamental environmental constraints for this corridor was the 20 cm maximum sea-level rise by 2100. Such a sea-level rise limit implies a longer term rise over the next several centuries of 40-60 cm given the inertia of the oceans and the time it will take for warming to spread throughout the entire world ocean. Temperature limits up to 2°C by 2100 above the pre-industrial global mean temperature produced the same corridor in this case as the 1°C limit i.e. the sea-level rise constraint is the most significant. The significance of the low growth scenario for developing countries (IS92d) is that it shows how this would effect "allowed" emissions in Annex I countries. A 10% reduction in the growth of non-Annex I (i.e. developing countries) emissions still requires major reductions in Annex I emissions by 2005.

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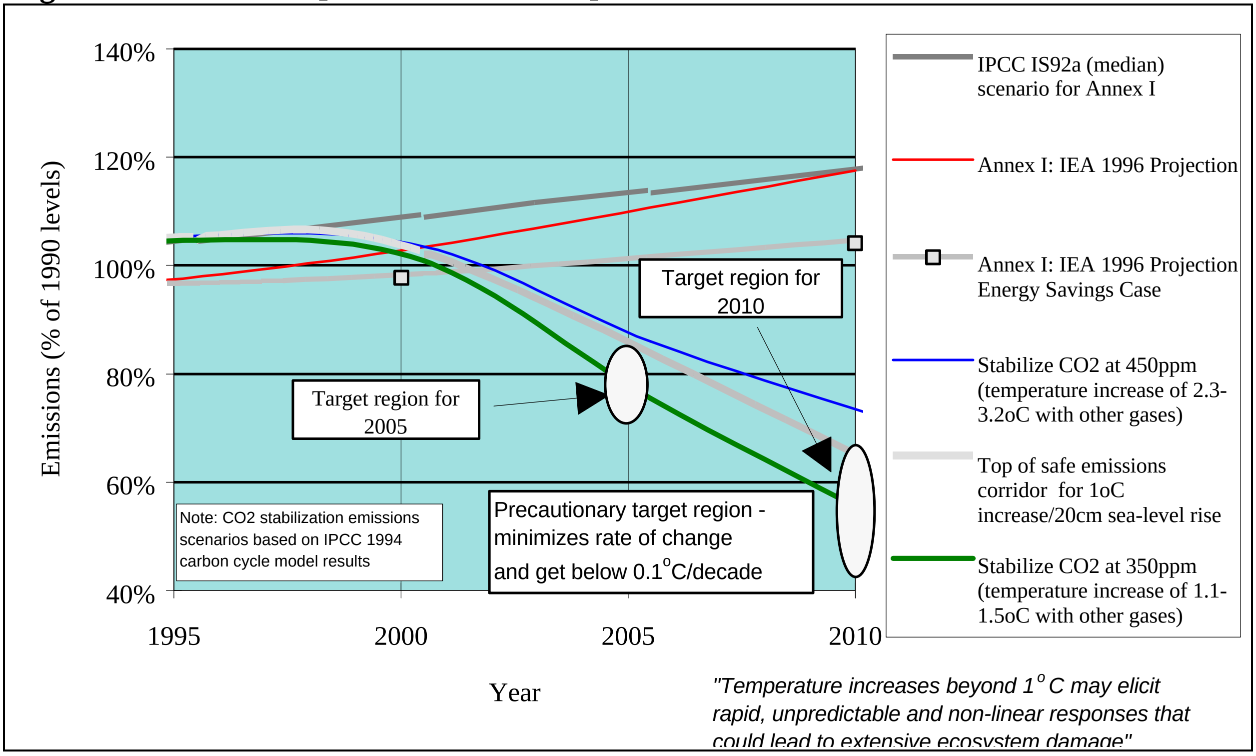
[82] These results were computed by M. Berk at RIVM, The Netherlands.

Figure 10 Annex 1 CO_2 Emissions and CO_2 Stabilization Scenarios



Annex 1 refers to the total emissions of industrialized countries included in Annex 1 of the climate convention.

3.5 Some key uncertainties in evaluating global ecological limits

A range of uncertainties lie behind any attempt to evaluate and set global ecological limits (and calculate corresponding carbon budgets) for an issue as broad and complex as climate change. These uncertainties include, but are not limited to:

(i) How sensitive the climate system is to human interference;
(ii) What kinds and levels of damage a given global temperature rise will cause;
(iii) What level of damage is acceptable to society i.e. what is dangerous climate change.
(iv) The future rate and cumulative volume of emissions.

The last uncertainty has been characterised in the preceding sections covering projections of emissions and their effects and will not be further discussed here.

The first type of uncertainty is explored below, in terms of the temperature rise that a given increase in carbon dioxide levels is expected to cause (climate sensitivity), the risk that temperature rises could be much greater, due to positive feedbacks in the climate system is also discussed. The effects of aerosols (small particles) in reducing this temperature rise is also discussed in this context. Uncertainties in relation to estimates of future sea-level rise are outlined.

The second type of uncertainty raises the question of how good an indicator of damages any global mean indicator can be. Actual impacts may well be driven by rates of change of temperature, local differences in warming and the resulting changes in weather, changes in the frequency of extreme events, shifts in regional climate systems (such as the monsoon or North Atlantic storm tracks) and whether or not major catastrophic events are triggered. These issues are not discussed in any detail here, but they should be borne in mind when ecological limits are considered.

Ultimately, since many of the above effects are difficult, if not impossible, to quantify, decisions must be based on broad indicators of the likely level of damage. Limits on the level and rate of temperature change and sea-level rise must be set so as to avoid dangerous change.

The determination of what is dangerous change is, up to a point, inevitably subjective and dependent on one's view point. Greenpeace believes, however, that a precautionary approach must be taken to uncertainties in our understanding of the climate system, and to what constitutes dangerous change.

3.5.1 Climate Sensitivity

The term "climate sensitivity" refers to the global temperature increase that would occur if atmospheric concentrations of CO_2 were doubled and the climate allowed to stabilize (or reach equilibrium). Since 1990 the IPCC's estimated range for climate sensitivity is between a 1.5 and 4.5^oC increase in global temperature with a 'best-estimate' of 2.5^oC. A higher sensitivity of 3.5^oC may better fit observations and recent advances in the understanding of the climate system.

The 1995 IPCC report provides empirical evidence that the 1990 'best-estimate' of the climate sensitivity is too low. Taking "best-estimates" of aerosol, ozone depletion and solar irradiance effects into account, Chapter 8 of the IPCC 1995 Science Assessment[83] argues that a "best fit" analysis of the recent climate record indicates that the climate sensitivity is more likely to be between 3°C and 4°C. If the best-estimate of climate sensitivity were increased from 2.5 to 3.5°C (or 4.5°C) this would increase the projected warming by 40% (or 80%). The most advanced climate models reviewed in the IPCC Second Assessment Report have climate sensitivities in the range 2.1-4.6^oC with the median of the models being around 3.7^oC[84].

Recent modelling of the role of the tropical ocean and of the operation of the thermohaline circulation system (see section 3.5.5) during the last glaciation, along with new geochemical evidence from fossil corals, groundwater and ice-records, of cooler tropical oceans during the last ice age, implies that the climate sensitivity may be around 4^oC[85]. Webb *et. al.* argue that their results imply that the climate sensitivity is higher than the IPCC 'best-estimate. Whilst these results are controversial, scientific commentators believe that from a risk-averse or precautionary policy perspective these

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[83] IPCC SAR WGI *op.cit.* Chapter 8, p. 424: Santer B. D., T.M.L Wigley, T.P Barnett, E.Anyamba. (1996) Detection of climate change and attribution of causes, Chapter 8 pp. 407-443.

[84] IPCC SAR WGI *op.cit.* Chapter 6, Table 6.3, pp. 298-299. Kattenberg A., F. Giorgi, H. Grassl, G. A.Meehl, J.F.B. Mitchel, R. J. Stouffer, T. Tokioka, A. J Weaver, T.M. L. Wigley (1996), Climate models - Projections of future climate.

[85] Webb, R.S., D.H. Rind, S.J. Lehmann, R.J. Healy and D. Sigman (1997), "Influence of ocean heat trasnport on the climate of the Last Glacial Maximum", Nature, vol. 385, pp.695-699.

results indicated that climate sensitivities higher than the IPCC 'best-estimate' still "have to be seriously considered."[86]

A higher climate sensitivity magnifies the risk created by an increase in greenhouse gas concentrations and also reduces the 'carbon budget' for any given set of global climate targets. From a precautionary policy perspective it would be prudent to base climate policy on a higher climate sensitivity than that adopted by the IPCC as its 'best-estimate'. As this work is oriented at policy based on the precautionary principle, a climate sensitivity of 3.5 °C will be generally used for the analysis. For comparative purposes the results corresponding to the IPCC 'best-estimate' of 2.5°C sensitivity is included in parentheses where appropriate.

Figure 11 shows the relationship between warming limits, equivalent CO_2 concentration (i.e. the concentration taking into account other greenhouse gases – see Section 6 Appendix) and the climate sensitivity. From this graph it can be seen that the higher the climate sensitivity the lower is the equivalent CO_2 concentration corresponding to a given warming limit. A similar relationship holds for the 'carbon budget', as is shown in the Appendix.

Figure 11 Equivalent CO_2 stabilization levels for temperature targets vs. climate sensitivity

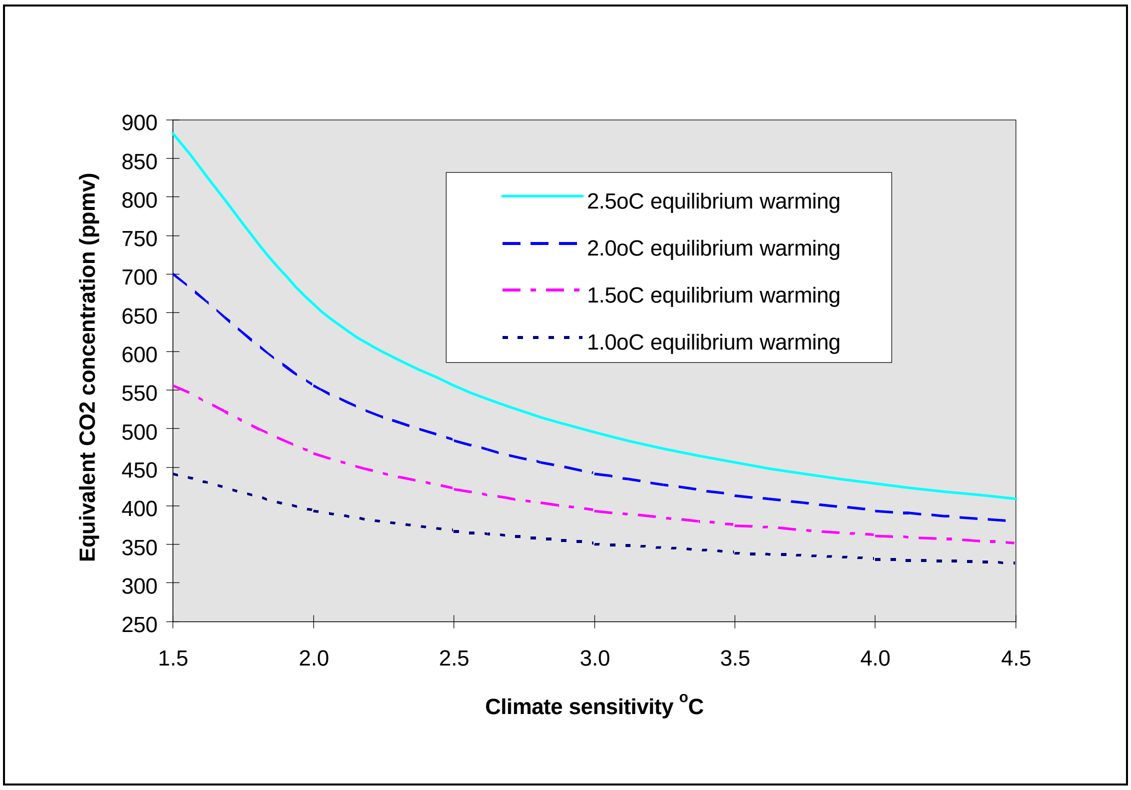

Table 14 illustrates the effect of the uncertainties in the climate sensitivity parameter, on the equivalent and actual CO_2 concentrations corresponding to two different ultimate temperature targets - a maximum increase of 2.0°C above pre-industrial levels

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[86] Harvey, L.D. of University of Toronto quoted in Global Environmental Change Report, vol. IX, no. 4, 28 February 1997, p. 2

and a 1.0°C maximum increase above pre-industrial levels. The latter can be considered a threshold for significant ecosystem damage whereas reaching an increase of 2.0°C would most likely bring about major damage.

The limit of 2.0°C requires that equivalent CO_2 be below 484 ppmv for the IPCC best estimate of climate sensitivity and below 413 ppmv for a sensitivity of 3.5°C. The actual CO_2 concentration (assuming that the forcing of other gases is equivalent to around 23 per cent of the effect of the CO_2 increase alone) is 436 ppmv and 378 ppmv in respectively.

A 1.0°C limit requires, in the long term, that equivalent CO_2 be below 367 ppmv for the IPCC 'best-estimate' of climate sensitivity and below 339 ppmv for a sensitivity of 3.5°C. The actual CO_2 concentration (assuming that the forcing of other gases is equivalent to around 23 per cent of the effect of the CO_2 increase alone) is 348 ppmv and 327 ppmv in respectively. Such levels could be reached in the 22 second century, but only as consequence of policies adopted early in the 21st.

Table 14 Temperature and CO_2 concentration targets vs. climate sensitivity

Climate Sensitivity for CO_2 doubling		CO_2 concentration (ppmv) for 1.0°C maximum increase above pre-industrial global mean temperature	CO_2 concentration (ppmv) for 2.0°C maximum increase above pre-industrial global mean temperature
2.5 °C IPCC "Best -estimate	Equivalent	367	484
	Actual	348	436
3.5 °C best fit to observations	Equivalent	339	413
	Actual	327	384
4.5 °C Upper end of IPCC range	Equivalent	324	378
	Actual	315	357

Other gases are assumed to contribute a further 23% of the radiative forcing of CO_2 only (see below for discussion).

3.5.2 Terrestrial biosphere feedbacks

The IPCC has consistently warned of the potential for human induced climate warming to amplify itself. The existence of powerful positive feedbacks, which act to amplify an initial warming (or climate forcing), is one of the most worrying aspects of the climate system, when considering rising levels of greenhouse gases. In 1990 the IPCC found, in relation to climate feedback processes "it seems likely that, overall, they will act to increase, rather than decrease, greenhouse gas concentrations in a warmer world"[87].

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[87] IPCC First Assessment Report, 1990, p. xviii: J.T. Houghton, G J Jenkins, and J.J. Ephraums (ed.'s) (1990), *Climate Change - The IPCC Scientific Assessment.* Report prepared for IPCC by Working Group I. Cambridge University Press.

Four years later the IPCC found that ice-core records over the past 220,000 years imply the existence of a significant positive feedback:

> *"Additional insights into climatic feedbacks come from ice core records going back over many thousands of years (known as palaeo-records). A clear correlation between atmospheric CO_2 concentration and global temperature (especially during warming periods) is evident in much of the palaeo-record over long time-scales, with increases of about 80 ppmv occurring during deglaciations. This relationship between CO_2 concentration and temperature may carry forward into the future, possibly causing a significant positive climate feedback on CO_2 fluxes."*[88]

Similar relationships for methane are observed from the palaeorecords, with the IPCC finding that that the positive relationship between CH_4 concentration and temperature, as for CO_2, may carry forward into the future[89].

The role of the terrestrial biosphere as a potential source of CO_2 and CH_4 emissions in response to rapid climate change is quite fundamental. The role of oceans is also important and is discussed in section 3.5.5 below.

The IPCC Second Assessment report has added to concerns over the role of the terrestrial biosphere indicating that climate warming could lead to it releasing major amounts of CO_2 and other greenhouse gases. Sustained, rapid climate change could lead to forest dieback altering the terrestrial uptake and release of carbon. The annual volume of carbon that could be released should the terrestrial biosphere release carbon in response to climate change is significant relative to human emissions. The IPCC found with medium confidence that:

> "*Large amounts of carbon may be released transiently into the atmosphere as forests change in response to changing climate and before new forests replace the former vegetation. The loss of above ground carbon alone has been estimated to be 01.-3.4 $GtCyr^{-1}$ or a total of 10-240 GtC."*[90]

Such large feedbacks would make it very difficult to control the problem of climate change once started. This issue is particularly pressing as these feedbacks were estimated in response to the equilibrium climate effects of CO_2 doubling. Doubling of equivalent CO_2 concentration (above pre-industrial levels) is likely to occur by 2030 or 2040, unless action is taken. Significant emissions from the biosphere could overwhelm attempts to stabilize CO_2 concentrations and meet ecological targets.

Other terrestrial feedbacks identified by the IPCC include[91]:

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[88] IPCC 1994, op.cit., p25.

[89] IPCC 1994, op.cit., p. 27.

[90] IPCC SAR WGII op.cit., p. 97: M.U.F Kirschbaum, A. Fischlin (1996) Climate change impacts on Forests, Part II Chapter 1 pp. 95-129.

[91] IPCC SAR WGI op.cit., Chapter 9: J. M Melillo, I.C Prentice, G.D. Farquhar, E.-D. Shultze, O.E Sala. (1996) Terrestrial biotic responses to environmental change and feedbacks to climate Chapter 9 pp. 445-481.

- Release of carbon from drying out of high latitude wetlands. Whilst the rate of release is uncertain the ultimate volume of carbon may be quite large as there are 450 GtC stored in these systems.

- Increased release of nitrous oxide from warmer, wetter soils.

- Effects of land-surface changes. Albedo changes from the replacement of tundra by forests in northern high latitudes with warming may amplify the initial greenhouse gas forcing.

- Plant physiological effects of CO_2 on climate. Reduction in stomatal conductance as CO_2 concentration increases could significantly enhance the surface warming over terrestrial areas as a consequence of reductions in evapotranspiration and increases in soil moisture.

- Carbon fertilization effect. Increases in CO_2 can enhance plant productivity, which is assumed to continue at a rate linked to the CO_2 concentration, and is a negative feedback. However the 1994 IPCC report concludes that “when the availability of water and nutrients is taken into account the fertilization effect is likely to be reduced; several model results suggest reduction by around a half”[92].

Overall, the effects of climate feedbacks on the biosphere, induced by rising CO_2 level’s could lead to CO_2, and other greenhouse gas levels, rising even faster, and potentially counteracting the effect of emission controls. If deforestation continues then the capacity of the forests and other natural vegetation to absorb CO_2 will be diminished and may even become negative, exacerbating this problem.

3.5.3 Role of Aerosols

At a global average level aerosols are calculated to have offset some of the effects of the increase in greenhouse gas concentrations to date.

In 1990 the CO_2 concentration of the atmosphere was 355 ppmv. Other greenhouse gases further increased the enhanced greenhouse effect to a level equivalent to 421 ppmv CO_2 (discounting the effects of sulphur aerosols)[93]. Such an increase corresponds to a long term warming commitment of 2.1°C (1.5°C). Inclusion of the globally averaged radiative effect of aerosols would reduce the calculated warming commitment to about 1.1°C (0.9°C), which would correspond to an equivalent CO_2 level of 343 ppmv. In terms of radiative forcing, the IPCC has estimated the radiative forcing increase over the period 1765-1990, including full aerosol effects, to be 1.32 W/m^2. Without aerosol effects it is estimated at 2.62 $W/m^{2,}$ with the CO_2 radiative forcing contributing 1.52W/m^2 . In

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[92] IPCC 1994 *op.cit*., p. 18.

[93] Equivalent CO_2 concentrations are defined by C_{equiv}=278*exp(ΔQ/6.3)where ΔQ is the radiative forcing due to the increase in greenhouse gas concentrations above pre-industrial levels. See Sect.6.3.2 of IPCC SAR WGI: Kattenberg A., F. Giorgi, H. Grassl, G. A.Meehl, J.F.B. Mitchel, R. J. Stouffer, T. Tokioka, A. J Weaver, T.M. L. Wigley (1996) Climate Models - Projections of future climate, Chapter 6 pp. 284-357.

other words, at a global level, aerosols reduce the net radiative forcing of all other greenhouse gases[94].

This situation has led some to argue for a trade-off between aerosol emissions and greenhouse gases. From a policy perspective, however, there several aspects of the role of aerosols that mitigate strongly against such an approach.

Aerosol cooling effects are limited in time and to particular regions, so are unlikely to significantly reduce actual damages from CO_2 emissions. The UK's Hadley Centre argues that "*although, at first sight, smaller globally-averaged temperature changes might be assumed to imply smaller impacts, this is not necessarily the case.*"[95] Cutting aerosol emissions in future, for example after allowing significant increase, would suddenly reveal a large underlying warming commitment that the high level of aerosol emissions had masked. Aerosol concentration drops quickly (i.e. within weeks) once emissions are reduced, whereas CO_2 concentration takes much longer (i.e. many decades).

In considering scenarios where CO_2 emissions are decreasing, sulphur aerosol emissions will also be declining and at a faster rate than CO_2 emissions. This means that the previous masking effect of aerosol emissions will be reduced, resulting in a positive increase in radiative forcing (relative to 1990) from this effect. However the overall effect on the rate of warming is very small. (Figure 10) shows the rate of warming for various emission scenarios. Emission scenarios lower than 450 ppmv produce a calculated warming rate of a few hundreths of a degree per decade more than the IS92a Scenario in the period to 2005. Beyond 2005, or 2010 at the latest, the rate of warming drops well below the business as usual levels.

The IS92a scenario used to calculate the results in Figure 10 differs from the IPCC in that the sulphur aerosol emissions have been modified to account for the second Sulphur Protocol and US Clean Air Act Amendments. In addition it was assumed that sulphur controls similar to those adopted by the OECD would be used by Asian countries in the future. As a consequence sulphur emissions in 2100 are about the same level as in 1990.

The direct effects of sulphate aerosols, which lead to acid rain effects, on the environment and agricultural systems are very large. As consequence it is quite unlikely that the emissions of aerosols projected in the IPCC scenarios will come about[96]. In other words "relying" on aerosols to "hide" some of the warming from CO_2 emissions would lead to greater risk in the future.

The regional effects of climate change are what are actually important for many climate induced damages and aerosols could have quite significant effects in modifying regional climates. The regional patchiness and short lifetimes of aerosols could increase the range of climatic extremes[97].

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[94] Raper et al (1996) op.cit., Appendix A

[95] Hadley Centre op.cit.

[96] See for example, Global Energy Perspectives to 2050 and Beyond WEC World Energy Council/IIASA International Institute for Applied Systems Analysis (1995).

[97] Hadley Centre op.cit.

From a precautionary perspective it is the long term warming commitment of greenhouse gas emissions that is of paramount concern. For this reason the analysis for evaluating the ‘carbon budget’ in this work will focus on the long term effects of greenhouse gas emissions and will not include aerosol effects.

3.5.4 Uncertainties in sea-level rise estimates

Profound uncertainties surround the projection of future sea-level rise arising from human induced climate change. In terms of improved certainty for policy makers the scientific assessment of this issue appears to have deteriorated significantly over the past decade.

The IPCC's 1990 ‘best-estimate’ of sea-level rise calculated from all sources (thermal expansion of the ocean, small glaciers, the Greenland Ice Sheet and the Antarctic Ice Sheet) was 10.5 cm with range from -0.5 to 22 cm. At that time the ‘best-estimate’ for observed sea-level rise over the past 100 years (to 1990) was 15 cm (with a range from +10 to +20 cm), leaving some 4.5 cm unexplained between the ‘best-estimate’ of calculated and observed changes.

Rather than reduce the uncertainties in explaining past sea-level rise the IPCC Second Assessment has indicated that there is a growing gap between the observed sea-level rise and that calculated to have occurred. The gap between the total best-estimate of calculated contributions to sea-level rise (8 cm) and the ‘best-estimate’ of observed sea-level rise (18 cm) has doubled. The range of uncertainty in the calculated sea-level rise has increased significantly and is now from minus 19 to plus 37 cm. At the same time the contribution of the Greenland Ice Sheet has been reduced to zero with a range of -4 to +4 cm, down from 2.5 +/-1.5 cm in the 1990 IPCC Assessment.

This situation should be sounding alarm bells to policy makers. Without improving certainty in explaining past sea-level rise their can be little confidence in the estimates of future sea-level rise. The state of understanding in relation to the contribution of the Greenland and Antarctic ice sheets to sea-level rise has not improved between the First and Second IPCC Assessment reports. The IPCC has however warned clearly of the implications of uncertainty in this area as small changes in these ice sheets could have large impacts on sea-level rise:

> *“of all the terms that enter the sea level rise equation, the largest uncertainties pertain to the Earth's major ice sheets”*
>
> and
>
> *“relatively small changes in these ice sheets could have major effects of global sea level, yet we are not even certain of the sign of their present contribution”*[98] (emphasis added).

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[98] IPCC SAR WGI Chapter 7, *op.cit.* p. 396

The future behaviour of the Antarctic ice sheet in response to greenhouse warming is one of the central issues of concern for the predictions of future rate and long term extent of sea-level rise. Profound scientific uncertainty plagues the assessment of the contribution of the Antarctic ice sheet both to sea-level rise over the past 100 years and to projections of future sea-level rise as a consequence of climate change. In the last six years scientific understanding of the quantitative contribution of the Antarctic ice sheet to past sea-level rise has, if anything, deteriorated. At the same time the IPCC 'best-estimate' of the projected Antarctic ice sheet contribution to future sea-level to 2100 has remained slightly negative[99]. If this turns out to be incorrect much larger sea-level rise than currently projected would eventuate in the longer term and possibly much larger rates of change in the shorter term. In addition, the potential instability of the West Antarctic Ice Sheet, whose collapse would raise sea-level by 5-8 metres over several hundred years is of major concern in the assessment of sea-level rise risk from global warming.

The contribution of Antarctica to past sea-level rise is highly uncertain.

The 1990 IPCC 'best-estimate' made for the Antarctic ice sheet contribution to sea-level rise over the past 100 years was zero cm (with a range of +/- 5 cm. Warrick and Oerlemans point out in summing up the evidence that:

> *"the 'zero' entries [for the Antarctic ice sheet contribution to sea level rise] should be interpreted as a reflection o f the current poor state of knowledge, rather than as an estimate of the current state of balance."*

and further that

> *"a large positive mass balance of both ice sheets would seem unlikely, as it would have led to a substantial sea level lowering and would therefore be highly inconsistent with the observed sea level rise."*[100]

In the 1995 IPCC Assessment it was found that disagreement over the contribution of Antarctica had widened:

> *"the paucity of data does not allow a meaningful judgement of the current state of balance of the Greenland and Antarctic ice sheet s. Different workers claim changes with even different sign..."*[101]

Whilst the 'best-estimate' of the calculated Antarctic ice sheet contribution to past sea-level rise remained zero the range was increased significantly to plus or minus 14 cm[102]. This uncertainty range is 160% of the 'best-estimate' for observed sea-level rise of 18 cm (range +10 to +25 cm).

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[99] IPCC SAR WGI Chapter 7, *op.cit.* p. 364

[100] Warrick. R.A. and H. Oerlemans (1990) "Sea Level Rise", Chapter 9 in IPCC SAR WGI *op.cit.*

[101] IPCC SAR WGI Chapter 7, *op.cit.* p. 376-377

[102] IPCC SAR WGI Chapter 7, *op.cit.* p. 380

In relation to future sea-level rise both the 1990 and 1995 IPCC Assessments found that the Antarctic ice sheet should contribute negatively to future sea-level rise as rising temperatures should lead to more precipitation over Antarctica (leading to a greater net accumulation of ice)[103]. However well based this judgement is it is fundamentally undermined by the fact the sea-level rise of the last century cannot be explained and where the sign of the role played by Antarctica (and to a lesser extent the Greenland Ice sheet) remain unknown.

The bottom line from a risk assessment perspective is that the large unexplained gap between 'best-estimate's of the calculated and observed sea-level rise could easily be explained by a negative mass balance for the Antarctic ice sheet that is:

- Well within the range of uncertainty in the IPCC estimates

- Consistent with estimates of Antarctic Ice Sheet mass loss not reported in the IPCC Second Assessment but reported in the peer reviewed literature[104].

  At present global sea-level appears to be rising by about 1 to 2.5 mm per year. Although both thermal expansion of the ocean and melting of small glaciers are accounted for in the estimates, the major source of water (25 per cent) for the current level rise is unknown[105]. It is possible that part of this "missing water" comes from meltwater escaping unnoticed for years from the polar glaciers[106]. On the basis of recent estimates of basal melting (melting from the bottom of floating ice shelves) Jacobs et.al.[107] have suggested that "the Antarctic ice sheet is currently losing mass to the ocean."

- Consistent with numerical modelling of the Antarctic ice sheet reported by the IPCC in 1995[108].

These factors point towards a serious concern that the IPCC assessment is not conveying sufficient information to policy maker on the grave risks posed in terms of large, long term, irreversible sea-level rise by the effects of greenhouse warming on the Antarctic Ice Sheet and to a lesser extent the Greenland Ice Sheet.

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[103] IPCC SAR WGI Chapter 7, op.cit. p. 363.

[104] Jacobs, S.S. (1992), "Is the Antarctic ice sheet growing?" Nature, Vol. 360 pp. 29-33., Jacobs, S.S., H.H. Hellmer, C.S.M. Doake, A. Jenkins and R.M. Frolich, (1992) "Melting of ice shelves and the mass balance of Antarctica" , J. Glaciology, Vol. 38 No. 130 pp. 375-386 and Jacobs, S.S., H Heller, A Jenkins (1996) "Antarctic ice sheet melting in the Southeast Pacific", Geophysical Research Letters, Vol. 23 No. 9 pp. 957-960.

[105] Zwally, H.J. (1994) "Detection of change in Antarctica", in: Hempel, G (ed.), Antarctic Science: Global Concerns, Springer-Verlag, Berlin, pp. 126-143.

[106] Jacobs et.al.(1992), op.cit.

[107] Jacobs et.al.(1996), op.cit. Floating ice shelves do not contribute do sea-level rise if they melt, however large melting rates may indicate a net movement of ice on the land (ice shelves and glaciers) to the sea, which would raise sea-level.

[108] IPCC SAR WGI Chapter 7, op.cit.

3.5.5 Oceanic feedbacks on the carbon cycle

Warming of the Southern Ocean (and surrounding oceans south of 30°S latitude) in response to rising CO_2 levels could play a significant role in determining the ultimate levels of CO_2 in the atmosphere. The oceans play a significant role in the global carbon cycle and hence in controlling the level of CO_2 in the atmosphere. CO_2 is taken from the atmosphere by the oceans and stored in the deep ocean, with the average ocean uptake over the 1980's being around 2 GtC/yr. offsetting some of the average 5.5 GtC/yr. emissions from fossil fuels over this period.

In calculating future atmospheric CO_2 levels the IPCC assumed that ocean currents and temperature would not change[109], however it is well established that global warming would lead to significant changes in the ocean circulation. Feedbacks from ocean circulation changes induced by climate change to the carbon cycle could play a significant role in determining the future levels of atmospheric CO_2.

There are three main processes which determine the future role of the ocean in terms of its capacity to take up a fraction of human emissions of CO_2:

- Sea-surface temperature feedback.

  Warmer sea surface temperature lowers the solubility of CO_2 in the oceans. In 1994 the IPCC estimated that there would be a weak positive feedback between a global increase in sea surface temperature and atmospheric CO_2 estimated at 10 ppmv of CO_2 for each 1 degree rise in temperature.

- Changes in the oceanic circulation

  Coupled Ocean-Atmosphere General Circulation Models (AOGCMs) indicate significant changes in the ocean circulation and in particular a weakening of the thermohaline system in response to rising greenhouse gas concentrations[110]. This would result in less transport of CO_2 enriched surface water to depth, reducing the capacity of the oceans to take up carbon.

- Changes in the marine biological carbon pump

  An important component of the carbon cycle is the so-called marine biological pump which “exports” excess carbon (dead organic matter) to the ocean depths. Modelling indicates that the marine biota plays a major role in regulating CO_2. In the atmosphere - without marine biota it has been calculated that the pre-industrial CO_2 levels would have been 450 ppmv rather than 280 ppmv.

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[109] Schimel et. al. (1996) Chapter 1 in IPCC SAR WGI op.cit. and Sarmiento, J.L. and C. Le Quere (1996) “Oceanic Carbon Dioxide Uptake in a Model of Century-Scale Global Warming”, Science Vol. 274 pp. 1346-1350.

[110] See for example Stocker, T.F. and A. Schmittner (1997) op.cit.

Scientific uncertainty in relation to competing processes in the response to global warming of the biological carbon pump and of the ocean circulation system, as well as a lack of data and adequate models, mean that it is difficult to ascertain the implications of rising CO_2 levels for this major component of the carbon cycle.

Since the conclusion of the IPCC Second Assessment Report Sarmiento and Le Quere[111] have published the first coupled AOGCM calculations of the effects of rising CO_2 levels on the oceanic uptake of carbon. Their model includes a simple representation of marine biological processes and has been used to estimate the effects of a doubling and a quadrupling of CO_2 concentration. The results show that the most of the oceanic uptake of carbon occurs in the Southern Ocean and that this ocean has the largest impact on the response of oceanic CO_2 uptake to global warming.

Several conclusions can be drawn from Sarmiento and LeQuere's calculations of the oceanic scenarios involving a doubling and a quadrupling of CO_2.

The weakening or collapse of the thermohaline circulation leads to a major reduction in the oceanic uptake of CO_2. This significantly increases the rate of growth of future atmospheric CO_2 concentrations. There is a 140 GtC reduction in CO_2 uptake between Sarmiento and Le Quere's baseline scenario (without ocean circulation changes) and the scenario including these changes over 100 years. This would represent a strong feedback to the climate system adding over 60 ppmv CO_2 to the atmosphere.

Changes to the marine biota are likely to offset some but not all of the effects of oceanic circulation changes[112]. The largest increase in biological CO_2 uptake is in the southern ocean.

The overall implications from a policy perspective of this work appears to that:

- The anthropogenic CO_2 emissions corresponding to concentration stabilization levels are likely to be lower than the IPCC has previously estimated when the effects of oceanic feedbacks are taken into account.

- Atmospheric CO_2 levels for a given set of emissions are likely to be greater and hence the global warming will be higher than the IPCC best-estimate calculations for emission scenarios.

3.6 Global Ecological Targets

Objectives for global ecological targets for climate policy need to be based on the precautionary principle, which is incorporated into the Climate Convention through its ultimate objective to prevent dangerous interference in the climate system. Ecological targets need, in effect, to be surrogate measures of the risk of climate change and

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[111] Sarmiento and Le Quere (1996) *op.cit.*

[112] See Table 3 of Sarmiento and Le Quere (1996) *op.cit.*

hence linked to both the rate and the magnitude of changes that occur as a consequence of increases in greenhouse gas concentrations.

Two kinds of global climate targets have been put forward, one based on the concentration of greenhouse gases and the other on surrogate measures of impacts - the rate and magnitude of global mean temperature and sea-level rise.

One of the key problems with concentration based goals is that dangerous rates of climate change are significantly determined by the trajectory (or time path) of emissions. Impacts of climate change are not caused by the increases in greenhouse gas concentrations but by the consequential changes in the climate. Concentration targets do not help deal with the question of the timing of emission reductions in order to minimise damage nor are they a good surrogate for impacts.

Uncertainties in the climate sensitivity make the use of long term concentration goals as a surrogate for the impacts of climate change misleading at best and at worst potentially quite dangerous. Whilst uncertainties in the climate sensitivity are relevant to any global ecological targets this presents peculiar problems for concentration goals. The key danger which arises from the use of a concentration target is that it does not focus policy attention on the inertia of the climate system . One of the most crucial and pragmatic questions of climate policy, that of what needs to be done in the short term in order that options are protected for the future, is answered in a potentially dangerous manner. In policy terms a concentration goal implies that the magnitude of emissions in the short term do not matter to the prevention of dangerous climate change. This overlooks the need to limit the rate of change.

If policy assumes that emissions in the short term do not matter, based on a concentration goal, and subsequently it is found that the concentration needs to be lowered considerably there is a significant risk that the second target may not be achievable. On the other hand policy based on the ecological targets described above, using an approach such as the “safe emissions corridor” methodology is capable of responding much more safely and dynamically to changing science and objectives

Efforts to set global ecological goals have tended to adopt, in a sometimes confusing manner, both a climate and a concentration target. The European Union Environment Council, for example, has proposed that the increase in global average temperatures should not be allowed to exceed 2°C above pre-industrial levels. However in doing so it also nominated a maximum CO_2 level[113]:

> *“Given the serious risk of such an increase and particularly the very high rate of change the Council believes that global average temperatures should not exceed 2 degrees (Celsius) above pre-industrial level and that therefore concentration levels lower than 550 (parts per million of)* CO_2 *should guide global limitation and reduction efforts. This means that the concentrations of all greenhouse gases should also be stabilised. This is likely to require a*

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[113] European Community (1996) Climate Change - Council Conclusions 8518/96 (Presse 188-G) 25/26.VI.96

> *reduction of emissions of greenhouse gases other than CO_2, in particular CH_4 and N_20."*[114]

The European Union's goal of not exceeding 2°C can be translated into a CO_2 equivalent concentration range of 380-560 ppmv depending on the climate sensitivity assumed for a CO_2 doubling. Figure 14 shows the large difference in CO_2 emissions corresponding to this range ranging from immediate reductions to approximately constant emissions at above current levels over the next century. With the IPCC best-estimate of climate sensitivity the EU target would correspond to 484 ppmv CO_2 equivalent. If the climate sensitivity is 3.5°C, as assumed in this report, then the equivalent CO_2 concentration would be 71 ppmv lower i.e. 413 ppmv. Whilst the EU Council Decision refers to atmospheric CO_2 concentrations being kept below 550 ppmv in order to not exceed the 2°C limit it is clear from both the wording of the decision and from the science that this is an extreme upper bound. In any event the European Union's 2°C limit itself carries with it the risk of large, irreversible and dangerous changes.

From the scientific domain, Azar and Rodhe argue that international climate policy should aim to ensure that that global mean changes should not "substantially" exceed the natural fluctuations of the last thousand years of around 1°C:

> *"The burden of proof must lie on those who argue that it is safe and acceptable to cause changes in the global climate system that substantially exceed the natural fluctuations during the past millennium. Given that this fluctuation in global average surface temperature is around 1°C (or less), a temperature increase by 2°C may be seen as such a critical level. Until it has been proven that a temperature increase above 2°C is safe or that the climate sensitivity is lower than the central estimate, ... the global community should initiate policies that make stabilization in the range of 350 to 400 ppmv possible."* [115]

With the radiative forcing assumptions made by Azar and Rodhe[116] this corresponds to an equivalent concentration range of 410-468 ppmv and an equilibrium warming of 1.4-1.9°C for the IPCC best-estimate climate sensitivity and 2.0-2.6°C for the climate sensitivity of 3.5°C used in this work.

From the point of view of the precautionary principle and taking into account knowledge of the impacts of climate change on species and ecosystems, Azar and Rodhe's target appears to high. A more robust approach would be to ensure that climate policies are aimed at making it possible to limit the long term warming to within the natural variability observed in the past few thousand years over periods of decades to centuries i.e. below 1°C. Given the large warming commitment built into the climate system as consequence of historic emissions this may mean that the

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[114] The Danish government has gone further in announcing that it is directing its energy and climate policy in manner that would be consistent with a global target of keeping CO_2 levels below 450 ppmv, with 20% reduction on 2005 and a greater than 50% reduction by 2030.

[115] Azar, C and H. Rodhe, "Targets for Stabilization of Atmospheric CO_2" in Science, vol. 276, 20 June 1997; p. 1818-1819.

[116] Azar and Rodhe assume a radiative forcing of 1 W/m^2 for non greenhouse gases.

observed warming over the next several decades exceeds this limit. Nevertheless, limiting the period of this exceedance maybe the only way of minimizing or avoiding dangerous impacts.

As can be seen from the foregoing discussion concentration goals such as 450 and 550 ppmv are far too high to be adopted as global ecological targets, quite apart from the general problems with adopting concentration goals as the basis for long term ecological targets.

As a consequence of these and other concerns Greenpeace believes that international climate policy on greenhouse gas emissions should aim to meet a set of global ecological targets:

(i) Limit the long term increase of temperature to less than 1°C above pre-industrial levels.

(ii) Bring the rate of climate change to below 0.1°C/decade as fast as possible, within a few decades at the most. Warming rates over the next century are projected to be in the range 0.2-0.3°C/decade.

(iii) Limit long term global average sea-level rise to less than 20 cm.

A sea-level rise of this extent would still lead to some damage for low lying islands and coastal areas, however higher levels would lead to rapidly rising risk. A warming limit of 20 cm by 2100 would entail an ultimate sea-level rise of 40-60 cm if there are no surprises in, for example, the behaviour of the large Greenland and West Antarctic Ice sheets. There is a high degree of inertia in relation to sea-level rise. It seems likely, for example, that around 10 cm of sea-level rise are already commited over the next century as a consequence of historic greenhouse gas emissions.

(iv) Bring the rate of sea-level rise to below 20mm/decade. This would permit the vast majority of vulnerable ecosystems, such as natural wetlands and coral reefs to adapt.

These four key global ecological targets need to be met simultaneously. In meeting these limits the emission pathway (i.e. the timing of emissions cuts) is very important. Given the uncertainties involved and the need to apply the precautionary principle, greenhouse gas emission policies aimed at meeting these targets should use a climate sensitivity of 3.5^{o}C rather than the ‘best-estimate’ of the IPCC.

The focus in the next section however is on overall limits to the emissions of CO_2. Whilst methodologicall this necessarily must focus on overall warming limits, rather than on the rate of change, the .

4. Carbon Budgets for warming limits

4.1 Calculating a 'carbon budget'

For the purposes of evaluating a budget for the period to 2100 a long term warming commitment is used as the fundamental constraint. This can be translated into an atmospheric CO_2 concentration making assumptions in relation to several factors including the climate sensitivity, the role of other greenhouse gases and the time horizon for the calculation. The cumulative CO_2 emissions that would lead to the level of CO_2 corresponding to these assumptions is then derived essentially using IPCC best estimates of the carbon cycle. Table 15 summarises the results of the 'carbon budget' analysis for specific concentrations levels and temperature targets. The Appendix to this report contains the basis for calculating the 'carbon budget' described here for different long term warming limits.

Uncertainties surround these calculations. The effects of those mentioned above and that of the trajectory of emissions and of carbon cycle model uncertainties, have been estimated in assessing the overall 'carbon budget'. If all sources of uncertainty are independent then the overall uncertainty in the 'carbon budget' for a given temperature target is around 50%. Uncertainties associated with the 'carbon budget' for a given CO_2 stabilization level are smaller, of the order of 15%. Much of the difference is due to uncertainty in the climate sensitivity.

Numbers in parenthesis in this section refer to estimates of climate change or carbon budgets for a climate sensitivity of 2.5^{o}C.

4.1.1 Ecological Target - 1^{o}C

The total allowed 'carbon budget' up to 2100 to limit long term global average temperature increase to below 1^{o}C above pre-industrial levels is in the range of 110-340 GtC for a climate sensitivity of 3.5^{o}C (150-455 GtC for a climate sensitivity of 2.5^{o}C). Central estimates respectively are 225 GtC and 295 GtC.

4.1.2 EU Temperature Limit - 2^{o}C

The central estimate of the total allowed 'carbon budget' up to 2100 that would limit the long term global average temperature increase below 2^{o}C above pre-industrial levels is 410 GtC for a climate sensitivity of 3.5^{o}C[117].

4.1.3 Concentration Limits

Discussion has occurred in the international climate negotiations on long term CO_2 concentration limits of, for example, 450 ppmv or 550 ppmv. Stabilizing actual or

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[117] The range is 205- 620 GtC. For a climate sensitivity of 2.5^{o}C the range is 295-875 GtC with a central estimate of 585 GtC

equivalent CO_2 at either of these levels would require that total carbon emissions be limited in the range of 500-870 GtC respectively over the next 100 years (See Table 15) The long term temperature rise corresponding to these levels would span 2.4 ^oC (1.7 ^oC) to 4.2 ^oC (3.0 ^oC), far in excess of the ecological limits outlined above.

Table 15 CO_2 Concentrations, cumulative emissions, global temperature increase

CO_2 Equivalent (ppmv)	339	350	369	413	450	484	503	550	643
CO_2 Actual (ppmv)	327	335	350	384	411	436	450	464	550
Temperature increase for 2.5^{o}C climate sensitivity	0.7	0.8	1.0	1.4	1.7	2.0	2.1	2.5	3.0
Temperature increase for 3.5^{o}C climate sensitivity	1.0	1.2	1.4	2.0	2.4	2.8	3.0	3.5	4.2
Estimated Cumulative GtC to 2100	225	250	295	410	500	585	630	720	870
Fossil fuel emissions (GtC) with no action to stop deforestation.	145	170	215	330	420	505	550	640	790

This table shows cumulative carbon emissions corresponding to CO_2 stabilization levels along the corresponding long term temperature increases taking into account the effects of other greenhouse gases. The carbon budgets 1^{o}C and 2^{o}C temperature limits, for both the 2.5 and 3.5^{o}C climate sensitivity levels, are shown. Equivalent CO_2 levels are calculated assuming that the additional forcing of the other greenhouse gases s is 23% of the CO_2 forcing. The uncertainty range for temperature targets is +/- 50%

4.2 *Allowed Fossil Fuel Budget*

An allowed fossil fuel budget corresponding to temperature limits is the total ‘carbon budget’ less net deforestation for the budget period. The IPCC CO_2 stabilization calculations assumed approximately 80 GtC of deforestation emissions over the period to 2100. The range in the IPCC IS92 emission scenarios was 30-95 GtC. In these calculations 80 GtC has been used as the standard deforestation estimate.

4.2.1 No Action on Deforestation

With no action to stop deforestation the fossil ‘carbon budget’ is 145 GtC (215 GtC) for the ecological target of a 1^{o}C maximum long term temperature increase.

For the EU limit of a 2^{o}C increase, the comparable fossil fuel budget is 330 GtC (505 GtC) or much less than half the currently known economically recoverable fossil fuel reserves.

4.2.2 Ecological Target - 1°C

Action to substantially reduce deforestation and to expand afforestation programmes would help stabilize the climate system. Mathematically, for a given total 'carbon budget' the more action than can be undertaken to limit deforestation the more of the total budget that would be available for fossil fuel use. If, for example, a combination of programmes to halt deforestation and to re-afforest were undertaken over the next century that resulted in no net deforestation over that period then the fossil fuel budget would equal the total budget for that period i.e. 225 GtC (295 GtC).

A 225 GtC budget with emissions constant at around 6.5 GtC from 2000 would be extinguished by 2025. With emissions growing at about 2%/year this budget would be used up by about 2020. On the other hand a reduction in Annex I emissions approximately in line with the "safe emissions" corridor analysis by 2010, followed by a steady, but rapid, decline in global emissions thereafter would limit global emissions to around 225 GtC.

Using the central assumptions adopted in this work for the climate sensitivity (3.5°C) and with this budget if CH_4 emissions are cut by 20% by 2015, N_2O 30% by 2020, (with both remaining constant thereafter), and halocarbons are phased out by 2025 then the increase in warming from the 1990 to 2100 is 0.5°C or approximately 1.2°C above the pre-industrial global mean. Temperature would be falling from a peak of about 1.4°C above pre-industrial levels (Figure 12). The best-estimate of the increase in mean sea-level above 1990 levels by 2100 would be around 19 cm and beginning to stabilize[118] (Figure 12). The rate of global temperature change for this scenario is shown in Figure 9 (above), where it is apparent that this scenario leads to quite a rapid drop in the rate of warming.

The effects of other greenhouse gases is quite significant. If the emissions of $CH_{4,}$ N_2O and fluorocarbons from IS92a scenario are used (i.e. no action on other gases) the warming above pre-industrial levels would be about 2°C and the sea-level rise about 31 cm above 1990 levels..

An example of this kind of scenario is the Greenpeace Fossil Free Energy Scenario (FFES)[119] which combines action to reduce fossil fuel emissions with action to halt deforestation and an extensive reafforestation programme. This scenario was designed using the IPCC best-estimate of climate sensitivity of 2.5°C and had a fossil fuel budget of approximately 305-345 GtC. Under this scenario deforestation was reduced by half to 40 GtC and afforestation projected to sequester 80 GtC over the period to 2100. The net emissions over this period were in the range 265-300 GtC.

A higher climate sensitivity of 3.5°C implies a significantly lower total 'carbon budget' than was used in the Greenpeace FFES. If the same deforestation and afforestation programme is assumed then the fossil 'carbon budget' would be around 265-270 GtC.

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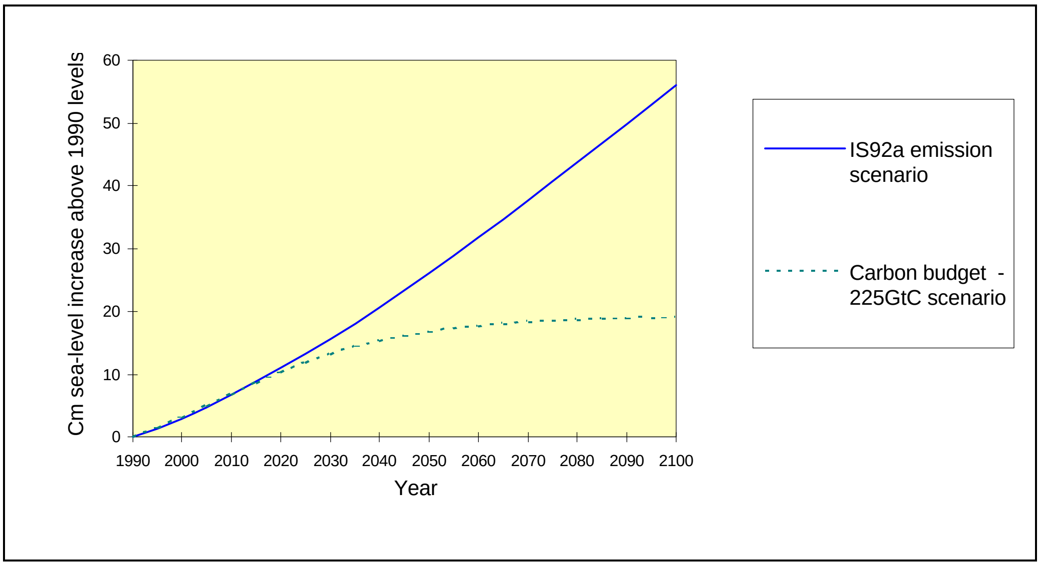
[118] The MAGICC model of Wigley and others has been used here with the IPCC best-estimate gas and sea-level rise parameters. For the emission assumptions described in the text the radiative forcing of the other gases is 21% of that of CO_2.

[119] Lazarus op.cit.

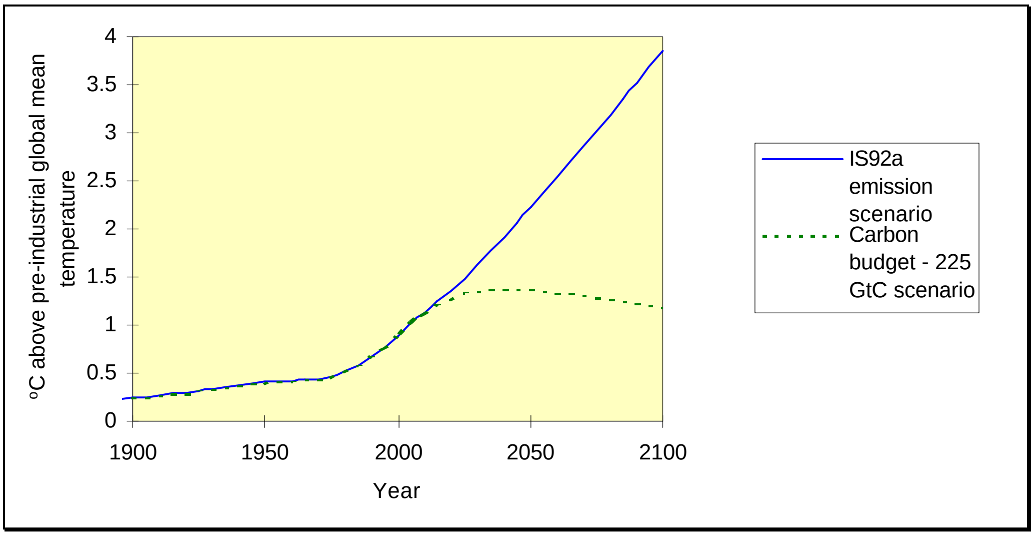
Assuming that the FFES afforestation scenario is close to an upper limit on what might be possible in this area the range of allowable fossil fuel emissions that would enable the ecological targets to be met is 145-265 GtC.

Figure 12 Sea-level rise and temperature increase for 225 GtC carbon budget

(a) Sea-level rise above 1990 levels



(b) Temperature increase above pre-industrial levels



See text for explanation of calculation. A climate sensitivity of 3.5°C was used in this calculation along with IPCC " best-estimates" for sea-level rise parameters.

From a policy perspective it would be necessary to actually achieve gains in emission reductions from deforestation over reasonable time periods (10-20 years) before it would be safe to assume that there could be some offset for fossil fuels within a total emission budget approach. A consequence of a failure to rigorously ensure that gains were made in this area could be that total emissions exceed the budget.

4.2.3 EU Temperature Limit - 2°C

For the EU temperature limit and assuming no net deforestation, the fossil fuel budget is around 410 GtC. This is somewhat higher than earlier estimates.

Krause[120] estimated a 'carbon budget' for fossil fuels for the period 1985 to 2100 based on a similar long term target. His calculations limited warming rates to below 0.1°C and the absolute warming to 2.5°C above 1860 levels, however the budget calculated is lower than that above being around 270 GtC for the period 1991-2100. The differences appear to be due to improvements in carbon cycle modelling. His calculation assumed no net deforestation over this period and a final atmospheric equivalent CO_2 level of 430-470 ppmv with an actual CO_2 level of 380-400 ppmv. This corresponds to a long term warming of 2.2-2.7°C Using current carbon cycle models a budget of 400-465 GtC would correspond to these concentration limits. With the standard IPCC deforestation assumptions this would correspond to a fossil 'carbon budget' of around 320-385 GtC for the period 1991-2100.

The assumptions used in this work yield a higher central estimate for emissions than that of Krause for several reasons. Krause's contribution from other gases is higher (c.a.48% compared to 23% used here). If Krause's assumptions were used here this would decrease the carbon budgets estimated in this work by about 20% (see Appendix). There have been improvements in the understanding of the carbon cycle since 1989 which also change the budget estimates. Taking these and other factors into account Krause's work is consistent with the results found here.

In terms of the overall feasibility of achieving the EU temperature target, the World Energy Council (a body representing the World's Energy Ministers) 'ecological scenario'[121] approximates the reductions and 'carbon budget' that would correspond to the EU limit. This work confirms the overall qualitative features of the FFES work.

The WEC's so called 'ecological scenario' has as its goal to "reduce CO_2 emission levels to 2 GtC by 2100 (corresponding to one-third of current emissions or the 60 percent fall from 1990 levels indicated by the IPCC's 1990 Scientific Assessment as required to stabilise the atmospheric concentration)."[122] In this scenario concentrations of CO_2 rise to 430 ppmv and decline, stabilising by 2100[123], thereby avoiding a doubling of CO_2 levels. In emission terms reductions of some 30% are required in OECD countries by 2020 and nearly 70% by 2050 and over 90% by 2100. In developing countries the rate of emission growth starts to fall below business-as-usual early in the next century and is 25% below this by 2020. Emissions stabilise around 2050 before declining.

The WEC also confirms the findings of the IPCC that early action is needed:

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[120] Krause, F.; W. Bach and J. Koomey (1989) Energy Policy in the Greenhouse: From Warming Fate to Warming Limit, Earthscan Publications Ltd, London.

[121] WEC/IIASA (1995), Global Energy Perspectives to 2050 and Beyond, World Energy Council/IIASA International Institute for Applied Systems Analysis.

[122] WEC/IIASA (1995) *op.cit.* p. 52

[123] WEC/IIASA (1995) *op.cit.* p. 90

> *"In each scenario, the discernible shifts after 2020 toward particular energy sources, fuels, and uses, turn out to be driven largely by choices and developments prior to 2020"*[124].

Whilst the WEC scenario does not slow the rate of warming fast enough nor does it limit the long term increase of sea-level rise and temperature to within the limits adopted here, it does show that large reductions can be achieved but that strong policy interventions are needed to achieve these.

4.3 Fossil fuel reserves

Economically recoverable conventional fossil fuel reserves total 820-1239 GtC. If burnt over the next 100 years this would lead to a long term temperature commitment well above 3.5°C. Unconventional oil and gas adds a further 233-262 GtC to this total, taking the warming commitment to well over 4.5 °C in the long term.

Table 16 summarizes the relationship between the 'carbon budget' for a range atmospheric stabilization scenarios and the total fossil reserve and resource estimates. For the Greenpeace Fossil Free Energy Scenario a total 'carbon budget' of around 300 GtC is used to 2100, which is approximately 30% of the total conventional reserves. The WEC so called 'ecological scenario' (which produces a temperature increase close to the EU 2°C maximum limit) burns around 550 GtC or close to 50% of the total fossil fuel reserves.

Table 16 CO_2 emission scenarios vs. estimates of fossil fuel reserves and resources

Scenario	GtC	% of IPCC Conventional Reserves Identified /Potentials by 2020-2025	% of IPCC Conventional and Unconventional Reserves Identified /Potentials by 2020-2025	% IPCC Resource Base Maximum Potentials
Fossil Free Energy Scenario (FFES)	300	37%	29%	7%
350 ppmv CO_2 stabilization scenario	300	37%	29%	7%
World Energy Council (WEC) 'Ecological Scenario'	550	67%	52%	13%
450 ppmv CO_2 stabilization scenario	630	77%	60%	15%
550 ppmv CO_2 stabilization scenario	870	106%	83%	21%
650 ppmv CO_2 stabilization scenario	1,030	126%	98%	25%
750 ppmv CO_2 stabilization scenario	1,200	146%	114%	29%
IS92a	1,500	183%	142%	36%

This table compares the carbon budgets for IPCC stabilization scenarios with estimates of fossil fuel reserves and resources.

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[124] WEC/IIASA (1995) op.cit. p. 92-93

4.3.1 Economically recoverable coal reserves

Economically recoverable coal reserves total over 646-1,034 GtC, and are enough in themselves to breach any of the ecological limits defined above.

4.3.2 Economically recoverable oil and gas reserves

Economically recoverable conventional oil reserves total in the range 110-124 GtC, which is quite close to the ‘carbon budget’ for the ecological target with no action on deforestation of 145 GtC. Taking into account unconventional resources boosts this amount to 240-275 GtC, about equal to the ecological targets outlined above with stringent action on deforestation.

Conventional gas reserves total in the range 72-81 GtC with unconventional reserves boosting this to 175-192 GtC.

The total of conventional and unconventional oil and gas reserves is in the range 410-467 GtC. This is in excess of the central estimate of the budget required to exceed the EU's maximum temperature increase target.

For all the cases examined involving the 1°C limit the total oil and gas reserves exceed the carbon budgets even before potential coal use and deforestation are accounted for. In this idealized calculations, if unconventional oil and gas are excluded from the assessment then nearly all scenarios would burn more carbon than occurs in reserves, however, the ratio would narrow considerably once coal use and deforestation are subtracted from the budget.

This table shows that the current economically recoverable reserves of oil and gas are sufficient on their own to breach the carbon budgets applying to both a 1 and 2°C temperature limit.

4.4 Fossil fuel resource base

The resource base is the theoretical maximum potential resources available and has been estimated to be over 4,000 GtC (Table 8). It is clear that only a very small fraction (less than ca. 5%) of this could be burnt over the next century if ecological targets are to be met.

5. Conclusions - The Carbon Logic

A number of conclusions can be drawn from the present analysis in relation to the use of fossil fuels and indeed of greenhouse gas emissions over the next century. With action on deforestation a budget for fossil fuels over the next century of around 225 GtC may enable long term warming to be limited to around 1°C.

The present findings are consistent with earlier work, taking into account both the improvements in scientific knowledge over the past decade and the changes in the international policy context.

The conclusion that there must be an ecological limit to burning fossil fuels is robust to a wide range of assumptions. Even if the climate is less sensitive to human interference than the current evidence suggests, or governments fail to take a precautionary approach to setting limits, a 'carbon budget' is will still result which is less than current fossil fuel reserves. This has several implications:

- Coal use needs to be phased out as rapidly as possible. Only a small fraction of the economically recoverable reserves can ever be used. Coal has the highest carbon intensity of the conventional fossil fuels. Coal is subsidised in many parts of the world and these subsidies should be moved, where necessary, to renewable energy systems.

- There should be no further exploration and development of unconventional oil and gas reserves. Estimated economically recoverable volumes of gas and oil in this category are sufficient alone to breach the 'carbon budget'. These resources should not be allowed onto the market as doing so will inevitably lead to cost reductions through production scale effects. This can only make it more difficult to phase out fossil fuels.

- There will need to be significant constraints placed on the technical development and exploration of known oil and gas reserves. Volumes in these reserves, particularly when taking into account the process of reserve appreciation following technical developments are sufficient already to breach the 'carbon budget'.

The timing and location of these actions is important. All of these actions should be undertaken by industrialized countries first as they have the responsibility under the climate convention to do so. It is important that policy signals are sent sooner rather than later. The recent move by Denmark to announce the phase out of the use of coal in that country must only be the beginning.

Greenpeace believes that ultimately CO_2 has to be stabilized at or below current concentrations and that the maximum long term increase in temperature that policy makers should have in mind is 1°C above pre-industrial levels. Avoiding dangerous climate change would require cumulative fossil carbon emissions over the next century to be less than 300 GtC and as low as 145 GtC if no action is taken on deforestation. The central estimate of an allowed fossil fuel budget that would meet the global ecological objectives set by Greenpeace is 225 GtC.

Delaying the beginning of the phase out of fossil fuels will just reduce the amount available for later generations. With the majority of current emissions being in developed countries this could also mean that the overall budget for developing countries would be smaller.

The most important short term step in beginning the phase out of fossil fuels is the adoption by industrialized countries of a legally binding CO_2 emission reduction target for the year 2005 at COP3 in Kyoto. At the same time national governments should be taking steps to:

- Begin the phase out of coal power stations and coal mining.
- Adopt policies to reduce emissions of CO_2 and other greenhouse gases
- Stop plans to allow the expansion of exploration for oil and gas reserves
- Stop all development of unconventional oil and gas reserves.

The ultimate phase out of fossil fuels is technically and economically feasible. The 'Fossil Free Energy Scenario' (FFES)[125] prepared by the Stockholm Environment Institute for Greenpeace in 1993 demonstrates that it is economically and technically feasible to phase out fossil fuels through major improvements in energy efficiency, especially in the transport, buildings and electricity sectors and rapidly introducing renewables such as wind, solar and biomass[126]. Based on a wide range of studies around the world and an economic analysis, the study predicts that a phase-out of fossil fuels can be achieved at a cost equal to or less than "business-as-usual" scenarios.

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[125] Lazarus *op.cit.* Apart from the climate constraint placed on the energy system the scenarios assumes the phase-out of nuclear power by 2010. Fossil fuels are eliminated between 2075 and 2100.

[126] The assumptions for the study were deliberately taken from conventional sources used in other global energy scenario studies, and include United Nations population forecasts of 11.3 billion people in the year 2100, and huge projected increases in global GDP (up by a factor of 14 over the study period) based on IPCC and World Bank studies. They also include assumptions that countries from the South will follow the Northern model of economic development (resource-intensive industrialisation, followed by a move towards the Services sector).

6. Appendix: Calculating a carbon budget

6.1 Introduction

Calculating a 'carbon budget' corresponding to ecological limits can be done in several ways:

1. Dynamic calculation of atmospheric concentrations profiles over time of CO_2 and other greenhouse gases that would conform with all of the limits specified using a climate model or an integrated assessment model. The emissions that correspond to CO_2 can either be back-calculated using a carbon cycle model, if such a model is not included in the original calculation, or a driven by the ecological constraints on the model run.

   Such a calculation requires assumptions be made in relation to the emissions of non-CO_2 gases and hence their role in relation to overall radiative forcing.

   Whilst this method would have the advantage of sophistication in meeting the rate limits of climate change, and in capturing the response times of the climate system, it has the draw back of complexity, model dependent outcomes and the inability to test the effect of different scientific assumptions such as the climate sensitivity.

2. Static calculation of the atmospheric CO_2 concentration corresponding to different temperature limits at equilibrium (or at a specified time in the future). The 'carbon budget' can then be back-calculated using carbon cycle models over different time horizons of interest.

   The focus here is on committed (or equilibrium) warming which is the increase in temperature once the climate system has come into equilibrium with a given increase in greenhouse gas concentrations. This is important to climate policy for several reasons:

   - As a consequence of the inertia of the climate system, whilst atmospheric concentrations are increasing, the observed warming lags behind the committed warming. What this means is that at present, for example, the observed warming is only about 30-50% of the long term committed warming of the increase in greenhouse gases since pre-industrial times. Once atmospheric greenhouse gas concentrations stabilize it will take from several decades to a century for atmospheric temperature to stabilize.

   - The large mass of the oceans mean that "sea-level rise will continue at a scarcely unabated rate for many centuries after concentration stabilization and/or the stabilization of global mean temperature."[127] In

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[127] IPCC SAR WG I Chapter 7.

the case of the lower ecological targets (i.e. 1^{o}C) the sea-level rise after stabilization may not be very large, however in nearly all other cases the sea-level rise after stabilization may be a factor or 2-3 above the rise to the point of stabilization[128].

- A a long-term temperature limit of 1^{o}C mean that global temperature increases may exceed this before atmospheric CO_2 levels decline from their peak values. A focus on long term warming commitment levels is thus essential in designing emissions policy.

The static approach to calculating the 'carbon budget' has the draw back that rate limits are not driving the calculation, however it does enable easy evaluation of the effects of uncertainties in the climate sensitivity parameter, the role of other gases and in the carbon cycle models. This approach may thus underestimate the allowed carbon budget if the rate of change limits are exceeded as a consequence of delayed action or where the rate of climate change or sea-level rise are the dominant constraints on emissions over the time period of the budget calculation. Nevertheless the static approach does provide a relatively easy means of evaluating an allowed carbon budget to meet long term climate constraints.

Taking these factors into account the static system has been used in the following calculation. It involves several steps which are shown schematically in Figure 13:

- Determining the ultimate atmospheric CO_2 concentration corresponding to the warming limit. This involves choosing the climate sensitivity and making assumptions as to the relative role of other greenhouse gases.

- Deciding on the carbon budget time-frame and calculating the carbon emissions that correspond within that time frame, to the warming limits. The warming limits approach adopted here is based on long term equilibrium warming commitment and the time taken to reach this limit may be greater than the time frame over which one wants to compare carbon budgets.

Each of these issues will be discussed below.

6.2 Carbon budgets corresponding to CO_2 concentrations

The purpose of this part of this work is to provide a simple system for estimating the cumulative carbon emissions budget to the year 2100 that would correspond to specific CO_2 concentration stabilization levels. These levels themselves are the product of the ecological limit assumptions and other parameters such as the climate sensitivity and the relative role of other greenhouse gases.

Whilst in principle, having determined an atmospheric CO_2 level corresponding to a set of assumptions, one could use an inverse carbon cycle model to calculate the carbon

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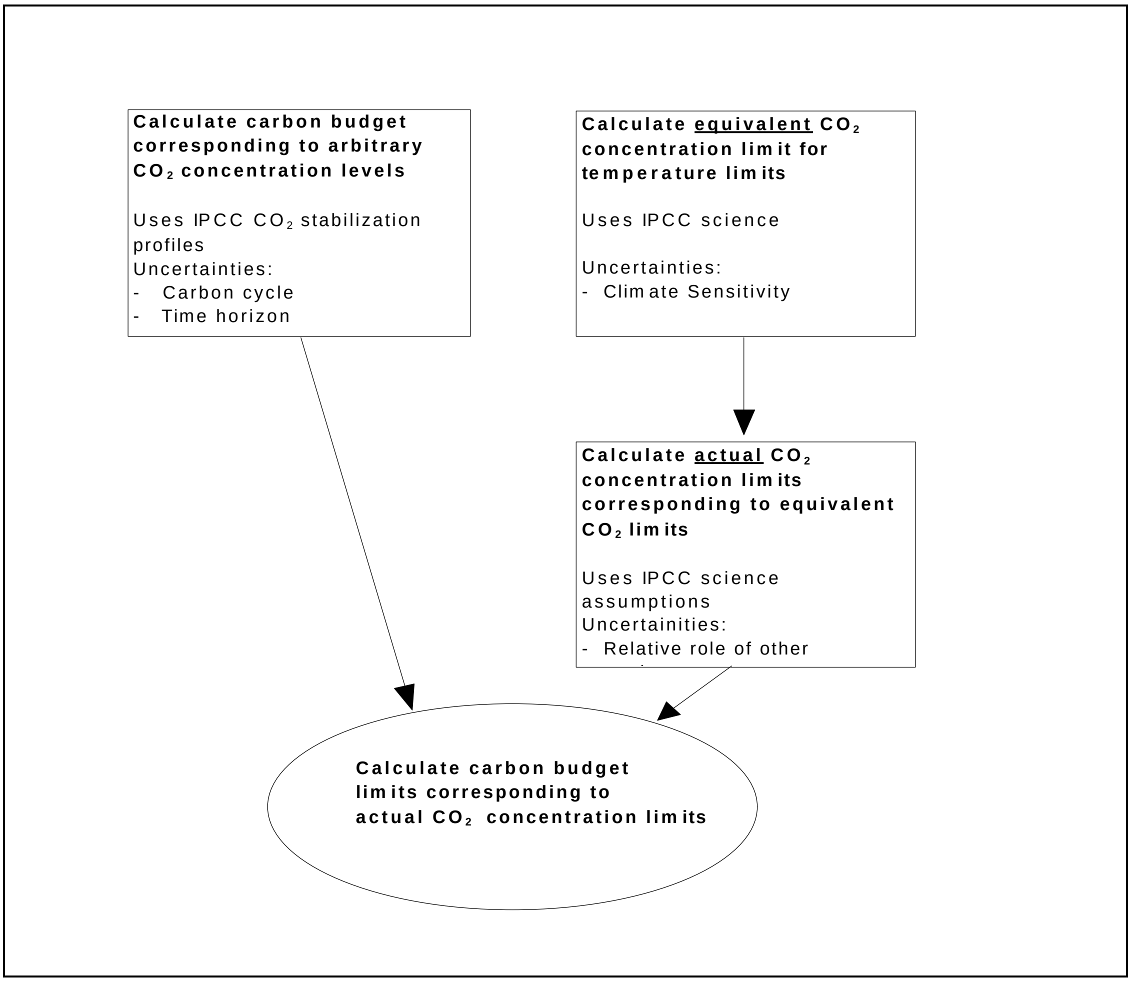
[128] Wigley (1995) *op.cit.*

budgets this would be a cumbersome process. Instead an attempt has been made to use the IPCC carbon cycle assessment and a simple calibration technique to arrive at a simple but relatively accurate means of estimating the carbon budgets.

Figure 13 Calculating the carbon budget



6.2.1 IPCC CO_2 stabilization scenarios

For the purposes of the carbon budget calculation it is useful to review several aspects of the IPCC CO_2 stabilization calculations. In 1994 the IPCC conducted a carbon cycle model intercomparison process which calculated, amongst other variables, the emissions that correspond to standards CO_2 concentration profiles for 350,450, 550, 650 and 750 ppmv.[129]

- Table 17 shows that there is a large range in the estimated emission budget for each CO_2 stabilization scenario. For the lower concentration scenarios the range of emissions is quite large in absolute terms relative to the overall budget. The range of the 350 ppmv scenario corresponds to an uncertainty range of

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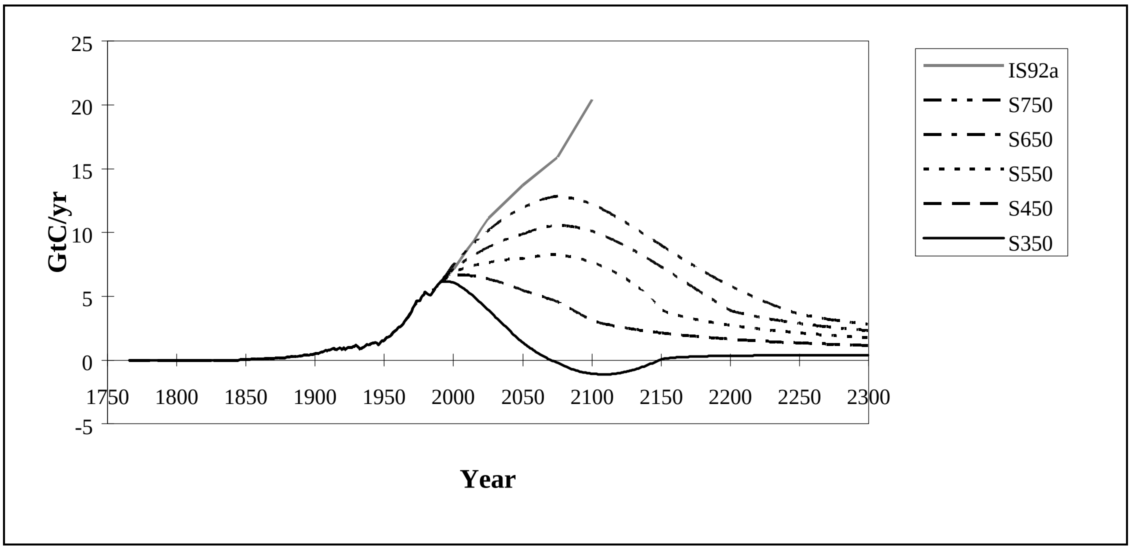
[129] Enting et.al. (1994) *op.cit.*

plus or minus 25% from the mid-range value. This reduces to an uncertainty range of plus or minus 15% for the 450 ppmv scenario.

- The budgets for the concentration scenarios were reduced by around 7% as a consequence of the incorporation of improved scientific understanding from the 1994 to 1995 IPCC Assessments (Table 17).

- The emissions pathway can affect the overall budget. Table 18 compares the budget for the standard IPCC scenarios and the so-called delay scenarios, where action to change the path of emissions from business as usual is delayed some 5-20 years (see caption to this table for explanation). The effects of the delay scenarios is to increase the total amount of carbon emitted that can be emitted because in the models higher CO_2 concentrations lead to larger rates of uptake of carbon by the oceans and the terrestrial biosphere. These effects are largest in the higher concentration cases and are negative from below 450 ppmv. However it is important to remember that delaying action could have other adverse effects, for example, increasing the rate of warming and likelihood of surprises and catastrophes.

Figure 14 Fossil CO_2 emissions corresponding to the IPCC stabilization scenarios



This figure shows the annual CO_2 emissions calculated for the IPCC concentration profiles outlined in Figure 8. In addition the IPCC business as usual emissions scenario (IS92a) is shown. Each of the S scenarios exhibit the same general feature - after a certain period emissions decline ultimately towards a lower level than in 1990.

Table 17 Carbon cycle model uncertainties

IPCC 1994 carbon cycle model budgets	Year of Stabilisation GtC	Min. GtC	Average GtC	Max. GtC	Range GtC	IPCC 1994 mid range estimates GtC	IPCC 1995 mid range carbon cycle estimates GtC	Difference GtC
S350	2150	258	345	415	157	322	300	-22
S450	2100	606	684	790	185	677	630	-47
S550	2150	860	936	1047	188	930	870	-60
S650	2200	988	1083	1225	237	1104	1030	-75
S750	2250	1207	1280	1405	198	1282	1200	-182

This table shows the relative uncertainties in the carbon cycle budgets used to derive the carbon budgets corresponding to the stabilization of atmospheric concentrations of CO_2. The range for the 350 ppmv scenario is from 260 to 415 GtC corresponding to fossil emissions of approximately 180-335 GtC (including 80 GtC deforestation) with a mid-range estimate of 220 GtC to the year 2100. The mid range 450 ppmv estimate for fossil emissions would be 550 GtC with a range of 440- 535 GtC.

Table 18 Total anthropogenic CO_2 emission budgets to 2100: delay vs. immediate action

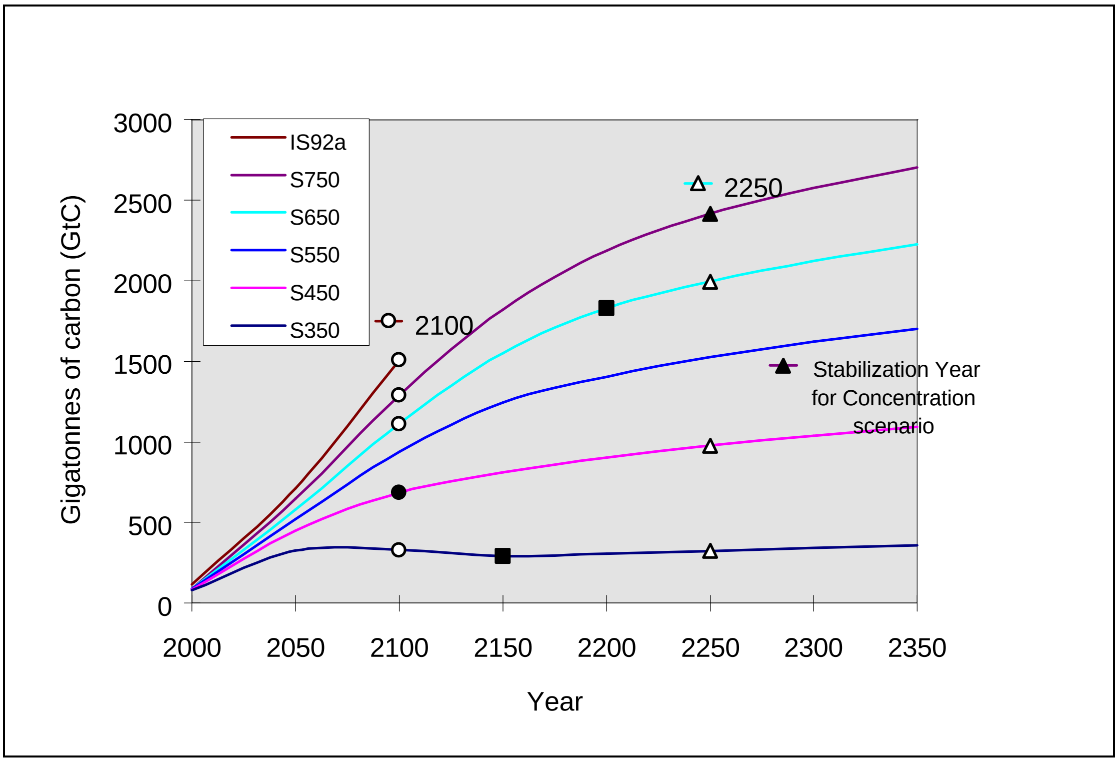
CO_2 stabilization level	IPCC 95a Immediate action trajectory (GtC)	IPCC95b Delay trajectory (GtC)	Difference (GtC)	% of IPCC95a
450 ppmv	630	650	20	3%
550 ppmv	870	990	120	14%
650 ppmv	1030	1190	160	16%
750 ppmv	1200	1300	100	8%

This table shows the small but significant effects of delay scenarios for CO_2 stabilization scenarios. The "delay" scenarios (IPCC95b) defer the point at which emissions are allowed to depart from the business as usual trajectory by some 5-20 years the almost immediate departure in the standard scenarios (IPCC95a). Note that for the 450 ppmv case the budget is virtually the same for both scenarios. If one views the immediate action and delay trajectories as extrema and the likelihood of adoption of one or the other as more or less random then the trajectory uncertainty is around plus or minus 5-8% for CO_2 stabilization in the range of 500-700 ppmv.

Looking beyond 2100 Figure 15 shows the cumulative emissions for the IPCC "mid-range" carbon cycle model for each of the stabilization scenarios. Except for the 350 ppmv scenarios the cumulative CO_2 emissions continue to rise beyond the moment of atmospheric stabilization, although at a much lower rate of increase. As can be inferred from this figure the carbon budget varies by the time period. Figure 16 shows explicitly the way in which the budget period varies by the time over which it is measured.

In relation to the carbon budget corresponding to specific CO_2 concentration stabilization levels it is often pointed out that to a first order estimate the ultimate concentration level determines the cumulative carbon irrespective of the detail of the emissions over time. Whilst this is true, Figure 16 also shows that where the time frame to stabilization is extended over centuries (as it was in the IPCC calculations) the flow of carbon which maintains the atmospheric CO_2 at a certain level, once that level been reached, is a significant fraction of the overall budget.

Figure 15 Cumulative carbon budget for CO_2 stabilization scenarios



This figure shows the cumulative emissions that correspond to the IPCC stabilization scenarios for the period 2000-2350. The black markers show the point at which atmospheric CO_2 is stabilized under each of the scenarios.

In summary, there are quite significant uncertainties in calculating the carbon emissions corresponding to a particular concentration of CO_2 deriving from incomplete knowledge of the carbon cycle and other model uncertainties and from incomplete knowledge of the future. Recognised uncertainties are likely to be in the range of plus or minus 25% in the lower concentration range and plus or minus 15% in the mid to higher concentration range over a fixed budgeting period.

In addition the time frame of the integration clearly affects the volume of carbon that can be emitted and still maintain a given atmospheric concentration of CO_2. This is particularly relevant limitation on the use of the IPCC stabilization scenarios budgets to 2100 as basis for calculating the carbon budgets to the year 2100 corresponding to arbitrary CO_2 concentrations. For all except the 450 ppmv scenario the specified concentration pathway does not coincide in 2100 with the final atmospheric CO_2 levels. The implications of this will be outlined in the following section.

6.2.2 Calibrating the carbon budget

The purpose of this exercise is to provide a means of calculating cumulative carbon budget to the year 2100 which would correspond closely with prescribed long term temperature limits. Figure 16 shows the results of several different ways of correlating a carbon budget with an atmospheric CO_2 concentration over different time frames and using different methods:

1. Integrated carbon emissions for IPCC CO_2 stabilization scenarios to 2250.

   This curve is drawn from the IPCC atmospheric CO_2 stabilization exercise with the integration period ending in the year in which the 750 ppmv stabilization scenario reaches its maximum concentration. As consequence it overstates the amount of carbon required to raise the atmospheric CO_2 concentration to levels below 750 ppmv.

2 Integrated carbon emissions for the IPCC CO_2 stabilization scenarios to 2100.

   These two curves (2a,b) are drawn from the IPCC atmospheric CO_2 stabilization exercise and correspond to the data presented in the 1994 and 1995 IPCC reports as the budget to the year 2100. The only IPCC CO_2 stabilization scenario, however, which actually stabilizes CO_2 in 2100 is the 450 ppmv scenario. Above this level the CO_2 concentrations are assumed not to stabilize until much later (see Table 17) and below this for the 350 ppmv scenario. not until 2150. In other words the IPCC budgets to 2100 do not actually produce, in the year 2100, the long term CO_2 stabilization levels that correspond to the long term temperature target.

3. Integrated emissions against actual concentration in 2100.

   This curve is based on the calculated concentrations in the year 2100 for a set of relatively smooth emissions profiles using the MAGICC model of Wigley. After 2100 sharp emission reductions would be needed in the case of the higher concentrations in order for atmospheric CO_2 levels to be stabilized at the concentrations prevailing in that year. As a consequence the emissions budgets are higher than for 2 above but much lower than for the longer integration periods. The gap between this curve and the higher curves of 1 and 4 is a measure of the budget timeframe effects beyond 2100. Table 19 tabulates the data from which this is drawn and shows that for the 450-750 ppmv scenarios the budget is approximately 50% higher for the 2250 integration than for this method.

   For the lower concentrations (close to current the current concentration +/-25 ppmv), which would correspond to strong environmental targets and to a higher climate sensitivity, estimating the carbon budget is more problematic. The dependence on time path is quite critical to the overall budget size. If for example all emissions ceased in the year 2000, the CO_2 concentration would be around 315 ppmv in 2100 for a total budget of around 80 GtC. In other words stabilization of atmospheric CO_2 at levels that would limit long term warming to one degree or so could not feasibly occur until sometime in the 22nd century. Hence the IPCC concentration profile and emission budget for low (i.e. 350 ppmv) CO_2 concentration will be more appropriate for estimating the realistic carbon budget for strong environmental targets.

4. Integrated carbon emissions for IPCC CO_2 stabilization scenarios to the year of atmospheric stabilization.

   This curve is included for illustrative purposes. It shows that the cumulative emissions to the year of stabilization for each of the scenarios rises gradually to meet the curve for integrated emissions to 2250. Cumulative emissions diverge from the curve for integrated emissions against actual concentrations from above 450 ppmv because the IPCC scenarios specify stabilization at 550 ppmv and above later than 2100. The divergence of this curve from the integrated emissions against actual concentration curve is a measure of the effect of the time frame for stabilization on the budget.

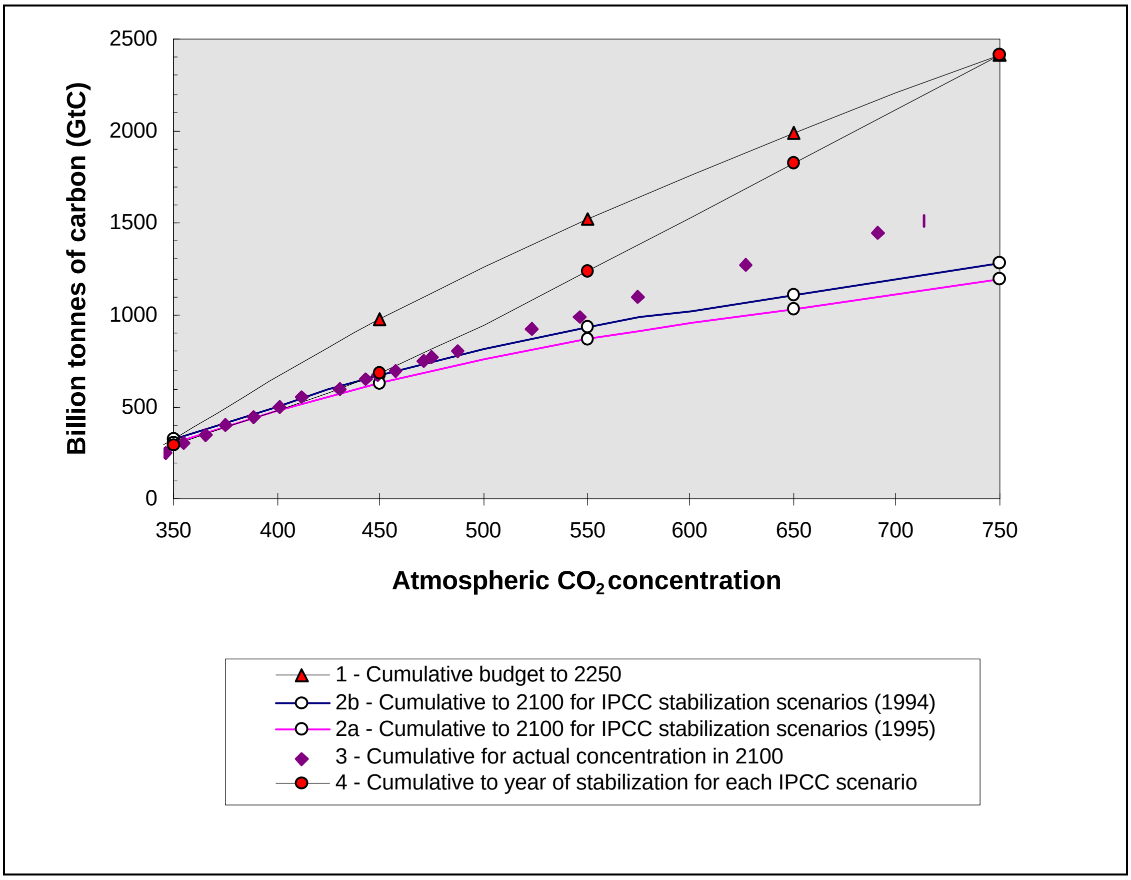
Table 19 Cumulative carbon emissions by scenario

Stabilization level ppmv	1. Year 2250	2a Year 2100 - IPCC 1994	2b Year 2100 - IPCC 1995	3. Year 2100 actual concentration
350	324	322	300	277
450	978	677	630	676
550	1525	930	870	1013
650	1994	1104	1030	1307
750	2417	1282	1200	1601

In summary, having looked at various ways of calibrating a carbon budget for atmospheric CO_2 concentrations the IPCC profile may provide the best means of doing this. The budgets correspond to relatively smooth concentration profiles and particularly when used to interpolate for low atmospheric concentrations take account of the fact that concentrations will rise above the final stabilization level before falling back to the level corresponding to the long term environmental target some time in the 22nd century. The limitations of the IPCC budgets are that they underestimate the budgets to 2100 for higher concentration levels above around 500 ppmv by 20-30%. Within the limits of the budget estimation exercise however and taking into account the environmental targets examined this is not a major limitation.

For the purposes of calculating the carbon budgets in this work the central results of the IPCC CO_2 stabilization scenarios will be used as the central estimate.

Figure 16 Cumulative CO_2 budgets by time horizon



This figure shows several different curves which could be used for calibrating the amount of carbon emissions (CCE) which correspond to a given atmospheric CO_2 level. The top curve shows the cumulative emissions to 2250, which is the stabilization year for the 750 ppmv CO_2 stabilization scenario, for a mid-range carbon cycle model. Below this is the curve for cumulative emissions to the year of stabilization in the IPCC scenarios. It can be seen that this curve gradually rises to meet the top curve, as the year of stabilization approaches the integration period for the top curve. The difference between these two curves is the carbon emissions required to sustain the concentrations from the year of stabilization to 2250. The middle curve shows the cumulative emissions corresponding to concentrations in the year 2100 calculated explicitly with the MAGICC model of Wigley which compares closely with the mid-range carbon cycle results. The calculation of this curve assumes that each of the concentration can be achieved in 2100 - the IPCC for example assumed that a return to 350 ppmv does not occur until 2150, hence the CCE corresponding to this pathway are higher. The bottom curves show the CCE to 2100 only for the same model reported by the IPCC in 1994 and 1995. These emissions correspond to the 2100 level, not the final CO_2 stabilization level, which except for the 450 ppmv case does not occur until later than 2100. In other words, for all except the 450 ppmv case the CCE shown in these two curves do not produce the final concentrations against which they are plotted.

Table 20 Total carbon budgets for different time horizons and calibration systems

	1°C warming limit			2°C warming limit		
Climate Sensitivity	Budget to 2100 by actual conc. (GtC).	IPCC stabilization profiles to 2100 (GtC)	IPCC stabilization profiles to 2250 (GtC)	Budget to 2100 by actual conc. (GtC)	IPCC stabilization profiles to 2100 (GtC)	IPCC stabilization profiles to 2250 (GtC)
1.5	510	481	682	1129	933	1628
2.0	365	361	445	832	722	1106
2.5	268	294	314	628	585	807
3.0	200	252	241	510	481	600
3.5	154	223	191	425	411	462
4.0	116	202	154	365	361	363
4.5	85	185	125	319	324	289

For the 1°C warming limit and with the climate sensitivity greater than around 3°C the calibration system used here for the carbon budget to 2250 based on the IPCC profiles produces a lower CO_2 budget than to 2100 for the IPCC profile for that year. This reflects that fact that CO_2 emissions need to be "negative" after 2100 to enable atmospheric CO_2 levels to fall to the required level. In practice this would mean that between 2100 and 2250 there would have to be significant net afforestation. For example, the difference between the IPCC 2100 budget and the IPCC 2250 budget is around 30 GtC , which can compared with land use emission from 1765 to 1990 of around 180 GtC.

6.3 Climate Sensitivity

The carbon budget corresponding to a given temperature limit is critically dependent in the assumed climate sensitivity - an increase in the sensitivity from 2.5 to 3.5C reduces the budget to the year 2100 by around 30%, for example. Table 21 shows the carbon budget to the year 2100 for two different warming targets (1°C and 2°C above pre-industrial levels) for the range of IPCC climate sensitivity assumptions. As can be seen from this table and Figure 17, this budget is very sensitive to the assumed climate sensitivity parameter:

- For 1°C limit the total carbon budget is 295 GtC and 223 GtC for the 2.5°C and 3.5°C climate sensitivity values respectively. (In the main body of this report 223 GtC has been rounded up to 225 GtC).

- For a 2°C limit the budget is 585 GtC and 411 GtC for the 2.5°C and 3.5°C climate sensitivity values respectively. (In the main body of this report 411 GtC has been rounded up to 410 GtC).

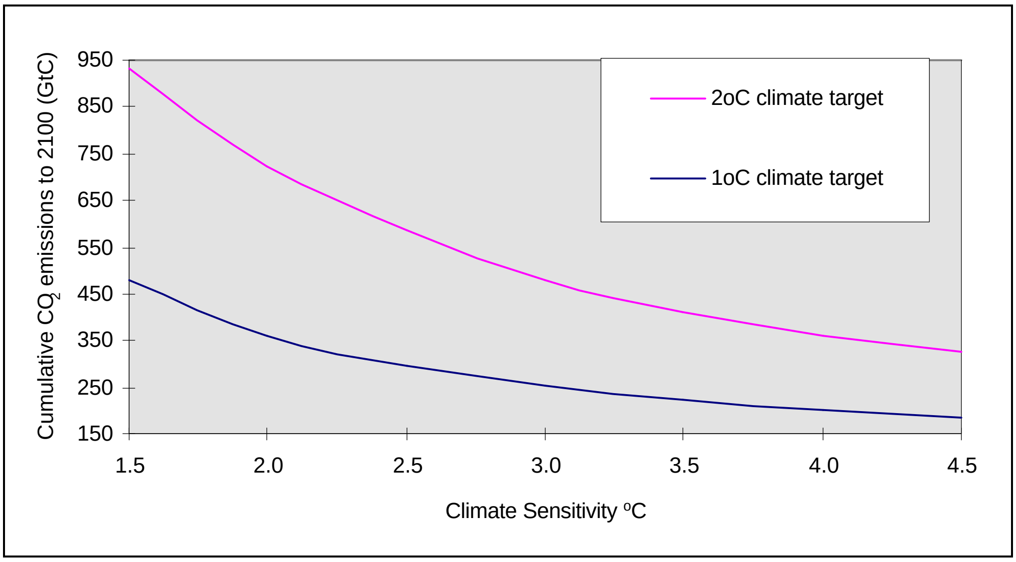
Table 21 Carbon Budget: Climate Targets vs. Climate Sensitivity

Climate Sensitivity (°C at equilibrium for doubling of CO_2)	Carbon Budget for 1°C climate target		Carbon Budget for 2°C climate target	
	Total Fossil and Deforestation emissions GtC	Fossil emissions GtC	Total Fossil and Deforestation emissions GtC	Fossil emissions GtC
1.5	481	399	933	851
2.0	361	280	722	640
2.5	295	213	585	503
3.0	253	171	481	399
3.5	223	142	411	330
4.0	202	120	361	280
4.5	186	104	324	242

This table shows the relationship between climate sensitivity and the carbon budget for two temperature targets. The carbon emissions due to deforestation over period to 1991-2100 are those assumed by IPCC 1994.

To look at the uncertainties in the carbon budget due to the uncertain nature of the climate sensitivity parameter it is useful to consider a sensitivity range of 2.5-3.5°C with central estimate of 3°C. For the 1°C target the uncertainty introduced into the budget of 0.5°C uncertainty in the climate sensitivity is around 15% and for the 2°C target around 20%.

Figure 17 Sensitivity of carbon budget to temperature and climate sensitivity



Throughout this work a climate sensitivity of 3.5°C will be used for the calculation of the central estimates of the carbon budgets.

6.4 Effect of other greenhouse gases

Other greenhouse gases (Methane, nitrous oxide, HFCs and PFCs) add significantly to the greenhouse effect. Inclusion of their contribution reduces the amount of carbon that can be emitted to meet any given warming limit when compared to a CO_2 only situation.

For a given set of scientific assumptions a specific CO_2 equivalent concentration limit corresponds to a long term equilibrium warming limit. If CO_2 were the only gas then CO_2 could be emitted until the actual CO_2 concentration equalled the CO_2 equivalent concentration corresponding to the warming limit. If other greenhouse gases are important then their contribution, in CO_2 equivalent concentration, will need to be deducted from the CO_2 equivalent concentration limit to arrive at the maximum actual CO_2 concentration corresponding to the temperature limit.

In 1990 the effects of the other greenhouse gases, excluding aerosols, amounted to 70% of the direct radiative forcing due to the increase in CO_2 278 ppmv in pre-industrial times to 355 ppmv[130]. When the effects of aerosols are included the net effect is negative, offsetting 14% of the CO_2 only forcing.

The IPCC 1992 emission scenarios to 2100 explicitly included estimates for the emissions of non- CO_2 greenhouse gases. For the IS92a scenario, excluding the effects of aerosols, the radiative forcing in 2100 of other greenhouse gases is 46% of the CO_2 only forcing[131]. Under the same scenario if aerosol emissions are held constant at 1990 levels the net radiative effect of the other reduces to 24%.

In the case of the CO_2 stabilization scenarios however, emissions of other gases were not estimated. Hence efforts to account for these have usually been based on assuming that these gases add radiative forcing equivalent to an arbitrary fraction of that produced by CO_2 alone. Wigley for example has assumed a ratio of 23%[132] closely based apparently on the ratio for the IS92a scenarios in 2100 assuming that aerosol emissions do not increase. Whilst this is lower than the direct forcing ratio from IS92a it is not unreasonable given that efforts to stabilize CO_2 concentrations will most likely be associated with strong action on the other greenhouse gases as well. Nevertheless, when one considers that under CO_2 stabilization policies SO_2 will also be reduced it is apparent that Wigley's assumption may be too low.

In order to better understand this relationship Table 22 shows some examples of the effect of other greenhouse gases on the actual CO_2 concentration calculated for a 1 and 2 degree temperature limit. There is a small but significant influence of the assumptions made in relation to the levels of other greenhouse gases.

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[130] Calculated from data in Kattenburg (1996) op.cit.

[131] See Table 6.4 of Kattenburg et al (1996) op.cit.

[132] Wigley (1995) op.cit.

Table 22 Non-CO_2 greenhouse gases and actual CO_2 levels

Total radiative forcing as % of CO_2	100% CO_2 only	110%	123%	133%	150%
1°C limit - 3.5°C sensitivity	339	333	327	323	317
1°C limit - 2.5°C sensitivity	367	358	348	342	334
2°C limit - 3.5°C sensitivity	413	398	384	374	362
2°C limit - 2.5°C sensitivity	484	460	436	422	402

This table shows the effects of other gases on the actual CO_2 concentration level corresponding to different warming targets and climate sensitivity values. The percentage of total radiative forcing is relative to CO_2 only, hence the second column shows the equivalent CO_2 level (i.e. as though CO_2 were the only gas) corresponding to the temperature and climate sensitivity in the first column. The column headed 123% is level used by Wigley (1995).

Assuming that policies aimed at stabilization of CO_2 concentrations would also address the other greenhouse gases it would be reasonable to estimate that a range of forcing ratios for the other greenhouse gases would be 10-33% using the 23% as a midpoint. From Table 23 it can be seen that this introduces an uncertainty into the carbon budget calculation of around plus or minus 10%.

Table 23 Effects of other greenhouse gases on the carbon budget

Total radiative forcing as % of CO_2	100%	110%	123%	133%	150%
1°C limit - 3.5°C sensitivity	264	244	223	210	193
1°C limit - 2.5°C sensitivity	356	325	294	275	249
2°C limit - 3.5°C sensitivity	508	460	411	381	340
2°C limit - 2.5°C sensitivity	712	655	585	537	473

This figure shows the effect on the carbon budget of different assumptions in relation to other trace gases. For example under the 1°C limit with a climate sensitivity of 3.5°C the budget ranges from 264 GtC for no other trace gases to 193 GtC if other trace gases contribute a radiative forcing equivalent to 50% of that of CO_2. The higher the temperature limit and the lower the climate sensitivity the larger is the effect of other gases on the budget. If the radiative forcing ratio of 123% is assumed to be the central estimate then an uncertainty of +/- 10% in this corresponds to a budget uncertainty of around 7-9%.

For the purposes of this work the relative contribution of greenhouse gases will be assumed to be 23%. It should be borne in mind however that this is at the low end of reasonable assumptions. A higher contribution would reduce the allowed carbon budget corresponding to a given target.

END