# The safe landing approach: risks and trade-offs in climate change

**Robert Swart, Marcel Berk, Marco Janssen, Eric Kreileman and Rik Leemans**

**The safe landing analysis has been developed to link short-term greenhouse gas emission targets to longer-term climate protection goals. The analysis was applied to the climate policy goals proposed by the European Union. This application and several presentations of the analysis during the negotiations on the Kyoto Protocol led to critical but constructive discussions. In this paper we discuss some of the key questions such as policy relevance, scientific credibility, use and adequacy of global indicators to determine impact levels, technological feasibility and economic aspects. The results from the safe landing analysis were generally accepted by the policy community because it bridges the gap between policy needs and the understanding derived from complex but scientifically rigorous integrated assessment models. The selected indicators of the safe landing analysis are evaluated. It is shown that the indicators describing rates of change are as important for defining impacts and response policies as those describing only cumulative or absolute change. Lower levels of climatic change generally coincide with lower impact levels. However, only the lowest rates and levels of climate change allow natural ecosystems to adapt. It is further shown that the level of additional energy expenditures needed to meet such low impact levels strongly depends on the assumed technological development rates.** 

The authors are with the National Institute of Public Health and the Environment, PO Box 1, 3720 BA Bilthoven, The Netherlands.

[1]J Alcamo, G J J Kreileman and R Leemans, 'Global models meet global policy – How can global and regional modellers connect

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At the first Conference of Parties (COP) of the Framework Convention on Climate Change (FCCC) in Berlin, 1995, the so-called 'Ad hoc Group on the Berlin Mandate' (AGBM) was established. AGBM was charged with the task of negotiating additional commitments to control greenhouse gas emissions in industrialized countries. The activities of AGBM resulted in the agreed reduction commitments at the Third COP in Kyoto at the end of 1997. One of the important questions in these negotiations was how the short-term nature of different targets and timetables (as negotiated in the AGBM) relates to the long-term 'ultimate' objective of FCCC (Article 2): 'stabilization of atmospheric concentrations at non-dangerous levels'. Can science help by providing the negotiators with usable information on the relationships between short-term policies and emissions, and intermediate and long-term impacts?

Alcamo *et al*[1] stress the importance of an intensive dialogue between scientists, policy makers and/or negotiators. The 'Delft dialogue workshops', in which researchers periodically convened with delegates from various countries and NGOs to address and discuss topical issues in the FCCC negotiations, were organized to address these questions.[2] These workshops attempted to bring the participatory component of what is currently called 'integrated assessment' into practice.[3] The 'safe landing analysis'[4] resulted from this process. It is a quick and interactive stand-alone software tool[5] which calculates 'safe emissions corridors' for particular target years. The calculations are based upon regressions of many IMAGE 2 scenarios. The corridor specifies the possible greenhouse gas emission levels in a short-term target year (e.g. 2010) that have at least one long-term (e.g. up to 2100) emissions profile that satisfies the specified long-term and intermediate climate protection goals. The tool allows policy makers to experiment with their preferred set of global indicator values and other assumptions and then to evaluate possible emissions by comparing different corridors.

This method, together with more in-depth analyses of IMAGE-based scenarios on regional emissions and impacts, was presented and demonstrated for both policy makers and scientific audiences on various occasions.[6] The approach was, for example, applied to evaluate the implications of various policy statements and protocol proposals, such as those of the European Union and the Alliance Of Small Island States (AOSIS)[7].

During these science–policy interactions, critical issues surrounding the applications emerged. Questions focused on both the ecological and socio-economic aspects of the approach. While the companion paper[8] discusses the concrete dialogue process from a social sciences perspective, this paper is aimed at addressing the main questions arising from the applications of the safe landing analysis. The majority of these relate to its policy relevance and scientific credibility, the selection, use and adequacy of global indicators to evaluate impact levels, and technological and economic aspects. Our objective therefore is to evaluate the policy relevance and scientific credibility of the safe landing approach by assessing and providing usable scientific information. An application of the safe landing analysis to the climate protection goal adopted by the European Union will be presented as an example to illustrate this. From this application, two important issues emerge which need further attention: (1) the relationship between globally averaged 'climate protection indicators' of the safe landing analysis and (regional) ecological impacts, notably in terms of rates of change, and (2) the selection and valuation of technological and economic indicators. These will be discussed in the subsequent sections. The paper concludes with discussion, conclusions and recommendations for further work.

## The implications of EU climate goals for short-term emissions

In 1996 the European Union (EU) adopted long-term climate goals stating that 'the global average temperature should not exceed the pre-industrial level' by more than 2°C and that therefore 'carbon dioxide concentration levels lower than 550 ppmv should guide global emissions reduction efforts'.[9] The safe landing analysis has been used to explore what these goals may imply for negotiable short-term emissions corridors for the world, and for the industrialized (Annex I) countries by subtracting emissions in the developing countries, as projected in the emission scenarios of IPCC.

Before we can apply the safe landing analysis to these EU goals, we have to make several additional assumptions. First, for IPCC's 'best guess' climate sensitivity (2.5°C), $CO_2$ concentrations of 550 ppmv (about double pre-industrial levels) complemented by non-$CO_2$ greenhouse gases will lead approximately to a rise in global average temperature of more than 2.5°C. Therefore we assume that an increase of 2°C is the strictest of the two EU goals. Only under the conditions that climate sensitivity would be towards the lower end of the IPCC range (1.5–4.5°C) or that sulphur cooling effects or other negative feedbacks would be much larger than currently envisaged, may this assumption not be valid. Second, we assume that the long-term targets should be reached by 2100. This is not explicitly defined in the EU proposal. Third, the global sulphur emissions do not increase and stay at their 1990 levels. Finally, we also assume a maximum rate of global annual emission reduction of 2% per year.

A temperature increase of 2°C since pre-industrial times is similar to 1.5°C after 1990, because some climate change is already apparent. We therefore start our analysis by using an overall temperature increase of

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with environmental policy makers? What has hindered them? What has helped?', this volume (pp 261–265)
[2]C E van Daalen, W A H Thissen and M M Berk, 'The Delft process: experiences with a dialogue between policy makers and global modellers', This volume (pp 267–285)
[3]P Bailey, C Gough, M Chadwick and G McGranahan, *Methods for Intergrated Environmental Assessment: Research directions for the European Union*, SEI Report, Stockholm Environmental Institute, Stockholm, 1996
[4]J Alcamo and E Kreileman, 'Emission scenarios and global climate protection', this volume (pp 163–192)
[5]G J J Kreileman and M M Berk, *The Safe Landing Analysis: Users Manual*, RIVM Report No 481508003, National Institute of Public Health and the Environment, Bilthoven, 1997
[6]C E van Daalen *et al*, *op cit*, Ref 2
[7]J Alcamo, G J J Kreileman and R Swart, 'The climate negotiations: climate goals and their emissions corridors', paper presented at the IPCC Asian-Pacific Workshop on Integrated Assessment Models, Tokyo, 1997
[8]C E van Daalen *et al*, *op cit*, Ref 2
[9]European Commission, *Communication on Community Strategy on Climate Change, Council Conclusions*, European Commission, Brussels, 1996

1.5°C between 1990 and 2100 as the only climate constraint in the safe landing analysis. In this case, the whole range of the IPCC IS92 scenarios falls within the emission corridor from 1990 to 2010, indicating that stringent controls of emissions up to 2010 would not be needed: the temperature goal can theoretically be achieved without reducing emissions before 2010 (or 2020). However, the analysis also indicates that emissions have to be reduced eventually, but with an assumed maximum annual emission reduction rate of up to 2%, these controls only need to be implemented later in the next century. This result is, of course, dependent on the assumed climate sensitivity: if this sensitivity turns out to be much higher than 'best guess', rapidly increasing emissions may be inconsistent with the EU goals. Accepting such 'best guess' sensitivity has consequences when some of the uncertainties surrounding climate change are considered more explicitly. These can also be evaluated with the safe landing tool.

The corridors are sensitive for additional constraints. If we add a further constraint on sea-level rise, the top of the corridor is only affected by a setting of sea-level rise between 1990 and 2100 of less than 30 cm. This is consistent with the observation that a maximum level of 20 cm – as advocated by the AOSIS group – would indeed imply an immediate reduction of emissions.[10] Both overall temperature change and sea-level rise are closely related to cumulative emissions over the period 1990–2100. Therefore, for constraints on sea-level rise of 30 cm or higher, high levels of emissions in the first decades of the next century can be compensated for by low levels later on. The timing of emissions is less of an issue.

This is not true for a constraint on the rate of temperature change. If we add a constraint of 0.15°C per decade (approximately the average value of a 1.5°C temperature increase over the next century) and allow this value to be violated during two decades to account for system inertia, the top of the emission corridor in 2010 is limited to 12.4 Gt C/yr (Figure 1a). If we only change the rate-of-change constraint to 0.2°C per decade, the top of the corridor rises to 14.4 Gt C in 2010. Alternatively, we can allow for three- instead of two-decade violations of the 0.15°C per decade value: in this case the top of the corridor increases substantially to 16.7 Gt C. From these examples it is clear that the assumed maximum rate of temperature strongly influences the width of the corridors. Furthermore, the number of decades that this selected rate-of-change target can be violated, determines allowable short-term emissions more than the long-term temperature change target. This finding indicates the importance of exploring the implications of various emission paths and their levels of climate change in more detail.

The safe landing analysis in principle determines only global emissions corridors. However, emissions corridors for the industrialized countries can be derived by subtracting possible non-Annex-I emissions from the global corridors. Here we use the IPCC scenario values for non-Annex-I countries from Leggett *et al*[11] and the earlier selected values for the indicators roughly consistent with the EU goal: a maximum of 1.5°C temperature increase after 1990 at maximally 0.15°C per decade, which can be violated for two decades, and maximally 30 cm sea-level rise. The top of the resulting emissions corridors for Annex-I countries when non-Annex-I emissions are assumed to follow the scenario IS92a of IPCC, lies about 5% above the 1990 level (Figure 2a). Lower or higher emissions in non-Annex-I countries would respectively lead to a wider and narrower

[10] J Alcamo *et al, op cit*, Ref 7

[11] J Leggett, W J Pepper and R J Swart, 'Emissions scenarios for the IPCC: an update', in J T Houghton, B A Callander and S K Varney (eds), *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge, 1992

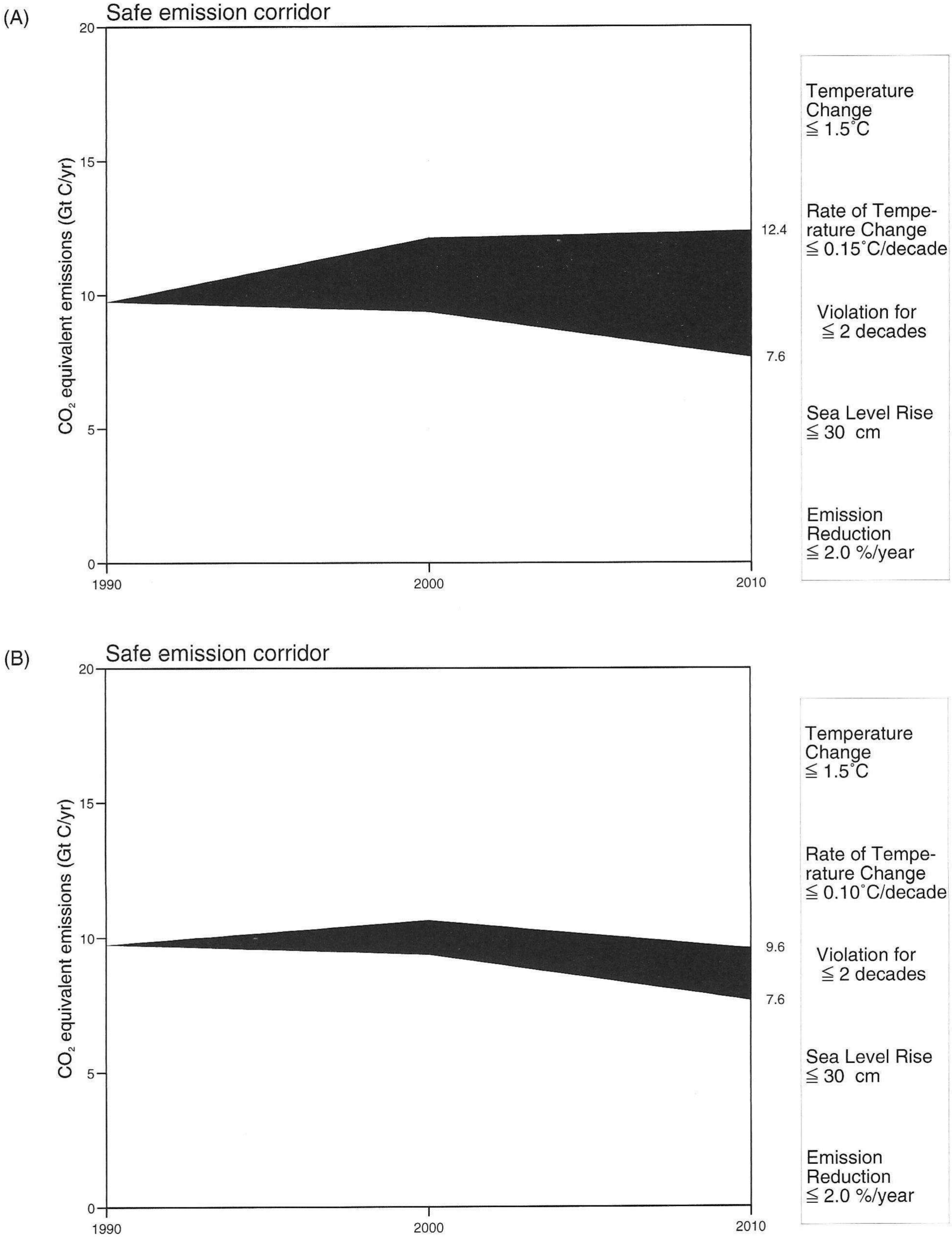


**Figure 1.** Two global emissions corridors for the EU objective with different rates of decadal temperature change: (a) 0.15°C per decade; (b) 0.10°C per decade.

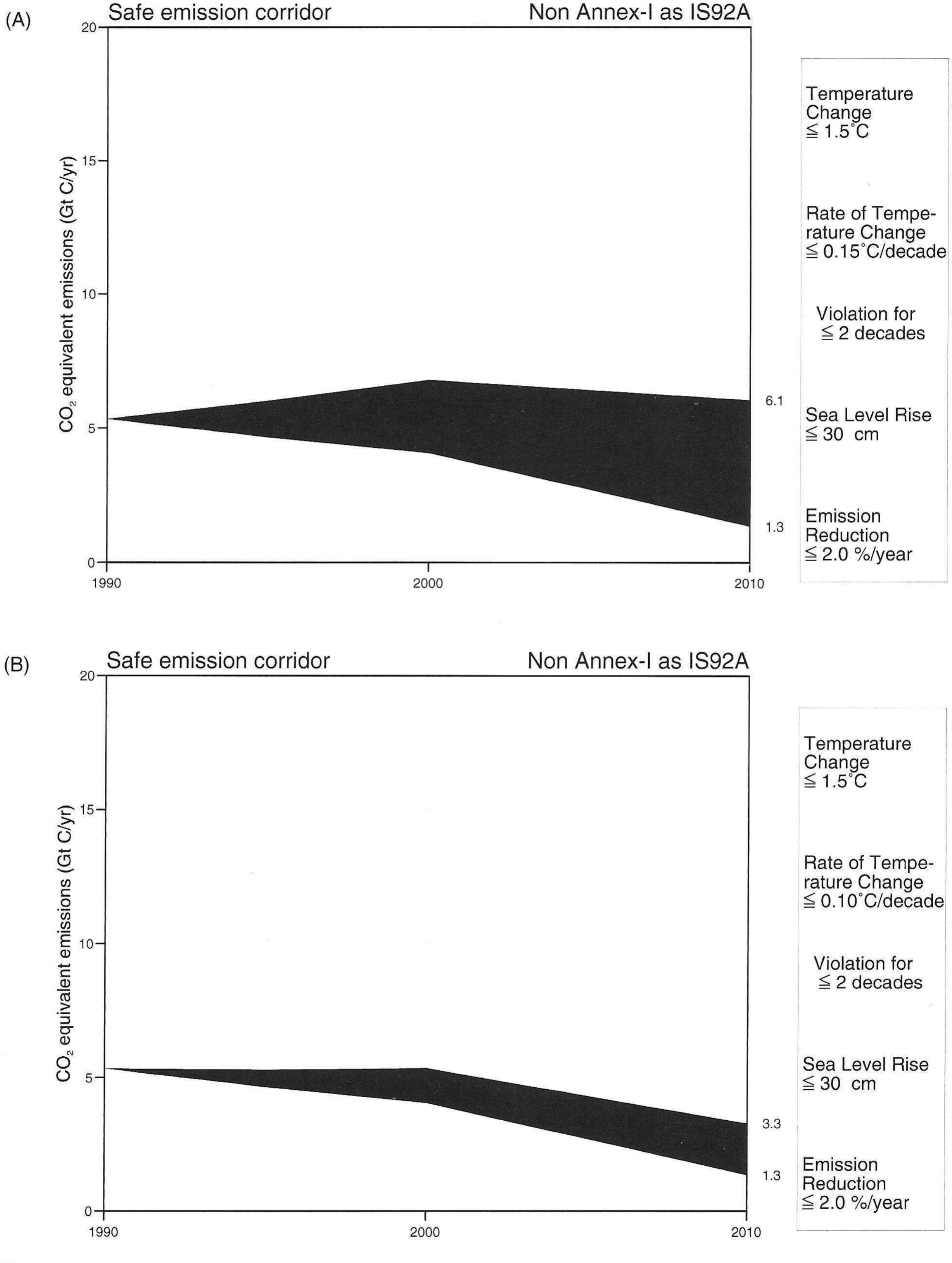


**Figure 2.** Two Annex-I emissions corridors for the EU objective with different rates of decadal temperature change: (a) 0.15°C per decade; (b) 0.10°C per decade.

Annex-I corridor, notably plus 22% above the 1990 level for the low-emission scenario IS92d and minus 7% for the high-emission scenario IS92e. Thus, these calculations show that emissions in Annex-I countries could increase until 2010 while meeting the EU climate goal if emissions in developing countries follow an emissions path according to IS92a or are lower. It is thus evident that the width of the emission corridors is sensitive to the selected values of the various indicators. For example, from an ecological, risk-aversive perspective, a maximum allowable rate of change of 0.1°C per decade has been proposed.[12] This rate could be related to the likelihood that 'ecosystems can adapt naturally to climate change'.[13] The emissions in 2010 (the top of the corridor) should be reduced by at least 5% globally and more than 40% for only the Annex-I countries as compared to 1990 levels if the allowable rate of temperature change is reduced from 0.15 to 0.1°C per decade (Figures 1b and 2b). A similar result is obtained when the number of violations is reduced from two decades after 2000 to one decade at 0.15°C per decade. By implicitly accepting a rate of temperature change of 0.15°C per decade, EU policy makers have implicitly accepted a certain level of risk of adverse climate impacts. It is therefore important to understand the relationship between the rates of global mean temperature change and impacts if avoidance of these impacts is to guide policy action. However, large emissions control efforts are needed to bring the rate of global mean annual temperature change down in the coming decades. Such efforts could be difficult from a socio-economic perspective.

Socio-economic constraints are approximated in the safe landing analysis by the maximum rate of emission reductions. A range of global $CO_2$-equivalent emission reduction rates of 1-4% per year is used by Alcamo and Kreileman.[14] In the example for the EU goal discussed above we assumed an annual rate of 2%. Figure 3 illustrates that the implication of this assumption for the width of the corridor is large. If we assume, very optimistically, that large and rapid global emission reductions are feasible in next century, there is less need to start reducing emissions now (Figure 3a). The corridor widens.[15] If we are less optimistic about the future emission reduction possibilities, the corridor narrows (Figure 3b). It turns out that the width of the corridor is especially sensitive to the assumed maximum rate of emission reduction when (1) the selected rate of temperature change is not constraining and (2) strict goals for sea-level rise are set (e.g. less than 30 cm by 2100). This sensitivity can be explained as follows. Strict goals for the rate of temperature change constrain future emissions immediately. Low rates of emission reduction then also suffice to enable meeting long-term climate goals. However, in the case of strict long-term climate protection goals, such as sea-level rise, there is less room for compensating a large initial growth in emissions by high emission reduction rates later. So the question emerges: 'Which emission reduction rates are realistic, and under which conditions?' The proposal of the AOSIS group to limit sea-level rise to maximally 20 cm make this question even more relevant (cf. Table 1, which shows the implications of a 20 cm sea-level rise profile in 2100).

The corridors in Figures 1 and 2 encompass all the simulated pathways from 1990 that comply with the selected climate goals. Most of the current decade has already passed without much control on the growth in greenhouse gases. If we consider the increase in global emissions since 1990 and the increasing trend in emissions by assuming that global emissions will follow a reference emissions pathway (IMAGE 2 Baseline A[16])

[12] F R Rijsberman and R J Swart (eds), *Targets and Indicators of Climatic Change*, Stockholm Environmental Institute, Stockholm, 1990

[13] Note that this is not completely consistent with the EU goal that would allow for an average rate of change of 0.15°C per decade over the next century.

[14] J Alcamo and G J J Kreileman, *op cit*, Ref 4

[15] However, as Grubb notes in 'Technologies, energy systems and the timing of $CO_2$ emissions abatement: an overview of economic issues' (*Energy Policy*, Vol 25, 1997, pp 159–172), a delay case (which can be associated with a high corridor) following the IS92a scenario for 40 years before deviating, implies investments in at least as much new $CO_2$-based capital stock over the next few decades as that incorporated in all of the world's energy systems today. So the number of options to reduce emissions rapidly in the future may not be as large as they will possibly need to be.

[16] J Alcamo, G J J Kreileman, J C Bollen, G J van den Born, R Gerlagh, M S Krol, A M C Toet and H J M Devries, 'Baseline scenarios of global environmental change', this volume (pp 97–139)

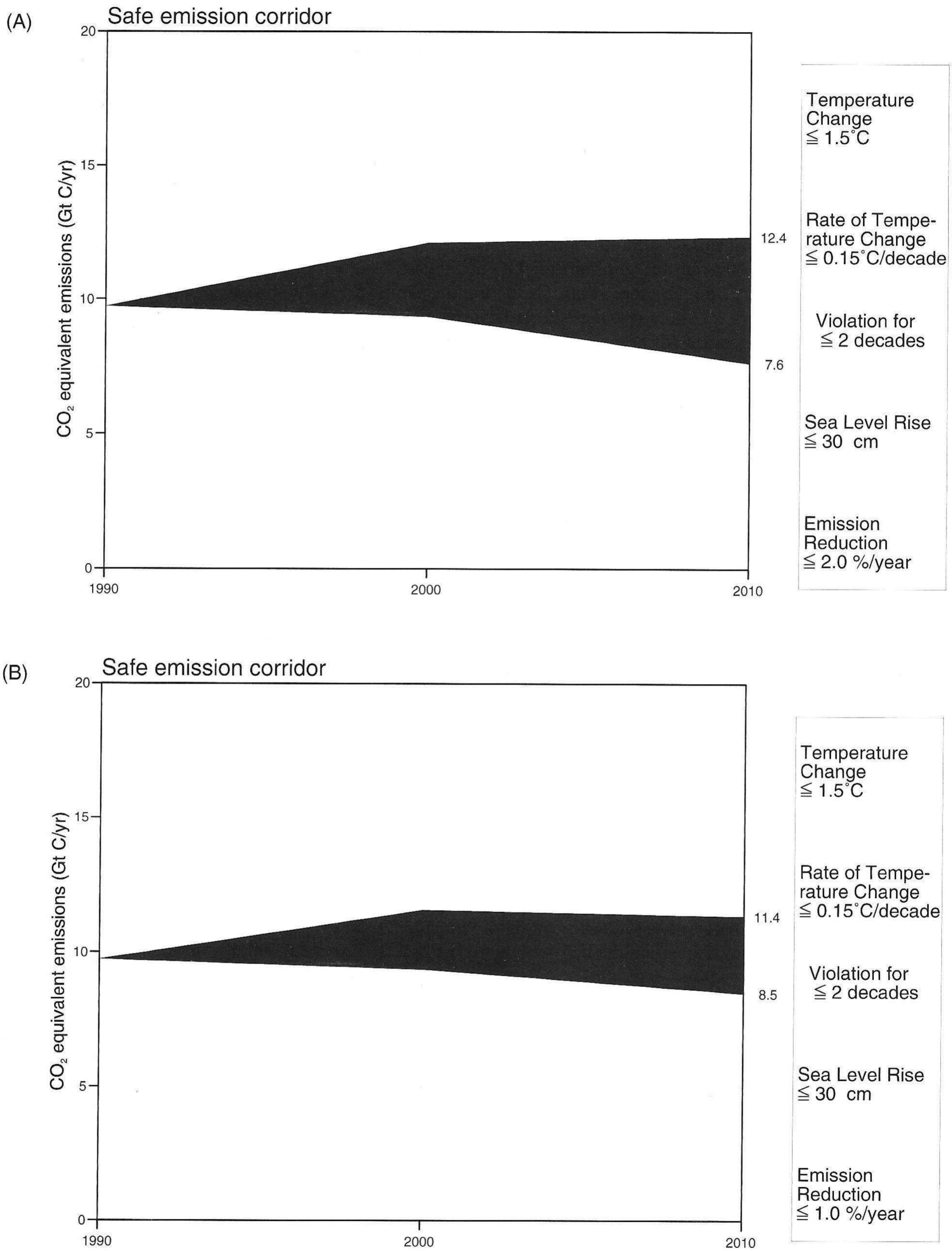


**Figure 3.** A global emissions corridor for the EU objective with different maximum rates of annual emission reductions: (a) 2% emission reduction per year; (b) 1% emission reduction per year.

**Table 1. Computation of long-term sea-level rise (cm) relative to 1990 for several stabilization scenarios of IMAGE 2.1**

| | Stabilization at 350 ppmv | Stabilization at 450 ppmv | Stabilization at 550 ppmv | 20 cm sea-level rise in 2100 |
|---|---|---|---|---|
| 2100 | 24 | 29 | 33 | 20 |
| 2200 | 41 | 56 | 66 | 30 |
| 2300 | 56 | 74 | 88 | 36 |
| 2400 | 68 | 90 | 106 | 38 |
| 2500 | 78 | 103 | 122 | 39 |

up to the year 2000, the associated corridor narrows considerably with the standard set of climate goals specifying the EU goals.

This implies that if Annex-I countries do not meet the FCCC commitment of bringing back their emissions to the 1990 level by 2000, achieving the EU climate goal could still be possible, but within a much narrower corridor. This means with much less opportunities and possibilities for increases in emissions, especially for the non-Annex-I countries. If global emissions followed the baseline up to 2010, no corridor would be left. This indicates that a 10-year delay in the control of global emissions – as apparently allowed for the EU goal according to the analysis above – may already result in a situation in which the climate goal can no longer be met. The agreed Kyoto protocol of reducing Annex-I emissions by approximately 5% with respect to 1990 is thus an important first step to achieve the EU goals.

The cumulative emissions over time are very important in both the safe landing approach and in approaches focusing on concentration stabilization.[17,18] When inter-generational aspects of long-term climate strategies are considered, a key issue is what the short-term emissions corridors imply for the possibilities of future generations. To explore this, a second corridor for the period 2010–2030 can be added. If emissions were allowed to rise towards the top of the global emissions corridor in 2010, they must be reduced by the maximum allowed rate of global emissions reduction thereafter, leaving little or no room to adjust climate protection goals if new evidence of climatic changes and negative impacts makes a tightening of these goals desirable. Clearly, this also applies to the EU goal (Figure 4a). Figure 4b indicates for the indicator settings associated with the EU goal that if non-Annex-I emissions grow unabatedly (IS92a), the allowable emissions in the Annex-I region become less than zero well before 2030. In other words, developing countries would have to control their emissions well before 2030 (as compared to the IS92a reference case[19]) to meet the EU climate protection goal. This implies two things. First, if Annex-I countries follow the top of their emissions corridor, the risk of not meeting their selected climate goal is very high if non-Annex-I countries are not able or willing to contribute to the desired timely global emission reduction. This provides a strong rationale for aiming at Annex-I emissions below the top of the corridor. Second, it would therefore seem important that Annex-I countries support non-Annex-I countries in limiting their emissions growth as much as possible.

From the policy applications of the safe landing analysis, such as the above EU example, the legitimacy of the approach in terms of the political and scientific value of its results was frequently questioned. Large parts of the discussions centred on the theme: 'To what extent is *safe*

[17] I G Enting, T M L Wigley and M Heimann, 'Future emissions and concentrations of carbon dioxide', Technical Paper No 31, CSIRO, Australian Division of Atmospheric Research, Mordialloc, Australia, 1994

[18] T M L Wigley, R Richels and J A Edmonds, 'Economic and environmental choices in the stabilization of atmospheric $CO_2$ concentrations', *Nature*, Vol 379, 1996, pp 240–243

[19] J Leggett *et al*, *op cit*, Ref 11.

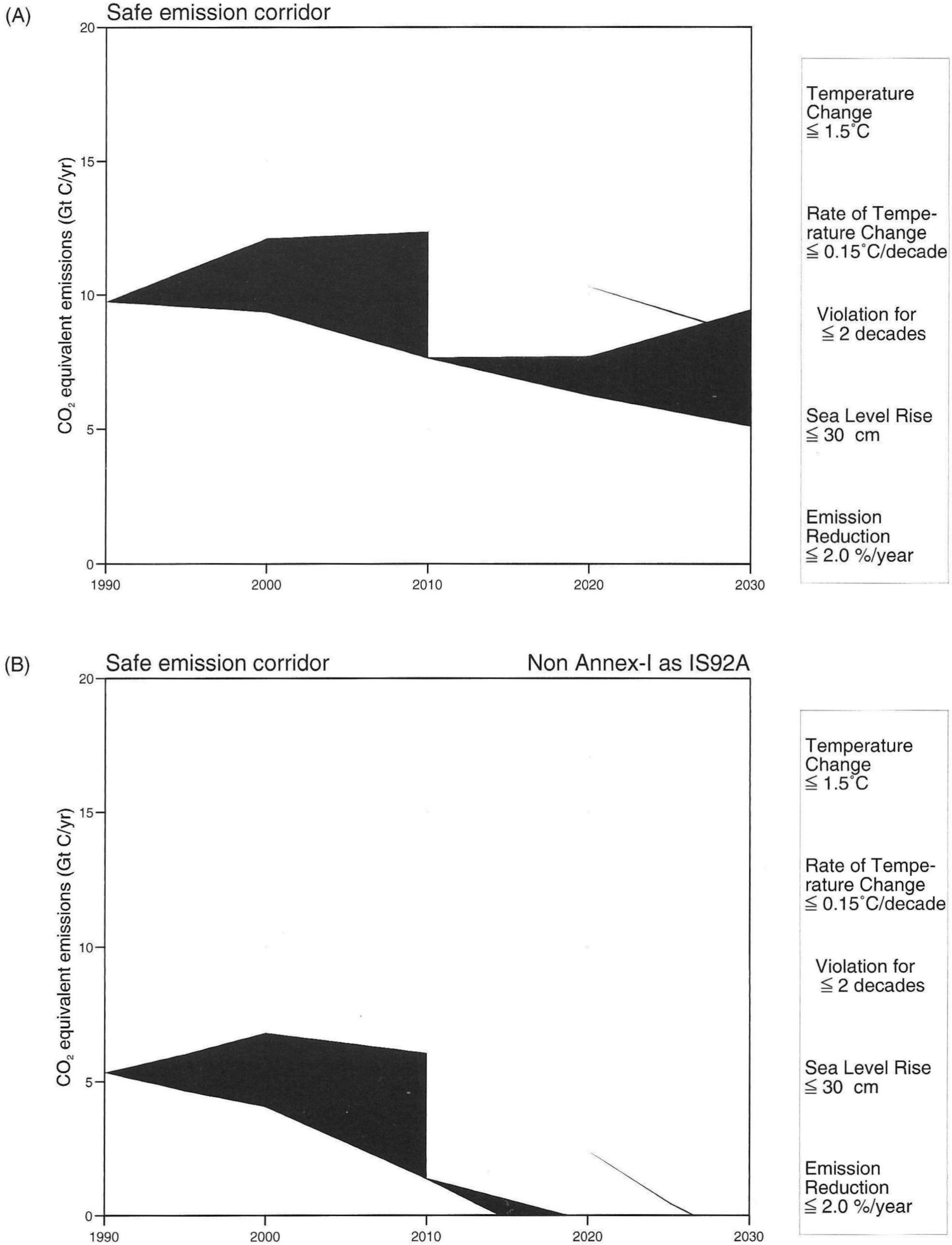


**Figure 4.** Emissions corridors from 2010 to 2030, starting from the top and bottom of the 1990–2010 corridor for (a) the world (global) and (b) Annex-I (with non-Annex-I emissions such as IPCC IS92a).

safe?' Although the method is assumed to be scientifically credible (reflecting the state-of-the-art understanding as assessed by the IPCC), this question remains.[20] In developing the safe landing analysis we recognized that target setting is a political issue. It is therefore the final responsibility of decision makers to select their preferred climate protection goals, to assess the feasibility of future emissions controls, and to evaluate the implications for short-term emissions constraints. However, the selection of indicators and particular values for constraints should consider all the available scientific knowledge to enhance understanding of the risks associated with the choices made. Unfortunately, the sensitivity, adaptability, resilience and vulnerability of managed and unmanaged ecosystems, and of social systems, are poorly known. Further, perspectives on the acceptability of and adaptability to impacts vary among people, nations and regions. Finally, the systemic dynamic properties of the climate system and the possible technical and societal responses are only roughly known and many uncertainties remain. This makes an unambiguous selection of targets extremely difficult.

*Safe* thus implies the likely risks that decision makers are willing to accept. Because of the well-articulated uncertainties in the climate debate, the safe landing analysis is meant to provide useful qualitative insights rather than quantitative results. The safe landing analysis is less useful for direct detailed political target setting. In the five Delft workshops to date, a mutual understanding between the researchers and negotiators involved has gradually evolved that legitimizes the use of the method and its results: '*safe*' is well understood to be a very subjective notion. The safe landing analysis may lead to initial changes in emission control, allowing for further changes along the way as new information and insights on impacts, adaptation and mitigation of climatic change become available. The safe landing analysis thus allows for an evaluation of the implications of future change in climate objectives for emissions corridors, enabling application of the analysis in a learning process.[21] So it is not surprising that many issues raised during the science–policy discussions about the safe landing approach relate to the need of policy makers to better understand the risks associated with particular choices for the indicator values. More specifically, the dialogue suggested that in order to assess the 'safety' of the emissions corridors, a better understanding of two main issues would be needed.

First, it is of key importance to improve the understanding of the relationship between the globally averaged climate protection indicators (such as change in temperature and sea level) and impacts that matter to policy makers (such as those related to the elements of Article 2). Here the rate of change is suggested to be of particular importance with respect to Article 2. Second, in order to assess the possibility of the world staying within a particular corridor, the technical feasibility of global emission limitations and their economic implications should be better understood. It is these two issues that we turn to in the following two sections.

## The meaning of global indicators for impact assessment

In selecting values for the indicators of the safe landing analysis, policy makers need to understand the implications of particular choices. Notably, the relationship between the globally averaged climate protection indicators and the impact levels that one wishes to avoid – usually at

[20] As the former IPCC chair Bert Bolin puts it: How can we talk about 'safe landing' when we don't know where the airport is?

[21] Evidently, as the understanding of the climate system changes, setting the variables for the method will have to be adjusted.

local or regional level – has to be understood as well as possible. Unfortunately, both regional climate change and its impacts are complex and diverse, and affect many sectors and systems.[22] This heterogeneity limited the conclusions of IPCC's second assessment report (SAR) on impacts. The overall conclusion of SAR that human-induced climate change adds an important new stress factor to natural and socio-economic systems is a clear statement, but difficult to operationalize or quantify for policy decisions (Table 2). The SAR further stresses the lack of understanding and comprehensive analysis of impacts and the need for additional research (Table 2). The SAR and the accompanying synthesis report[23] unfortunately do not provide much guidance on an appropriate selection of global indicator values as used in the safe landing analysis.

We have therefore chosen a different approach using the impact assessment capabilities of the IMAGE 2.1 model.[24] This geographically explicit model can effectively assist in evaluating different global and regional impact levels that coincide with specific emissions scenarios. As such, it gives important clues to define what selected global indicator values could mean. This is much less possible with approaches focusing solely on stabilization of greenhouse gas concentrations. The safe landing analysis further accounts directly for the time path towards such long-term indicator values. This capability seems crucial to estimating 'acceptable' or 'non-dangerous' impact levels and allows assessment of the adaptive capabilities of many systems.

To explore the meaning of global mean climate protection indicators for regional impacts, we have estimated the regional and time-dependent aspects of impacts by analysing the trends for climate change (the global indicators) and globally aggregated and regional impacts for baseline scenarios[25] (high and medium), different stabilization scenarios[26] (stabilization at 650, 550, 450, and 350 ppmv $CO_2$), and two emission reduction scenarios (1% or 2% annual reduction). These emission reduction scenarios assume a continuous annual reduction of 1% or 2% respectively of global GHG emissions stemming from all anthropogenic sources. These scenarios are not intended to mimic realistic policy scenarios but are implemented to illustrate the consequences of rapid global emission reductions. They are the only possible types of IMAGE scenarios with an immediate decrease in the rate of climate change and, as such, very relevant to evaluate the consequences for impact and adaptation levels.

All these scenarios span a wide range of possible emissions (4.4–38 Pg C/yr in $CO_2$-equivalent emissions in 2100; Figure 5a), concentrations (400–1000 ppmv $CO_2$-equivalent in 2100; Figure 5b) and climate change (global mean temperature increase of 0–3.3°C since 1990; Figure 5c). Although IMAGE 2.1 calculates most impacts on a 0.5° longitude and

**Table 2. Major conclusions of the IPCC Working Group II: Impacts, adaptations and mitigation of climate change: scientific-technical analysis**

1. Human-induced climate change adds an important new stress to natural and socio-economic systems.
2. Most systems are sensitive to climate change.
3. Impacts are difficult to quantify and existing studies are limited in scope.
4. Successful adaptation depends on technological advances, institutional arrangements, availability of financing, and information exchange.
5. Vulnerability increases as adaptive capability decreases.
6. Detection will be difficult and unexpected changes cannot be ruled out.
7. Further research and monitoring are essential.

[22] R T Watson, M C Zinyowera and R H Moss (eds), *Climate Change 1995: Impacts, adaptations and mitigation of climate change: scientific-technical analysis*, Cambridge University Press, Cambridge, 1996

[23] IPCC, 'IPCC Second assessment synthesis of scientific-technical information relevant to interpreting Article 2 on the UN Framework Convention on Climate Change' in Intergovernmental Panel on Climate Change (ed), *IPCC Second Assessment: Climate Change 1995*, Intergovernmental Panel on Climate Change (IPCC), Geneva, 1996

[24] J Alcamo, G J J Kreileman, M Krol, R Leemans, J C Bollen, M Schaeffer, A M C Toet and H J M De Vries, 'Global modelling of environmental change: an overview of IMAGE 2.1', this volume (pp 3–94)

[25] J Alcamo *et al*, *op cit*, Ref 16

[26] J Alcamo and E Kreileman, *op cit*, Ref 4

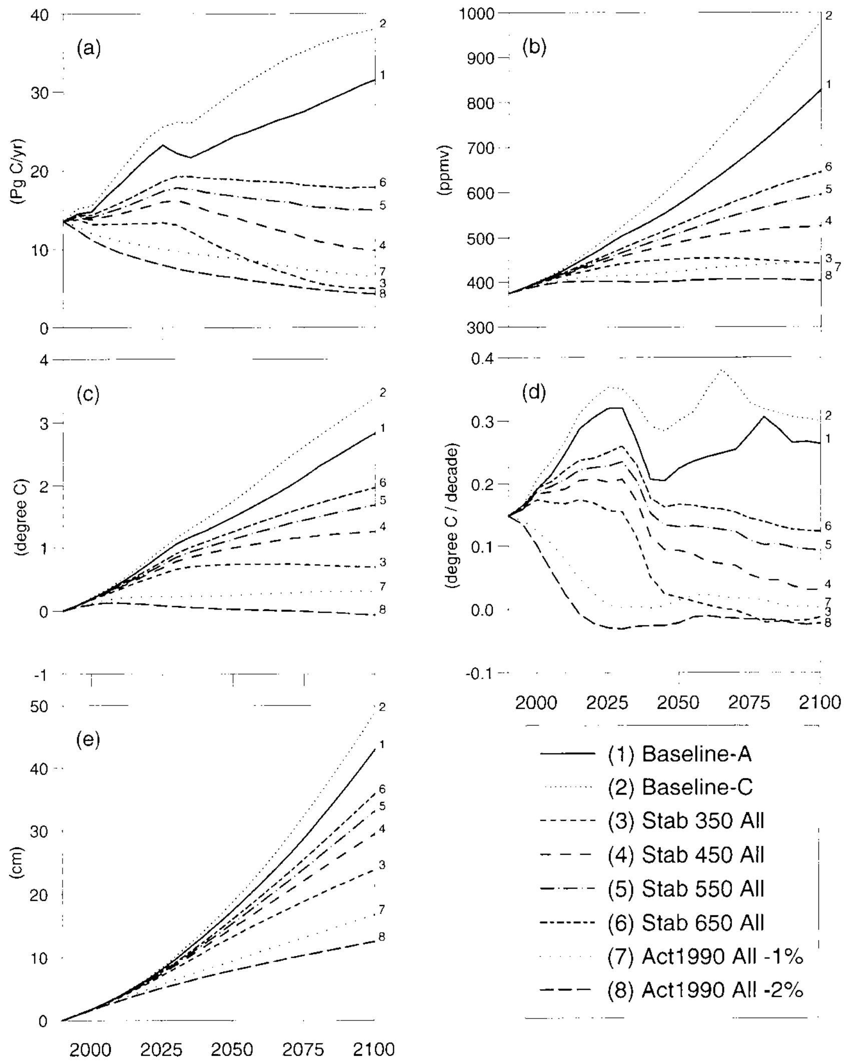


**Figure 5.** IMAGE scenarios for (a) global emissions, (b) concentrations, (c) temperature change, (d) decadal rate of temperature change, (e) sea-level rise. Scenarios: (1) Baseline A; (2) Baseline C; (3) stabilization at 350 ppmv; (4) stabilization at 450 ppmv; (5) stabilization at 550 ppmv; (6) stabilization at 650 ppmv; (7) 1% decrease in global annual emissions after 1990; (8) 2% decrease in global annual emissions after 1990.

latitude grid, we have aggregated the results to the coarser world regions and the whole globe.

*Definitions of climate and impact indicators*

The globally averaged climate indicators selected in the safe landing analysis act as coarse indicators of overall levels of climate change accepted by policy makers in the negotiation process. Here we will review their roles in defining impact levels and then evaluate their changes between 1990 and 2100 globally (Figure 5). The indicators are:

*Change in global mean annual temperature (°C) with respect to 1990.* Global mean temperature approximates different climatic factors. Changes in global mean temperature can be linked to both regional temperature and precipitation patterns.[27] Temperature plays a major role in many systems; it strongly determines plant growth. Further, temperature is important in defining sea surface temperatures and influences processes in the cryosphere. As such, it is one of the most important

[27] T R Carter, M L Parry, H Harasawa and S Nishioka, *IPCC Technical Guidelines for Assessing Impacts of Climate Change*, IPCC Special Report CGER-1015-'94, Intergovernmental Panel on Climate Change, WMO and UNEP, Geneva, 1994

determinants of sea-level rise. Higher temperatures also coincide with higher evapotranspiration rates and thus influence moisture availability and runoff.

The temperature changes in the scenarios are based on the climate sensitivity of IMAGE 2.1, which is 2.37°C for $CO_2$ doubling. This sensitivity is a result of the model parameterization[28] and lies within the range of sensitivities (1.5–4.5°C) given by IPCC.[29] The IMAGE 2.1 simulations suggest a somewhat higher temperature increase over land, a much larger increase at high latitudes and a lower increase in the tropics. Precipitation also increases during the simulations, but less in the southern hemisphere than the northern hemisphere. Increases in mid- and high latitudes are also higher than at low latitudes.

The simulated temperature changes differ for each scenario (Figure 5c). Generally, they increase continuously, although at different rates. The highest temperatures increases are observed for the two Baseline scenarios while the emissions reduction scenarios show the smallest changes. Although temperature increase in 2100 for the lowest stabilization scenarios are similar to the reduction scenarios, the time path differs strongly, especially in the earlier decades.

*The decadal rate of global mean temperature change (°C per decade).* This indicator is selected because it relates directly to the adaptability and resilience of many natural systems. High rates of change probably define lower levels of adaptability, an earlier breakdown of resilience of many systems, and thus, generally, higher potential impact levels. When high rates of temperature change are sustained over longer periods, irreversible responses cannot be excluded. Although little direct empirical ecological evidence exists, paleo-ecological studies show a lagged response of ecosystems to large-scale rapid climate change.[30] During a period of rapid change during the last deglaciation, vegetation was only in equilibrium with climate on time scales larger than several centuries.[31] The adaptability of vegetation patterns to rapid climate change is thus limited. Modern fragmented landscapes could further reduce this adaptability. This would lead to additional risks to ecosystems, food security and sustainable development – the elements of Article 2 of the Climate Convention.

The decadal rate of temperature change is directly derived from the temperature change profiles in IMAGE 2.1 by calculating a running mean over a 10-year period. The calculated decadal rate over the last two decades (1970s and 1980s) is somewhat higher than 0.15°C. This is close to the observed rate of 0.13°C per decade. All scenarios start at this level but follow largely different paths afterwards (Figure 5d). Initially, all baseline and most stabilization scenarios show a slight increase in the rate of climate change. The rate of change in the baseline scenarios remains at high levels, while in the stabilization scenarios it declines rapidly after 2030 to lower levels. In the emission reduction scenarios it declines immediately over the next decades and stabilizes at different but low levels.

*Sea-level rise after 1990 (cm).* Sea-level rise – mainly resulting from thermal expansion of the oceans and the melting of ice from glaciers, but also from the net melting of the ice caps on Greenland and Antarctica – affects coastal areas.[32] For example, coastal mud-flats and mangrove forests are sensitive to a rapid sea-level rise. Further, higher sea

[28] B J de Haan, M Jonas, O Klepper, J Krabec, M S Krol and K Olendrzynki, 'An atmosphere-ocean model for integrated assessment of global change', *Water, Air and Soil Pollution*, Vol 76, 1994, pp 283–318

[29] J T Houghton, L G Meira Filho, B A Callander, N Harris, A Kattenberg and K Maskell (eds), *Climate Change 1995: The science of climate change*, Cambridge University Press, Cambridge, 1996

[30] B Huntley, W P Cramer, A V Morgan, H C Prentice and J R M Allen (eds), *Past and Future Rapid Environmental Changes: The spatial and evolutionary responses of terrestrial biota*, Springer, Berlin, 1997

[31] I C Prentice, P J Bartlein and T Webb, III, 'Vegetation and climate change in eastern North America since the last glacial maximum', *Ecology*, Vol 72, 1991, pp 2038–2056

[32] R A Warrick, C Leprovost, M F Meier, J Oerlemans, P L Woodworth, R B Alley, R A Bindschadler, C R Bentley, R J Braithwaite, J R de Wolde, B C Douglas, M Dyurgerov, N C Flemming, C Genthon, V Gornitz, J Gregory, W Haeberli, P Huybrechts, T Jóhannesson, U Mikolajewicz, S C B Raper, D L Sahagian, R S W van de Wal and T M L Wigley, 'Changes in sea level', in J T Houghton, L G M Filho, B A Callander, N Harris, A Kattenberg, K Maskell (eds), *Climate Change 1995: The science of climate change*, Cambridge University Press, Cambridge, 1996

levels require a stronger protective infrastructure if significant damages to coastal structures are to be avoided. Small islands states are especially vulnerable in this respect. Determining local and regional sea-level rise, however, is difficult because of the diversity of coastal land forms, land upheaval due to post-glacial rebound, and sedimentation rates influencing the observed rates.

The response of sea level in all scenarios lags behind the increase in air temperature because ocean water temperatures increase more slowly than air temperatures and melting large bodies of ice takes time. Even if temperatures stabilize over the next century, the sea level will continue to rise for decades, although at slower rates (cf. Table 1). Sea level continues to rise in all scenarios although at different levels in 2100 (Figure 5e). Again, the baseline scenarios show the highest levels of 40–50 cm in 2100. The stabilization scenarios show a slower increase in sea level and reach levels between 20 and 35 cm by 2100. The emission reduction scenarios give the lowest levels (10–25 cm in 2100).

The above three impact-related indicators do provide some rough guidance for impact evaluation, but are not easily linked to impacts on ecosystems or societies at the regional and local level, the level which most policy makers are ultimately interested in. The comprehensive results of the IMAGE 2.1 model can be used to calculate impact levels for various indicators. Here, we focus on only two indicators related to unmanaged ecosystems, because they are at the core of Article 2. We do not present other indicators that can be evaluated with IMAGE because these are presented elsewhere.[33] The indicators are presented as percentages to allow comparison among indicators. The indicators are:

*Areas carrying a risk for natural potential vegetation.* The natural potential vegetation in all regions is determined by IMAGE 2.1 on the basis of local climate and soil characteristics. If climate changes, these potential vegetation patterns will shift accordingly. These potential shifts are recognized as one of the most important aspects of climate change by IPCC.[34] The percentage area where natural potential vegetation shifts from one potential vegetation class to another is considered to be 'at risk'. These shifts are determined relative to 1990.

*Areas with adapted or non-adapted vegetation.* Shifts in potential vegetation are calculated in IMAGE 2.1, but the actual change from one type to another is not instantaneous. When the actual shift (= adaptation) occurs depends on dispersal and establishment capabilities (a function involving plant and vegetation type and distance).[35] After becoming established, a plant takes time to grow to maturity (a function that depends on the new vegetation type) and to disperse again. Vegetation response is thus a function of the distance to a source, growth and dispersal characteristic of a plant type and local environmental conditions. The spread of new vegetation types often lags behind climate change. However, such lags are negligible for future vegetation types such as deserts, small for grass and shrublands (less than 20 years) and large for forests (much more than 20 years). If a plant type has not yet reached an area, this area contains non-adapted vegetation. A degraded type of the original vegetation will probably develop because it is not well

[33] J Alcamo and G J J Kreileman, *op cit*, Ref 4
[34] R T Watson *et al*, *op cit*, Ref 22
[35] J G van Minnen, K Klein Goldewijk and R Leemans, 'The importance of feedback processes and vegetation transition in the terrestrial carbon cycle', *Journal of Biogeography*, Vol 22, 1996, pp 805–814

adapted to the prevailing climate conditions.[36] This indicator is sensitive for the rate of temperature change.

*Results for impact indicators*

There are large differences between the scenarios in shifts in potential natural vegetation (Figure 6a). The baseline scenarios show large impacts. Between 40% and 50% of all vegetation will shift into another vegetation type by 2100. All risk levels tend to level off somewhat after 2050, mainly because little original vegetation remains to be affected. The stabilization scenarios all show impact levels ranging from 15% to 30% by 2100. High stabilization levels coincide with higher impacts. Only the emission reduction scenarios show low levels. The 2% emission reduction scenario does not lead to significant impacts. Only in the early phases of the simulation are some regions affected. Up to 2025 most scenarios show similar impacts. They only diverge beyond 2025. This is due to the lag time in the climate systems. The impacts are directly linked to temperature and precipitation changes in IMAGE 2.1, which again follow emissions and concentration changes that only start to diverge significantly after some time.

Large differences emerge when regional patterns are evaluated (Figure 7a). Boreal, temperate and subtropical latitude regions display the largest impacts, while in the tropical regions impacts are less apparent. The most northern regions show a very clear time path. Initially, the level of

[36] A M Solomon and R Leemans, 'Boreal forest carbon stocks and wood supply: past, present and future responses to changing climate, agriculture and species availability', *Agricultural and Forest Meteorology*, Vol 84, 1997, pp 137–151

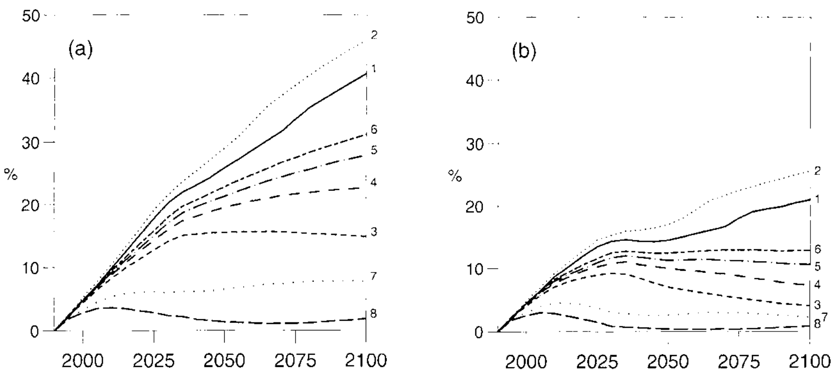


**Figure 6.** Global risks for (a) global potential natural vegetation and (b) the vegetation that does not adapt for different scenarios. Scenarios: (1) Baseline A; (2) Baseline C; (3) stabilization at 350 ppmv; (4) stabilization at 450 ppmv; (5) stabilization at 550 ppmv; (6) stabilization at 650 ppmv; (7) 1% decrease in global annual emissions after 1990; (8) 2% decrease in global annual emissions after 1990.

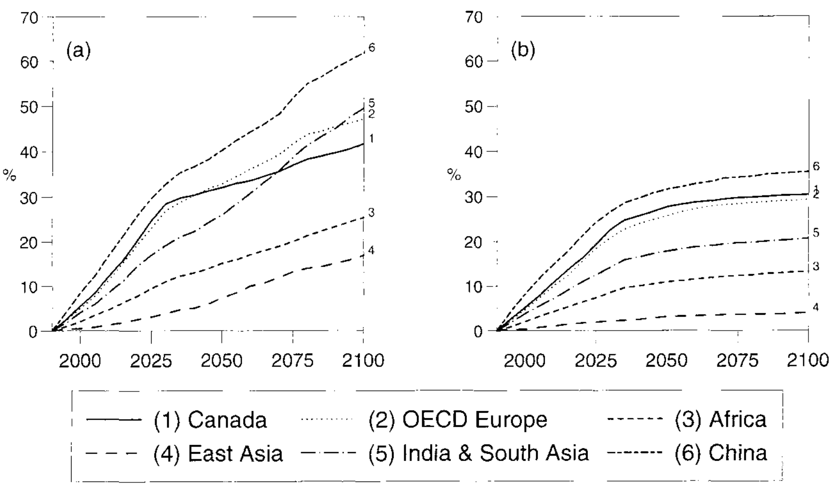


**Figure 7.** Regional risks for natural potential vegetation for two different scenarios: (a) Baseline A; (b) stabilization at 450 ppmv. Regions: (1) Canada; (2) OECD Europe; (3) Africa; (4) East Asia; (5) India and South Asia; (6) China and CP countries.

impacts increases rapidly but slows down after 2025. These patterns can easily be explained by the pattern of climate change and the sensitivity to climate change of different vegetation types. Simulated climate change is most pronounced in high-latitude regions and less in the tropics. The most sensitive vegetation types are boreal forests and tundras which are well adapted to cold conditions. Small increases in temperatures lead to disproportionate changes in the length of the growing season and thus growth conditions. These ecosystems will thus respond almost immediately to relatively minor changes. This has already been observed in these ecosystems.[37] The slower rate of increasing impact levels in these systems is partly due to physical limitation to shifting further northwards due to the border with the polar ice sea. The impact level is thus a function of the regional level of climate change and the sensitivity of the vegetation type.

Figure 6b illustrates for the scenarios the percentage of non-adapted vegetation after a climate change. Different adaptation levels can easily be distinguished for the different scenarios, with results suggesting that between 20% and 70% of the vegetation could be in a non-adapted stage by 2100. The scenarios with a larger climatic change show a much larger fraction of the impacted vegetation that will be non-adapted. The total extent of adapted vegetation increases slowly with time. When the total impact levels level off or stabilize, the adapted percentage can eventually catch up. In scenarios with higher impact levels, this catching-up occurs beyond the selected time horizon (beyond 2100, Table 3). The shape of the adaptation curve is similar to the rate of temperature change curves (Figure 5d), giving some qualitative support to the hypothesis that the adaptive capability of ecosystems is a function of the rate of climate change. It also highlights the fact that lower impact levels have faster and better adaptive capabilities. These conditions coincide with lower rates of change.

The safe emissions corridors are particularly sensitive to the rate of temperature change. Table 3 addresses this issue in the results of the IMAGE 2.1 calculations, where adaptation has been taken into account. According to our calculations, rates of decadal temperature change below 0.1°C allow more than 50% of the impacted ecosystems to adapt relatively rapidly to climate change (before 2050). Rates between 0.1 and 0.2°C per decade lengthen the adaptation process for the impacted ecosystems considerably. Rates beyond 0.2°C per decade do not allow for adaptation within the next century. Only decadal rates below 0.05°C per decade, however, lead to low overall impact levels (Table 4).

[37]R B Myneni, C D Keeling, C J Tucker, G Asrar and R R Nemani, 'Increased plant growth in the northern high latitudes from 1981 to 1991', *Nature*, Vol 386, 1997, pp 698–702

**Table 3. Characteristics of the impacts on ecosystems and their adaptation potential**

| Scenario | Temperature change in 2050 (°C) | Mean rate of temperate change 1990–2050 (°C/decade) | Vegetation at risk in 2050 (%) | Temperature change in 2100 (°C) | Mean rate of temperate change 2050–2100 (°C/decade) | Vegetation at risk in 2100 (%) | Year when half of the vegetation is adapted |
|---|---|---|---|---|---|---|---|
| Baseline C | 1.8 | 0.29 | 29 | 3.4 | 0.33 | 46 | >2100 |
| Baseline A | 1.5 | 0.25 | 26 | 2.8 | 0.27 | 41 | >2100 |
| Stab. at 650 ppmv | 1.3 | 0.21 | 23 | 2.0 | 0.14 | 32 | 2070 |
| Stab. at 550 ppmv | 1.1 | 0.19 | 22 | 1.7 | 0.11 | 28 | 2055 |
| Stab. at 450 ppmv | 1.0 | 0.17 | 19 | 1.3 | 0.05 | 23 | 2050 |
| Stab. at 350 ppmv | 0.7 | 0.12 | 15 | 0.7 | −0.01 | 16 | 2045 |
| 1% emission red. | 0.2 | 0.04 | 6 | 0.3 | 0.01 | 8 | 2030 |
| 2% emission red. | 0.0 | 0.00 | 2 | 0.0 | −0.02 | 2 | 2025 |

**Table 4. Regional impacts compared with the global average for IMAGE 2.1 Baseline A scenario in 2100**

| Region | Temperature change | Potential vegetation | Decrease in cereal yield | Decrease in rice yield | Change in extent of cereals | Change in extent of rice | Change in extent of Malaria |
|---|---|---|---|---|---|---|---|
| Canada | + | 0 | + | n.a. | + | – | – |
| USA | + | + | + | + | – | + | – |
| Latin America | – | 0 | 0 | + | – | + | – |
| Africa | 0 | – | + | – | – | – | – |
| OECD Europe | 0 | + | – | – | + | – | + |
| Eastern Europe | 0 | 0 | – | + | 0 | – | + |
| CIS | + | 0 | – | – | + | + | + |
| Middle East | + | + | – | + | + | + | + |
| India and South Asia | 0 | + | + | 0 | – | – | – |
| China and CP Asia | 0 | + | – | + | + | + | + |
| East Asia | – | – | – | + | – | 0 | – |
| Oceania | 0 | – | + | – | – | – | + |
| Japan | – | – | – | – | 0 | + | 0 |

Note that these calculations do not take into account real world conditions because adaptation and migration are likely to be constrained (sometimes also stimulated, e.g. by the introduction of alien species) by natural and man-made barriers. The results could thus be over-optimistic. These findings are coarse estimates and therefore have to be interpreted with some caution, since we present only average rates of change over a century and aggregate impacts, while the actual impacts are clearly also dependent on the local and regional conditions and dynamic changes therein.

The regional impacts patterns, however, cannot be generalized. Earlier assessments, for example, have shown that arid areas in tropical regions could well lead to larger declines in crop productivity, while the conditions for crops in boreal regions generally improve. Table 3 shows a summary of regional impacts for other impact indicators not discussed in detail in this paper but elsewhere.[38] These results show that each impact affects all regions differently. The impact patterns are very heterogeneous and no clear patterns emerge. The two different scenarios (Figures 7a and 7b) show, however, that lower levels of climate changes generally lead to lower impact levels.

### *Conclusions for impact indicators*

The above analysis illustrates the importance of potential climate impacts and links them to global climate indicators. The levels of impacts vary depending on the scenario: scenarios with high emissions levels lead to larger climatic change, globally and regionally. This can also be observed in the impact levels. However, we should use these results with some caution. This analysis with the IMAGE 2.1 model is based on a single climate sensitivity (2.37°C for $CO_2$ doubling), which is coupled to regional climate change patterns resulting from a single simulation with a General Circulation Model (GCM). The use of other GCM simulations gives different results.[39] The conclusion could therefore be influenced by the selected GCM run. The differences between different GCMs probably become smaller when the results are aggregated to large regions or the globe, as is done in the analysis presented here. Higher climate sensitivities also lead to higher impact levels. If a different sensitivity were to be used, this would not change the relative impacts between scenarios and

[38] J Alcamo and G J J Kreileman, *op cit*, Ref 4
[39] J Alcamo *et al*, *op cit*, Ref 24

regions, only their levels. Therefore we do not expect these uncertainties to influence our main qualitative conclusions from this analysis. These are:

- *Risks cannot be fully eliminated.* In a scenario with decreasing greenhouse gas emissions significant impacts also remain. Only scenarios where emissions are immediately reduced globally by 1% or more, display very low impact levels.
- *Risks are not uniform.* Impacts vary across regions.
- *Reducing global risks means reducing regional risks.* In general the regional risks are considerably smaller in a scenario with low greenhouse gas emissions than in one with high emissions.
- *There will be risks in all regions.* In all regions risks appear for at least one of the indicators analysed. There seem no clear winners or losers.
- *Importance of rate of change.* Immediately reducing the rate of climate change reduces global and regional impact levels, with the impacts tending to stabilize earlier in time.
- *Lower rates of climate change also increase the capability of ecosystems to adapt naturally.* Ecosystems are much less vulnerable to climate change if the decadal rates of global mean temperature change remain below 0.05°C per decade.

These findings can be related to the selection of indicator values for the safe landing analysis. Tables 1, 3 and 4 specify impact levels. Roughly, the 350 and 450 ppmv stabilization and emission reduction scenarios can be considered consistent with strict safe-emissions corridors. These can be associated with the climate protection goal of the EU or stricter goals that take into account a limit on the rate of change of global mean temperature. The stabilization scenarios still result, however, in considerable impact levels, while the immediate reduction scenarios allow vegetation to adapt much more rapidly. Naturally, this finding is directly linked to two indicators in the safe landing analysis: the annual emission reduction potential and the rate of change of emission growth or reduction between decades (i.e. the 'inertia' of the socio-economic system). If the emission reduction potential is assumed to be high and inertia low, impacts can be more easily limited. If the feasibility of emission reductions is low and the system inertia high, impacts can probably not be mitigated in line with the ultimate objective of the Climate Convention. The next section will therefore address the feasibility of various rates of emission reductions and the economic implications of the safe emissions corridors.

## Technological and economic aspects of the safe landing analysis

The application of the safe landing approach to policy questions has clearly shown that technological change and costs of response measures are crucial issues in the climate debate. The indicator in the safe landing analysis that reflects the socio-economic dimension is the maximum annual emission reduction rate. Here we will address the following issues in more detail: (a) 'What are maximum feasible rates of global emission reduction?' and (b) 'How would economic constraints influence emission corridors?'

The safe landing analysis was originally developed primarily as a method to determine safe emissions corridors associated with different impact (or risk) levels. From this perspective, the evaluation of the socio-economic consequences of policies required to stay within a particular corridor is a complementary effort, for which other tools (e.g. economic models) would be needed. Alternatively, economic constraints could be introduced directly into the safe landing analysis, as was sometimes proposed in the policy dialogue. A preliminary example is discussed of how this could be done. We will base our analysis on a literature assessment and the use of some other models.

*The feasibility of various rates of global emission reductions*

Although non-$CO_2$ and land-use-related emissions should not be neglected, the feasibility of various rates of global emissions reductions is mainly determined by $CO_2$ emission from fossil-fuel use. There are two major factors determining the global $CO_2$ emissions. The first is the future level of economic activity, which is some function of population development and average income growth. The second factor is the future state of technology, determining both energy-use efficiency and technological options available to generate energy to meet demand. Technological developments not only determine the technical feasibility, but also influence the economic feasibility of emission reduction options.

In the short term, the emission reduction rate is constrained by the existing energy infrastructure, which has an average turnover time of several decades. In the long run, however, it is limited by the expected growth of the global energy demand. In a typical 'conventional future' future increases in energy and material-use efficiency, together with structural economic change, will reduce the energy intensity of the world economy. This process will reduce the growth of world energy demand but, at least in the foreseeable future, it is unlikely that it will reduce emissions in absolute terms. To achieve large absolute cuts in global emissions which are required to meet stringent climate protection goals, it is essential to substitute fossil fuels by alternative energy carriers such as modern biomass, hydropower, nuclear or solar energy. However, the introduction of these supply-side alternatives is currently hindered by the availability of large reserves of relatively cheap fossil fuels, especially coal. Technological developments will therefore play a major role in making such alternative energy resources more attractive by improving their performance and reducing their overall costs.

The 'continuity rate'[40] is mentioned in the literature as one of the obvious mechanisms to reduce emissions. This rate determines the speed at which fossil fuels could be phased out in approximate synchrony with turnover of capital stocks. It avoids idling or premature retirement of productive capacity. Substitution on the supply side could (optimistically) reduce carbon emissions related to fossil fuels by 2.5–3.0% per year and efficiency improvements could add an annual reduction of about 2.5–3.0% on the demand side.[41] Theoretically, for a world economic growth of 3.0% this would lead to a maximum feasible emissions reduction of approximately 2.0-3.0%. Clearly, in the real world economic, political and social realities will reduce the feasibility of such potentially achievable reduction rates. Renewable energy sources would have to be made more competitive either by subsidizing them or making fossil fuels more expensive. This will surely meet strong opposition from vested interests

[40]F Krause, W Bach and J Koomey, *Energy Policy in the Greenhouse*, Vol 1: *From Warming Fate to Warming Limit. Benchmarks for a Global Climate Convention*, International Project for Sustainable Energy Paths, El Cerrito, California, 1989

[41]F Krause *et al*, *op cit*, Ref 41

from the fossil-fuel industry and exporting countries. Moreover, making such a worldwide shift would demand enormous efforts in the transfer of technologies, the training and education of people and the development of supporting energy infrastructure and service networks. It could well take 30–40 years to transfer and implement the appropriate technologies in developing countries.

A different way of looking into the question of the feasibility of different rates of emissions reduction is to examine available low-fossil-energy scenarios. We selected the WEC/IIASA 'Ecologically Driven' scenario[42] and the LESS Biomass-Intensive Scenario (LESS-BI).[43] These scenarios embody extensive expert knowledge with respect to feasible changes in the energy system.

The 'Ecologically Driven' scenario was originally developed by the World Energy Council[44] and was later updated and extended in collaboration with IIASA.[45] The scenario assumes ambitious policies to accelerate energy efficiency and to develop and promote environmentally benign decentralized energy technologies. The policy measures include, for example, the support of R&D programmes and the introduction of a carbon tax. Its demographic and economic assumptions differ slightly from the IS92a scenario. Reductions in energy intensity reductions are high (1.5% per year average between 1990 and 2100). This results in a global energy demand of 895 EJ in 2100. Global $CO_2$ emissions decrease from 6.3 Gt C in 2020 to 5.4 Gt C in 2050 and 2 Gt C in 2100.[46] The average annual global emission reduction rate for $CO_2$ is approximately 0.5% between 2020 and 2050 and 2.0% thereafter.

The LESS-BI scenario has been especially developed to illustrate the technically possible mitigation potential of energy supply. The scope of the scenario was limited to known, technically feasible and potentially commercial technologies. It emphasizes the potential of energy production from biomass to reduce global greenhouse gas emissions. However, not only was a strong shift in the energy supply mix assumed, but also a 50% lower growth in global energy demand in 2100 compared to the IPCC scenario IS92a[47] (707 and 1454 EJ per year respectively). With its relatively high mean annual economic growth of 3% for the period 1990–2100, the energy intensity decreases by a factor of 4 in 2100 compared with IS92a. The resulting rate of global annual $CO_2$ emission reduction in the LESS-BI scenario is about 1.2% per year between 2025 and 2050, 1.6% per year between 2050 and 2075, and 1.8% per year between 2075 and 2100. Emissions from other sources are not considered in LESS-BI. These values are similar to the 'Ecologically Driven' scenario, although the shift towards renewable energy carriers is faster.

To assess the implications of LESS-BI for land use and land-use-related greenhouse gas emissions, Leemans *et al*[48] implemented the scenario in the IMAGE 2.1 model. To allow for better comparison with other IMAGE scenarios, the IS92a assumptions for population and economic growth were adopted, assuming less economic growth than in the original LESS BI scenario (2.3% vs. 3% average per year between 1990 and 2100).[49] Not only energy-related $CO_2$ emissions, but all greenhouse gas emissions were calculated with the IMAGE 2.1 model. Due to a slower shift towards non-fossil fuels, the global annual emission reduction rate in the IMAGE LESS-BI scenario for energy-related $CO_2$ between 2025 and 2050 is lower than in the original LESS-BI scenario: 0.8% vs. 1.2%. This is compensated for by a somewhat faster rate between 2050 and 2100 (1.8% vs. 1.7%). If all anthropogenic greenhouse

[42]WEC/IIASA, *Global Energy Perspectives to 2050 and Beyond*, Joint IIASA-WEC Study Report, World Energy Council and International Institute for Applied Systems Analysis, London, 1995

[43]H Ishitani, T B Johansson, S Al-Khouli, H Audus, E Bertel, E Bravo, J A Edmonds, S Frandsen, D Hall, K Heinloth, M Jefferson, P de Laquil, III, J R Moreira, N Nakicenovic, Y Ogawa, R Pachauri, A Riedacker, H-H Rogner, K Saviharju, B Sørensen, G Stevens, W C Turkenburg, R H Williams, F Zhou, I B Friedleifsson, A Inaba, S Rayner and J S Robertson, 'Energy supply mitigation options', in R T Watson, M C Zinyowera and R H Moss (eds), *Climate Change 1995: Impacts, adaptations and mitigation of climate change: scientific-technical analysis*, Cambridge University Press, Cambridge, 1996

[44]WEC Commission, *Energy for Tomorrow's World: The reality, the real options and the agenda for achievement*, Kogan Page, London, 1993

[45]WEC/IIASA, *op cit*, Ref 42

[46]There are two variants of the 'Ecologically Driven' scenario: one with a phase-out of nuclear energy (C1) by 2100 and one including nuclear energy (C2). The figures refer to the C1 variant; in the C2 variant, $CO_2$ emissions in 2050 are 5 Gt C; $CO_2$ emissions in 2100 are the same in both variants

[47]J Leggett *et al*, *op cit*, Ref 11

[48]R Leemans, A van Amstel, C Battjes, G J J Kreileman and S Toet, 'The land cover and carbon cycle consequences of large-scale utilizations of biomass as an energy source', this volume (pp 235–257)

[49]However, even with these lower economic growth assumptions, extremely high levels of energy efficiency improvements had to be assumed to arrive at the same energy demand (e.g. an average of about 3% per year in the use of industrial heating in India and East Asia between 2000 and 2060).

gas emissions are taken into account the picture changes considerably: the rates of reductions in greenhouse gas emissions in equivalent $CO_2$ are generally lower: 1.1% and 0.5% for the years 2025–2050 and 2050–2100, respectively. This decrease is caused by the inclusion of land-use-related emissions, which follow the original baseline emissions.

While all these scenarios enable a quick scan of implied emission reductions rates, they do not allow for a thorough analysis of the forces driving these rates. Therefore we will use the TIME model to further evaluate the effectiveness of additional energy expenditures to raise global emission reduction rates. TIME is a global energy model that simulates both energy demand and supply dynamics.[50,51] The model focuses explicitly on issues of technology development and diffusion, including induced technical change and the inertia of energy systems. The approach differs therefore from the more generally applied general equilibrium models. The TIME scenarios were developed in response to two long-term energy scenarios, 'Sustained Growth' and 'Dematerialization', developed by Shell.[52] These scenarios contrast strongly with traditional non-intervention scenarios, which usually project a sustained increase in fossil-fuel consumption. The Shell scenarios assume high rates of efficiency improvements or rapid shifts towards non-fossil energy resources in the next century. This results in relatively low baseline projections of $CO_2$ emissions. The TIME-1 scenario mimics 'Sustained Growth' and assumes a large (autonomous) shift in the future mix of energy carriers towards non-fossil fuels. The TIME-2 scenario resembles 'Dematerialization' and assumes high rates of (autonomous) energy efficiency improvements. We further combined the ideas of both scenarios – efficiency improvements plus fuel shift – in TIME-3a. This scenario arrives at even lower emissions than TIME-1 and TIME-2.

Figure 8 depicts the energy supply by carrier of these scenarios. Figure 9 shows the resulting $CO_2$ emissions. TIME-1 and TIME-2 illustrate how neither efficiency improvements nor a shift to non-fossil fuels alone would lead to substantial reductions in future $CO_2$ emissions. This is, however, achieved in the TIME-3 scenario, which combines technologically optimistic assumptions for both future energy supply and demand. No explicit policy intervention is assumed. Resulting global $CO_2$ emission reduction rates in TIME-3 are: 1.1% between 2025 and 2050, 0.8% between 2050 and 2075, and 1.3% between 2075 and 2100. These average values are lower than both the LESS-BI and the 'Ecologically Driven' scenario.

These latter scenarios do, however, assume strong policies to support the development and implementation of renewables and to stimulate energy savings. To explore under which conditions higher rates of global emission reductions could be achieved, the TIME model was used to assess cases with explicit policy interventions, resulting in additional expenditures in the energy system.[53] The policy interventions applied to the model are (1) the application of a carbon tax and (2) additional expenditures on R&D programmes in biofuels and other renewable electricity carriers. A carbon tax enhances energy efficiency and reduces the attractiveness of fossil fuels. The additional expenditures on R&D programmes enhance the competitiveness of non-fossil fuels. Two cases were investigated on the basis of TIME-3a with policy measures resulting in additional energy expenditures up to a maximum of 1% of world GDP (TIME-3b) and a maximum of 2% of world GDP (TIME 3c). The results show for both scenarios an emission reduction rate of energy-related $CO_2$

[50]The so-called TARGETS/IMAGE energy model was developed in response to the demand in the policy debate for enhanced representation of the energy sector in the IMAGE model (forming the basis of the safe landing approach presented here). The TIME demand submodel is based on the energy model of IMAGE 2.1. In contrast with IMAGE 2.1, TIME also contains a global energy supply model, which calculates the energy supply mix given assumptions on future technological developments and other factors determining the future costs of energy resources. A fully regionalized version of the model (TIMER) is at present under development and will be included in the next version of the IMAGE model.

[51]H J M de Vries and M A Janssen, *Global Energy Futures: An integrated perspective with the TIME model*, RIVM Report, Bilthoven, 1997

[52]P Kassler, 'Energy for development', Shell Selected Paper, London, 1994

[53]Note that TIME is a globally averaged model, which does not include technology transfers and joint implementation, which may reduce the cost. Furthermore, the economic consequences of the policy interventions cannot be assessed by the energy model, TIME. Shifts in economic activities due to increasing energy costs may lead to more effectiveness of policy interventions.

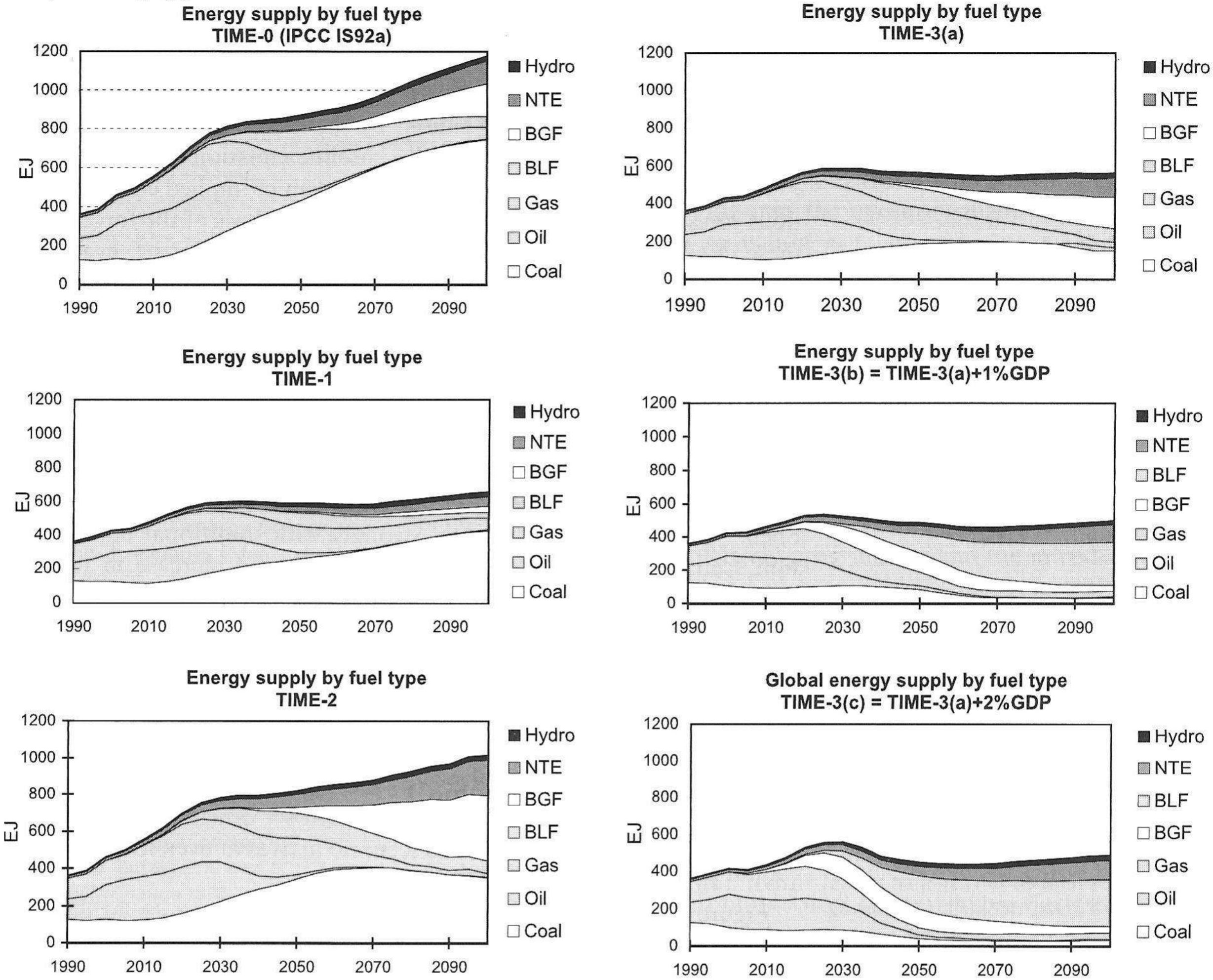


**Figure 8.** Energy supply by fuel type of the various TIME scenarios.

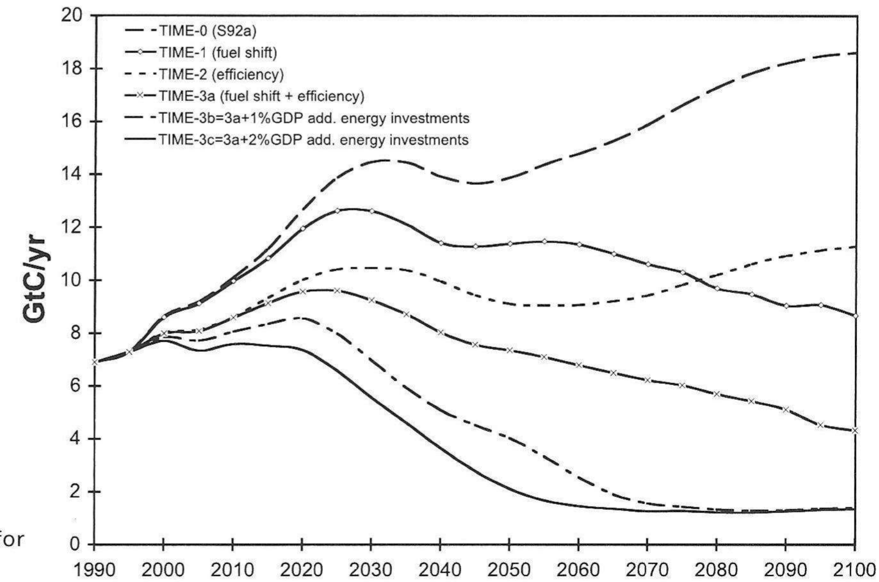


**Figure 9.** Global $CO_2$ emissions for the various TIME scenarios.

of 3–5% per year for a limited period in the next century. The analysis suggests that in order to achieve global annual emission reduction rates of more than 2% per year, substantial policy measures are required, even in the case of optimistic assumptions on technological change.

The scenarios presented offer a considerable spectrum of possibilities for technological change in the energy sector. If we compare the various low-emissions scenarios, annual reduction rates for energy-related $CO_2$ emissions range between 0.5% and 2%. The TIME experiments indicate that higher global emission reduction rates require strong policy interventions and very optimistic assumptions with respect to technological developments. Moreover, reduction rates of more than 2% are only achieved during limited periods. In the safe landing analysis, if emissions are near the top of the corridors in the target year (e.g. 2010), they would have to be reduced by the maximum allowed rate afterwards. It is therefore highly uncertain that rates of around 2% per year or higher can be maintained over such long periods of time.

### *The economic implications of the climate constraints*

In the above analysis we approached possible emission reduction primarily from an ecological perspective, by emphasizing climate protection goals and making necessary, but somewhat arbitrary, assumptions on the future feasibility of different rates of emissions reduction. This approach relates to the precautionary principle. We did not analyse any cost-effectiveness of policies that could be associated with particular emissions corridors. Yet, reducing emissions rapidly may involve high economic costs. Costs are usually a major factor in developing policies, more so than technical feasibility. Policy makers suggested several times that the inclusion of economic constraint in the safe landing analysis should be explored.

TIME will be used here again to examine the consequences of such constraint. To obtain total equivalent-$CO_2$ emissions, non-energy-related greenhouse gases from the IMAGE Baseline A scenario were added to the energy-related emission calculated by TIME. Low-cost global emission paths up to 2010 were constructed to define the potential top of the corridor, meeting both the earlier climate protection goals and the constraint set on additional future energy expenditures. The lower limit of the corridor is determined by making additional expenditures in the energy sector instantaneously and continuously up to the predefined constraint on additional expenditures. A disadvantage of this method is the necessity of choosing an (arbitrary, 'non-intervention') reference scenario for comparing costs.

Two different sets of scenarios were analysed in this approach: (1) with supply and demand assumptions in the TIME model comparable to the IPCC IS92a scenario (TIME-0) and (2) with energy supply and demand assumptions of the TIME-3a scenario. The standard set of constraints on emissions corridors[54] was evaluated for each scenario. Additional energy expenditures were limited to a maximum of 3% of global GDP because higher expenditures were assumed to be unrealistic. TIME-0 only complies with the widest emissions corridor. This implies that even an additional energy expenditure of up to 3% of global GDP would not suffice to meet stricter climate constraints, such as in the EU proposal. The results of TIME-3a (a technologically more optimistic scenario), however, differ strongly. In the strictest case there is no real emission corridor

[54] J Alcamo and G J J Kreileman, *op cit*, Ref 4

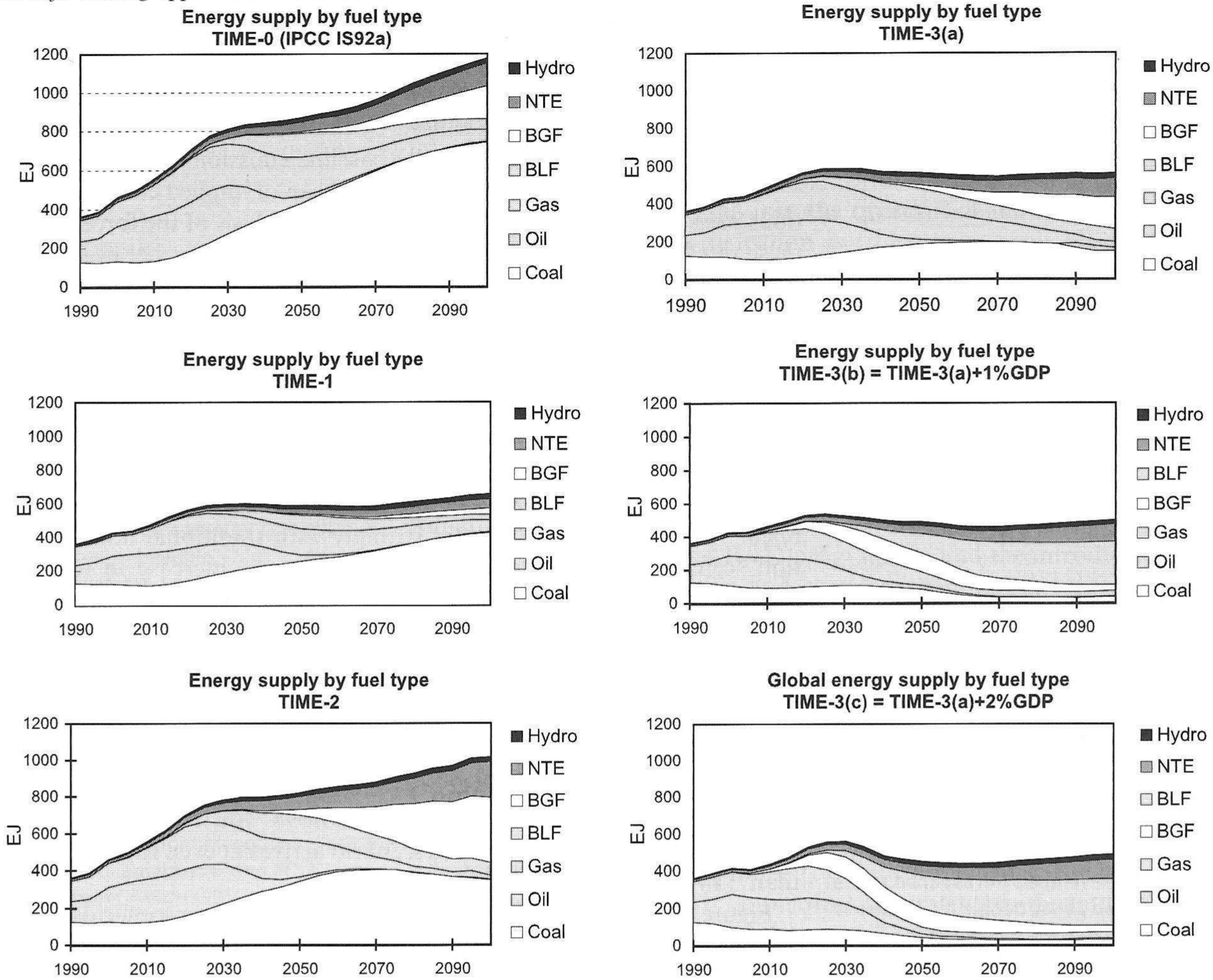


**Figure 8.** Energy supply by fuel type of the various TIME scenarios.

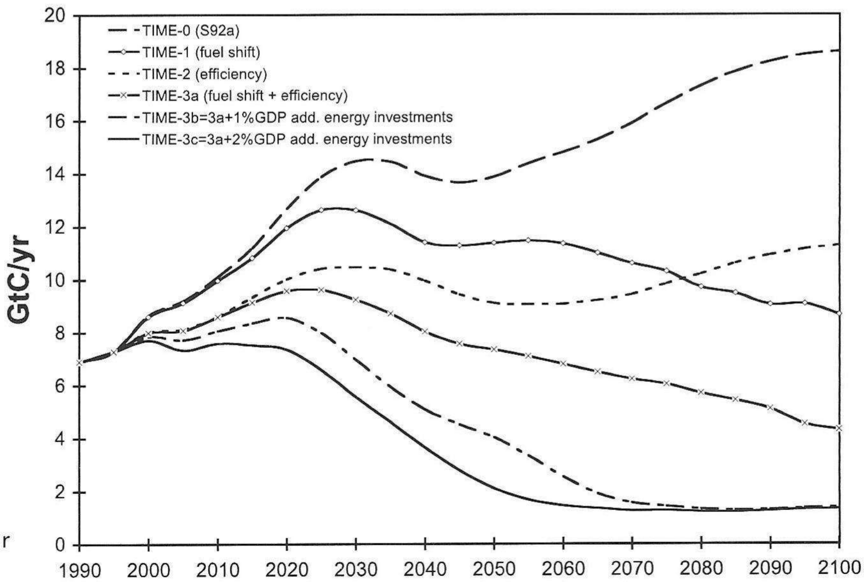


**Figure 9.** Global $CO_2$ emissions for the various TIME scenarios.

of 3–5% per year for a limited period in the next century. The analysis suggests that in order to achieve global annual emission reduction rates of more than 2% per year, substantial policy measures are required, even in the case of optimistic assumptions on technological change.

The scenarios presented offer a considerable spectrum of possibilities for technological change in the energy sector. If we compare the various low-emissions scenarios, annual reduction rates for energy-related $CO_2$ emissions range between 0.5% and 2%. The TIME experiments indicate that higher global emission reduction rates require strong policy interventions and very optimistic assumptions with respect to technological developments. Moreover, reduction rates of more than 2% are only achieved during limited periods. In the safe landing analysis, if emissions are near the top of the corridors in the target year (e.g. 2010), they would have to be reduced by the maximum allowed rate afterwards. It is therefore highly uncertain that rates of around 2% per year or higher can be maintained over such long periods of time.

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as these climate goals are only met with the full 3% additional energy expenditure. The global emissions in this case are 9.5 Gt C/yr. In the somewhat less strict case (compatible with the EU climate goals) at least 1% additional energy expenditures are needed just to stay within the corridor ranging from 9.5 Gt C/yr to 10.6 Gt C/yr. For 2% or 3% additional expenditures, the emissions would be 10.2 Gt C/yr and 9.5 Gt C/yr respectively. In the least strict case no additional expenditures are needed to stay within the safe emissions corridor. However, higher short-term expenditures offer more flexibility after 2010.

These results demonstrate that assumptions on technological change in scenarios largely determine the costs of meeting particular climate change targets. They also suggest that – even under optimistic technological change assumptions – proposed climate protection constraints can only be met by additional expenditures in the energy sector. The narrow corridors illustrate the inertia of the global energy system, which hamper the possibilities for short-term reductions of greenhouse gas emissions, even if substantial additional expenditures are made. Given this inertia in the energy system, the rate of decadal temperature change becomes especially the most difficult environmental constraint to be met.

This analysis represents a preliminary attempt to tie cost constraints to the 'safe landing analysis'. Its exploratory nature does not yet allow for any straightforward quantitative conclusions. The main shortcomings of the analysis still are: (1) that non-energy-related options for emission reduction are not yet included; (2) that the TIME model does not include feedbacks between energy expenditures and the rest of the economic system, which – especially given the magnitude of the additional energy expenditures considered – will affect both energy demand and economic development; and (3) that region-specific detail would have to be included in order to improve the calculations. Moreover, as the use of an economic constraint make the outcomes scenario-dependent, other sets of scenario assumptions (e.g. those for population and economic growth) should be evaluated as well in order to determine their influence. However, the analysis does clearly show the feasibility of using additional economic constraints in the safe landing analysis.

## Discussion and conclusions

When the policy applications of the safe landing analysis were discussed, the AGBM negotiations were marked by a controversy between proponents of 'early action' and those advocating a 'delayed response'. The safe landing approach was used by various participants in the negotiations as support for the first viewpoint. The starting point of the safe landing approach is climate protection rather than economic efficiency. From an economic perspective, however, it can be argued that to achieve stabilization of atmospheric concentrations, cumulative emissions over a longer period are more important than annual emissions. This allows for more flexibility in the timing of the actual emissions controls[55] because the inertia of the socio-economic system does not allow for immediate global emissions reductions. Although under the Kyoto Protocol some emissions will be reduced, there are many economic arguments for letting emissions decline proceed as slowly as possible, at least for some decades. For example, this creates time to develop effective emission reduction technologies. With such technologies, large future

[55]T M L Wigley *et al*, *op cit*, Ref 18

emission reductions will be much cheaper and will then achieve similar stable concentration levels as in the case of early reductions. This is the so-called 'when flexibility'. There are many arguments against this view.[56,57] An important one concerns the long-term rates of technological improvements. Are they sufficient to reduce the cost of non-carbon technologies while less expensive conventional alternatives remain available? Our analysis further points out that 'interim' impacts that are caused by a more rapid climate changes should not be neglected. In determining impact levels, not only absolute levels of change but also the rate of change should be considered. A delayed control of emissions leads to higher initial rates of climate change, rapidly limiting the adaptive capabilities of ecosystems (Table 3).

There is increasing evidence that rates of change are at least as important as cumulative change, not only from ecosystem research but also from the sensitivity of changes in ocean circulation.[58] Our analysis using the IMAGE 2 model confirms that low rates of change coincide with lower interim impacts: at rates of temperature increase of 0.2°C per decade or higher, adaptation of most ecosystems within the next century would be impossible. Rates between 0.1 and 0.2°C per decade would lengthen the adaptation process considerably, while rates below 0.1°C per decade would allow adaptation of roughly more than half of all affected vegetation types according to our calculations. This confirms that a value of 0.1°C per decade, as proposed ten years ago,[59] may not only define a value beyond which adaptation is limited, but may even have overestimated the actual adaptability of ecosystems.

Our economic analysis has shown that the level of additional energy expenditures needed to meet certain climate protection goals, strongly depends on assumptions with respect to autonomous technological development on both the demand and supply sides. From the analyses so far it can be concluded that annual emission reduction rates may be achieved for global $CO_2$ emissions up to 2%, but only if one assumes (1) IPCC IS92a-like assumptions for economic growth and population development, (2) optimistic technological assumptions with respect to future energy efficiency improvements and future costs of non-fossil energy resources, and (3) emission mitigation policies in the energy sector, which may include the use of a carbon tax. It seems unlikely that this rate will be as high for equivalent $CO_2$ emissions, although this needs to be analysed in more detail by including options to reduce non-$CO_2$ and non-energy-related greenhouse gases.

Our analysis of the EU climate goal suggests an achievable goal for the selected additional set of climate constraints, but only if significant and early emission reductions in Annex-I countries are accomplished, followed soon thereafter by emission limitations and reductions in all other regions. The Kyoto Protocol fulfils this requirement. This analysis makes some important trade-offs explicit. If we combine the insights of the environmental and climatic impact analysis with that of technological and economic issues, the following trade-offs become evident:

1. *Ecological or economic risks.* Climate goals which are too stringent seem incompatible with technological or economic possibilities; however, too little effort to control greenhouse gas emissions means high risks for ecosystems, including interim impacts and adaptation possibilities. The safe landing approach allows emis-

[56] H-H Rogner, 'Stabilization of atmospheric $CO_2$ concentrations: the role of technology change', paper presented at an informal session at the 5th meeting of the Ad Hoc Group of the Berlin Mandate, Geneva, 1996.

[57] M Grubb, 'Technologies, energy systems and the timing of $CO_2$ emissions abatement: an overview of economic issues', *Energy Policy*, Vol 25, 1997, pp 159–172

[58] T F Stocker and A Schmittner, 'Influence of $CO_2$ emision rates on the stability of the thermohaline circulation', *Nature*, Vol 388, 1997, pp 862–865

[59] J Jaeger, *Developing Policies for Responding to Climatic Change*, WMO Technical Document No. 225, World Meteorological Organisation, Geneva, 1988

sions corridors to be found in which both types of risks are reduced.

2. *Acting now or later*. Premature action is likely to meet with serious economic and technological constraints, but delayed response poses serious environmental risks and shifts the responsibility for addressing climate change to future generations, including those in developing countries. The safe landing approach provides a mechanism for evaluating the consequences of differences in the timing of policies.

The safe landing approach, supported by its interactive software, has already been shown to be useful through various applications in support of the policy negotiations in the Ad Hoc Group on the Berlin Mandate, the European Union and several individual countries. This demonstrates that the development and application of simple tools, based on scientifically established models, can, in an iterative dialogue with policy makers, help to bridge the gap between global policy development and scientific research. However, the policy dialogue has also revealed the need for further elaboration and scientific support to manage uncertainties – notably, the selection and valuation of appropriate indicators, which should be policy relevant and scientifically credible, deserve further debate. Especially the linkage of the global average climate protection indicators to regional adaptation of ecosystems should be evaluated and synthesized in a scientifically credible and policy-relevant manner. Here, especially, the importance of the rate of change is crucial, since this indicator can have a great impact on short-term emissions corridors.