

INTEGRATED ASSESSMENT OF LONG-TERM CLIMATE POLICIES: PART 2 – MODEL RESULTS AND UNCERTAINTY ANALYSIS

FERENC L. TOTH^{1*}, THOMAS BRUCKNER², HANS-MARTIN FÜSSEL¹,
MARIAN LEIMBACH¹ and GERHARD PETSCHL-HELD¹

¹*Potsdam Institute for Climate Impact Research, Postfach 601203, D-14412 Potsdam, Germany*
E-mail: toth@iiasa.ac.at

²*Institute for Energy Engineering, Technical University of Berlin, Marchstr. 18, D-10587 Berlin, Germany*

Abstract. An integrated assessment model (IAM) is applied to explore options for long-term climate policy by identifying permitted emission corridors. The options are determined under various assumptions about constraints related to acceptable impacts of climate change in terms of alterations induced in natural ecosystems in protected areas and about acceptable mitigation costs, burden sharing principles, and implementation flexibility. The results show that about 25% of the protected areas worldwide will witness ecosystem transformation in the next century even if the costs of emission reduction are allowed to reach 2% of per-capita consumption. An uncertainty analysis surveys the implications of modifying selected key model variables on the existence and shape of the emission corridors. Within plausible ranges of parameter variations, the emission corridor turns out to be rather sensitive to impact constraints, climatic constraints like the magnitude and rate of the global mean temperature increase, and to aerosol emission scenarios.

Keywords: climate change, integrated assessment, tolerable windows approach, emission corridors, uncertainty analysis

1. Introduction

Part 1 of these two companion papers (Toth et al., 2003) presents an Integrated Assessment Model (IAM) developed as part of the project on Integrated Assessment of Climate Protection Strategies (ICLIPS), explains its main modes of utilization, and illustrates its use by some simple applications. The first goal of this paper is to present a set of additional examples of using the ICLIPS IAM in inverse mode. We recall that the inverse mode means identifying the corridor of future CO₂ emission paths (typically the collection of all possible emission reduction strategies) based on exogenously defined long-term environmental goals and economic constraints. The second objective is to conduct an uncertainty analysis that shows the implications for the long-term emission corridors of varying some key parameters that represent user decisions or are part of the underlying model.

Section 2 presents the most important scenario assumptions for all case study assessments. The subsequent analysis takes climate change-induced modifications of the terrestrial ecosystems as the indicator to help determine at what level an-

* Present affiliation: International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria



thropogenic climate change might become dangerous. Corridors containing all permitted emission paths for industrial CO₂ are presented for different levels of tolerable ecosystem transformations and limiting the costs of climate policy at 2% consumption loss on the one hand, and for different levels of permitted income losses and limiting the magnitude of ecosystem transformation to 30% of the protected areas worldwide, on the other. Section 3 takes a small set of decision and scenario variables to investigate the importance of the uncertainties behind them in determining the existence and the shape of the emission corridors. Section 4 summarizes the main results and conclusions.

2. A Case Study of Corridor Assessment

This section presents a case study with the integrated ICLIPS model. We show necessary emission corridors based on externally specified constraints for maximum climate change impacts and acceptable welfare losses that also incorporate equity considerations. The impact sector considered in the case study is natural ecosystems, one of the impact domains explicitly named in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) as a possible clue to determine what might constitute a dangerous anthropogenic interference with the climate system.

The case study involves using Climate Impact Response Functions (CIRFs) and inverse runs of the ICLIPS model to determine the corresponding emission corridor. In order to illustrate the trade-offs between impacts and mitigation costs, the level of acceptable impacts and the magnitude of welfare loss due to climate policy are varied and the resulting emission corridors are plotted together. All corridors are necessary corridors in the sense that any emission path leaving the corridor is known to violate at least one user-specified constraint, but not all paths inside the corridor are automatically permitted paths.

2.1. UNDERLYING SCENARIOS AND KEY PARAMETERS

Most parameters of the various ICLIPS IAM components (climate, aggregated economy model) are left at their default values as specified in the respective papers in this issue. In order to harmonize assumptions underlying the three main economic components of the ICLIPS framework, parameter values of the Aggregated Economic Model have been calibrated to replicate the IIASA-WEC A2 scenario. This resembles the new IPCC (2000) A1FI scenario of the Special Report on Emission Scenarios (SRES). It involves a medium population growth and high productivity growth, and convergence of world regions in terms of per capita incomes over the 21st century. The emission of non-CO₂ greenhouse gases follows the IPCC IS92a scenarios with the exception of chlorofluorocarbons (CFCs). Emissions of the ozone-depleting substances regulated under the Montreal Protocol are assumed

to follow the limitations agreed under the Montreal Protocol and its amendments. Similarly to the illustrative example presented in the previous paper, SO₂ emissions are linked to industrial CO₂ emissions, but decline at an annual rate of 1.25% globally.

Assumptions about burden sharing arrangements take the grandfathering principle as a starting point. A gradual transition to an equal per capita allocation of emission rights (based on the 1990 populations) is completed by 2050. As far as implementation mechanisms are concerned, there are virtually no limits to the inter-regional trade of emission permits. However, banking of permits is not allowed in the present model version.

2.2. RESULTS OF THE ECOSYSTEM CASE STUDY

The impact constraint in this case study aims at operationalizing the objective of the UNFCCC Article 2 to protect the earth's ecosystems by limiting the percentage of protected areas where the current biome becomes unsuitable under altered climatic conditions and CO₂ levels. Biomes (e.g., tropical evergreen forest, temperate deciduous forest, or tundra) are broad vegetation classes. In contrast to Toth et al. (2000), where incremental vegetation transformation is depicted for the entire terrestrial areas, we restrict the geographical scope of the analysis to protected areas because they are explicitly designated by societies to be preserved in their present state. A drastic change in the dominating vegetation will therefore threaten in most cases the very reasons for their protection.

Limits on vegetation change in protected areas are translated into constraints for maximum acceptable changes in climate and CO₂ concentration by climate impact response functions (CIRFs). The CIRF applied here is based on multiple computations with a modified version of the BIOME-1 equilibrium vegetation model (Prentice et al., 1992). This model computes the dominating biome in each 0.5° by 0.5° grid cell of the terrestrial land surface, using monthly data for temperature, precipitation, and cloudiness. The direct effect of enhanced CO₂ levels on the water-use efficiency of plants is considered as well. Future climate projections are derived from the ECHAM4 general circulation model by using the scaled scenario approach. See Füssel et al. (2003) for details of the impact model, the impact indicator, and the climate change scenarios.

In addition to the assumptions presented in the previous subsection, two main decision variables shape the emission corridor. The first one is an impact constraint and assumes that the percentage of the world's nature reserves where the presently dominating ecosystems would be no longer feasible under changed climatic conditions should not exceed 30%. This is a global averaged figure and as such it ignores the differences in the current areas and the relative ecological importance of nature reserves across regions. It does not account for the regional differences in the extent of climate change impacts on ecosystems either. Yet it is suitable for our illustrative example to demonstrate the operation of the ICLIPS framework.

The earth's ecosystems face multiple threats, including climate change, elevated CO₂ concentration, land-use change and associated landscape fragmentation, biotic exchange, nitrogen deposition, and acidification. For a qualitative assessment of their relative importance, see Sala et al. (2000). A global integrated assessment model of climate change cannot fully address all potential drivers of biodiversity decrease simultaneously. The vegetation model applied in the ICLIPS framework considers three factors that determine the distribution of ecosystems on earth: climate, atmospheric CO₂, and soil conditions. The first two drivers are varied in the tolerable windows analysis. The spatially explicit model results are aggregated to derive a "conservative" impact indicator. This indicator denotes the fraction of protected areas where the current biome (a broad vegetation category) would be no longer viable after certain changes in climate and atmospheric composition will occur. We favor this indicator over alternative ones which might assign greater weights to ecosystems changes in biodiversity hotspots because it appears to be more accessible to policymakers. Since climate change is but one of the many factors that threaten biodiversity, this indicator should be regarded as a low estimate of long-term changes in terrestrial ecosystems.

The 30% limit may appear to be a rather arbitrary figure and it can cause misunderstanding. It is important to note that this limit serves only the purposes of illustrating how the ICLIPS model can be used to assess the emissions-related implications of an externally chosen impact limit. The 30% limit should not be interpreted as the "dangerous impact level" put forward by the authors or as the desirable impact limit in terms of ecosystem change proposed by them. The limit is chosen from the perspective of a global care-taker who might get worried to see about a third of the highly valued natural ecosystems undergoing profound changes. The meaningfulness of the selected thresholds can only be discussed when applying the ICLIPS model in real policymaking context. The specified limit is taken to be the long-term constraint for ecosystem change: GHG emissions need to be controlled in such a way that the resulting climate change will not give rise to biome shifts in more than the specified fraction of protected areas.

The second key input to an inverse experiment with the ICLIPS model is the specification of the upper limit to the socially acceptable mitigation cost. The model allows the user to specify different cost limits for different regions, but for the sake of simplicity, we assume that per-capita consumption losses, compared to the reference case, should not exceed 2% in any region in any time period. This cost constraint is also selected to serve the purposes of the illustrative analysis and should not be interpreted as a policy proposal by the authors. It is clearly in the range of the estimated costs of stabilizing CO₂-equivalent GHG concentrations between 350 and 650 ppm. Hourcade et al. (2001) review the results of modeling experiments with the IPCC SRES scenarios to stabilize CO₂ concentration at 550 ppm and find that economic losses measured as fraction of the Gross Domestic Product (GDP) in 2050 range between 0.2 and 1.8% of the baseline values across the scenario groups. Toth et al. (2001) report a similar range of GDP losses based

on their survey of stabilization cost assessments. There are many unresolved issues in this field and the debate among modeling groups about the stabilization costs continues. See Azar and Schneider (2002) and Manne and Richels (2002) for recent contributions.

Another way to put this cost limit in context is to compare it to current environment-related expenditures. In the late 1990s, total expenditures on pollution abatement and control in the OECD countries spread between 0.7 and 2.0% of their GDP (OECD, 2001). Considering the differences in the metric between GDP and consumption, the 2% consumption loss limit implies outlays for climate protection alone that exceed historical environment-related expenditures. It is difficult to compare the opportunity cost of this expenditure to damages associated with single events like major natural disasters, because the 2% consumption loss is a “never to no-one” limit (none of the regions in none of the 10-year periods throughout the time horizon of the model run) that is approached by some regions in some critical decades only. It depends heavily on the acceptable impact limit, of course, how closely and for how long actual climate protection expenditures approach the specified cost limit.

Figures 1 and 2 show global corridors for industrial CO₂ emissions computed by the ICLIPS IAM subject to the pre-defined constraints presented above. As a default target, the acceptable magnitude of ecosystem transformation in protected areas worldwide is assumed to be restricted to 30%. In Figure 1, we also show corridors for relaxed constraints that permit biome changes in 35%, 40%, and 50% of protected areas, respectively. These corridors demonstrate the sensitivity of the available option space for long-term climate policy to the social perception of the level at which ecosystem transformation becomes a “dangerous” impact. The corridor vanishes at the 25% limit which means that at least one quarter of the nature reserves on the earth are likely to witness changes in their currently dominating biomes under the given cost constraint and in the constellation of all other model parameters. In contrast, the willingness to accept higher ratios of ecosystem transformation would substantially widen the emission corridor: from a peak level of about 12 GtC annual emissions for the 30% limit to over 17 GtC for the 40% limit.

Mitigation costs are limited to a maximum consumption loss of 2% in the default case. In Figure 2, we show the effect on the size and shape of the emission corridor of increasing this limit to 5% and 10%, respectively. We recall that all analyses are based on the assumption that an equal per capita allocation of emission rights is achieved by 2050, and that there are virtually no caps on the trading of emission rights. In this experiment, we allow mitigation costs go up to 10% of the per-capita consumption, admittedly an unrealistically high number. This case implies allowing emissions to increase in the near-term and reducing them at a faster rate later in a cost-effectiveness framework. In the long run, however, the factor limiting fast emission reduction is not the mitigation cost, but rather the 4%/year limit to emission reduction that is specified to avoid implausibly high

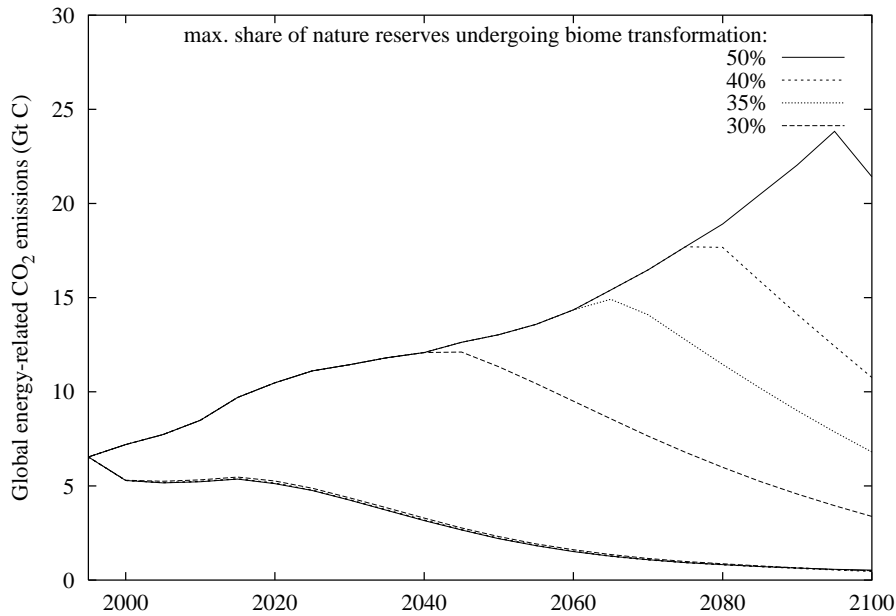


Figure 1. Necessary corridors for industrial CO₂ emissions under various impact constraints when mitigation costs are limited to 2% of per capita consumption. The fraction of nature reserves undergoing biome changes is limited to 30% in the default case. The constraint is relaxed to 35, 40, and 50% in the sensitivity runs.

rates of decarbonization in such cases. As part of the permitted emission corridor, the ICLIPS framework also identifies emission paths that decline in the early phase of the scenario horizon and allow higher emissions later. Nevertheless, the main lesson from Figure 2 is that, even under radical assumptions about acceptable mitigation costs, the size of the emission corridor does not increase significantly.

Even a casual comparison of Figures 1 and 2 reveals that in this case study impact constraints play a dominant role in determining the shape and width of the emission corridor relative to the constraints on mitigation costs. This indicates the limits to the so-called “when-flexibility” (see Wigley et al., 1996; Ha Duong et al., 1997; and Hourcade et al., 2001 for a recent review) when long-term climate change constraints are defined in the realm of tolerable impacts. Even the combination of the underlying dynamic cost functions (that make each unit of additional emission reductions less and less expensive in later periods) and a higher mitigation cost constraint does not help if the impact limits are tight. The relatively high fraction of 25% of nature reserves where biome change cannot be prevented even under unrealistically high mitigation cost assumptions stems from the amount of GHGs already vented into the atmosphere combined with the inertia and delays in the atmosphere-terrestrial biosphere system. An additional explanation is that, except for CFCs, non-CO₂ emissions follow the unmitigated IS92a scenario,

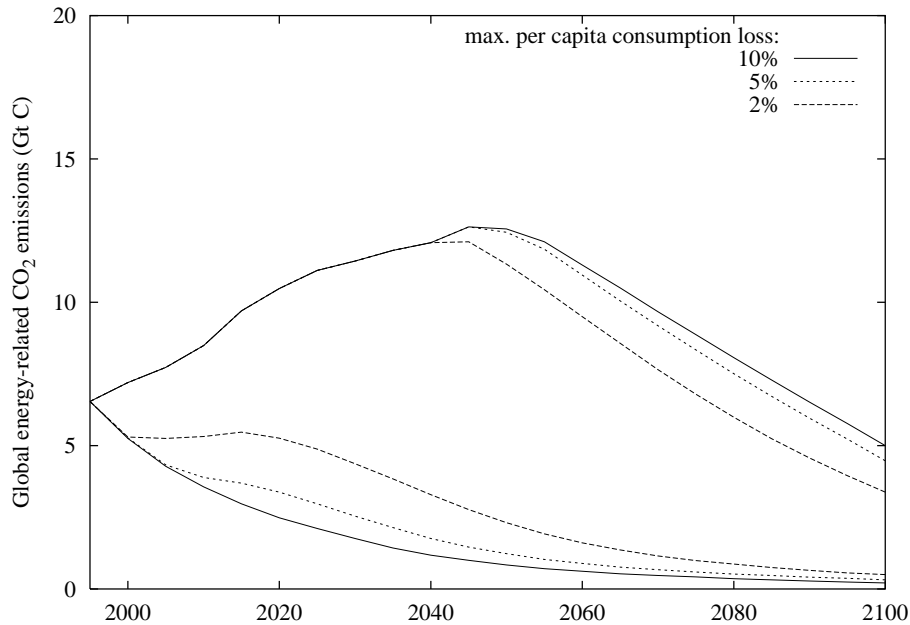


Figure 2. Necessary corridors for industrial CO₂ emissions under various cost constraints to prevent more than 30% of the nature reserves undergoing biome change. The regional mitigation cost is limited to 2% of per capita consumption in the default case. The constraint is relaxed to 5 and 10% in the sensitivity runs.

shifting all reduction burdens to energy-related carbon emissions. The dominance of the impact constraints nevertheless clearly demonstrates how important it is to improve our knowledge about climate change impacts and adaptation opportunities (including “ecosystem engineering” to help their adjustments) as well as our understanding of what really constitutes a dangerous climate change impact.

3. Uncertainty analysis

The ICLIPS assessment framework includes a number of reduced-form models that involve feedback processes and nonlinearities. When the components are combined, the integrated system produces complex interactions of the processes modeled. The complications of the inverse calculation procedures provide yet another reason that makes uncertainty analysis difficult.

For the purposes of the present analysis, we distinguish three kinds of uncertainties. The first category includes scientific uncertainties, like processes of atmospheric chemistry that determine the fate of greenhouse gases in the atmosphere once they are emitted. The general assumption is that such uncertainties can be gradually resolved by investing into scientific research. The second type

TABLE I
ICLIPS IAM: Uncertainty analysis

Variable	Default	Range					
Temperature change limit ($^{\circ}C$)	2.5	1.0	1.5	2.0	2.5	3.0	
Temperature change rate ($^{\circ}C/decade$)	0.2	0.1	0.15	0.2	0.25	0.3	
Permitted welfare loss (%)	2	0.5	1.5	2.0	2.5	3.0	4.0
Transition time to per capita emission rights allocation (<i>years</i>)	50	25	50	75	100		
Aerosol emission reduction rate (<i>%/year faster than CO_2 reduction</i>)	0	1	2	5	10		

of uncertainties is future related. Although our understanding of the relationships between human activities and greenhouse gas emissions has improved a lot over the past decades, forecasting future trends (like changes in societal values and lifestyles) and future events (technological inventions and innovations) remains uncertain. These uncertainties will be resolved as we approach the time point for which the forecasts had been previously made. For example, emission data for 2010 can be assumed to become available with reasonable precision in 2011. The third type of uncertainties belongs to the realm of policymaking. Perceptions of environmental risks and aspirations in managing them tend to change over time in most societies. This has crucial implications for what will be perceived as acceptable climate change impact or tolerable climate protection cost in the future. These changes are partly dependent on the progress in scientific understanding of the problem and its possible remedies that can trigger fundamental shifts in the social aspirations and the resulting climate policy objectives.

Table I presents an overview of the uncertainty analysis to be presented in the rest of this paper. With a view to the intended policy applications of the inverse approach, we focus on target-related uncertainties and select four decision variables to explore the effects of policy/target-related uncertainties on the shape of the emission corridors. This is complemented by a short discussion of key scientific uncertainties and corridor presentations for one variable associated with future-related uncertainties. The second column of Table I lists the default values of these variables for the analysis. We take one variable at a time and alter its value across the specified range while keeping all other variables at their default values. In each case, the objective is to explore the sensitivity of the emission corridors to variations in these key variables across a plausible range.

In order to make the uncertainty analysis more transparent, the climate change-related constraints are shifted from the impact domain (like the fraction of nature reserves undergoing biome changes presented in Section 2 above), to the climate domain. This involves the specification of explicit restrictions for the magnitude

and the rate of increase in global mean temperature. This illustrates the flexibility of using the ICLIPS IAM: climate-change limitations can be specified directly for impact sectors for which the current integrated system does not include Climate Impact Response Functions. Moreover, this feature makes it easier to directly compare the ICLIPS model results with those of other IAMs that explore emission paths associated with different global temperature change limits. It is important to note that the climate-related variables and their ranges in the uncertainty analysis are not directly related to the impact-determined (ecosystem transformation) emission corridors presented in the previous section.

The fully integrated climate–economy model is used for this uncertainty analysis with the default values listed in Table I. First we study the effects of varying the temperature change limit: what are the implications for the emission corridor, if the world can tolerate more or less change in global mean temperature compared to the default 2.5°C. Figure 3 suggests the following insights. If we permit an increase of 3.5°C in global mean temperature up to the year 2200, there is not much reason to worry about emissions through the first half of the 21st century. If, however, the desired temperature change limit turns out to be the 2.5°C, this would call for emission reduction by about 2030 to 2040. The corridor narrows dramatically, when we specify the temperature change limit at 2.0°C. Finally, the corridor vanishes when the limit to the increase of annual global mean surface air temperature is set lower than 2.0°C.

The above results underline the importance of future emissions of other (non-CO₂) greenhouse gases (not controlled in the current version of the ICLIPS model) and the magnitude of the delay resulting from historical GHG emissions. Their combined effect produces a global warming of about 1.5°C. The other reason for the sensitivity of the carbon-emission corridor is that in these model runs SO₂ emissions are assumed to be reduced at the same rate as CO₂ emissions. Due to the very short atmospheric residence times of sulfur aerosols, this is equivalent to a fast lifting of the aerosol mask. The warming suppressed by aerosols becomes visible and this makes it impossible to prevent a warming lower than 2.0°C by controlling industrial CO₂ emissions alone even at the maximum acceptable climate protection cost.

For a number of climate impact sectors, especially those associated with unmanaged systems such as terrestrial and aquatic ecosystems, the rate at which key climatic attributes are changing might be more important than the magnitude of changes over a longer period of time. The next set of model runs looks at the implications of varying the limits to the rate of increase in global mean annual temperature on the existence and shape of the emission corridor. The results are plotted in Figure 4.

The warming rate of 0.2°C/decade has been proposed by various sources as the upper limit sensitive ecosystems can cope with. This is also chosen as our default value. Given the constellation of other default values, this would require emission reduction action by about 2030. Interestingly, allowing a faster rate of temperature

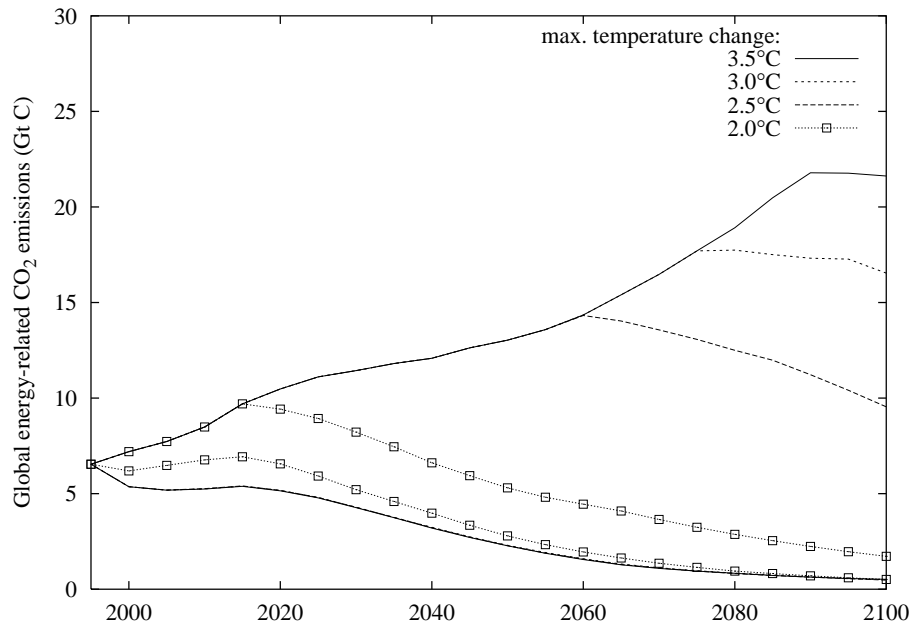


Figure 3. The influence of global mean temperature change constraint on the shape of the emission corridor.

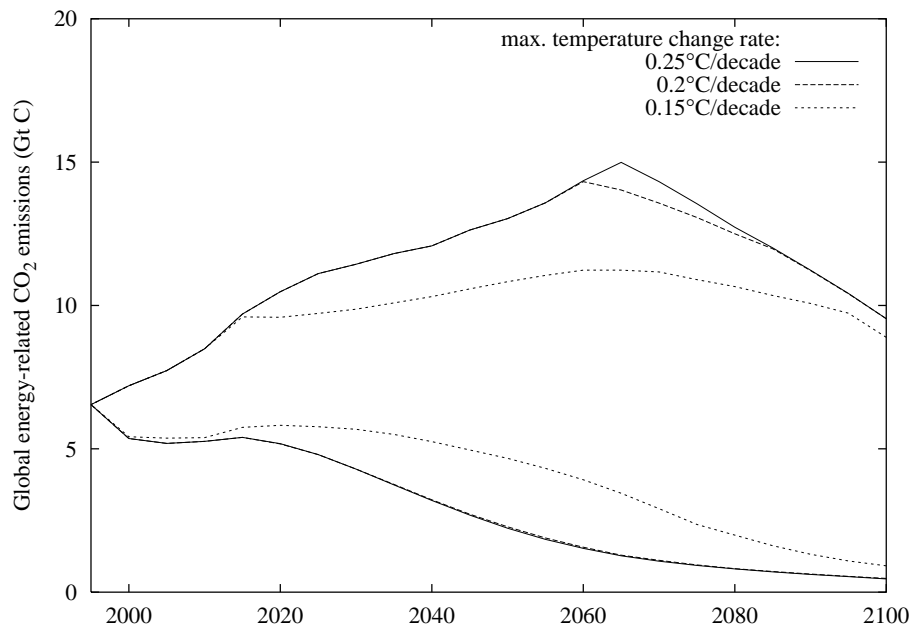


Figure 4. The influence of the limit to the rate of increase in global mean annual temperature on the shape of the emission corridor.

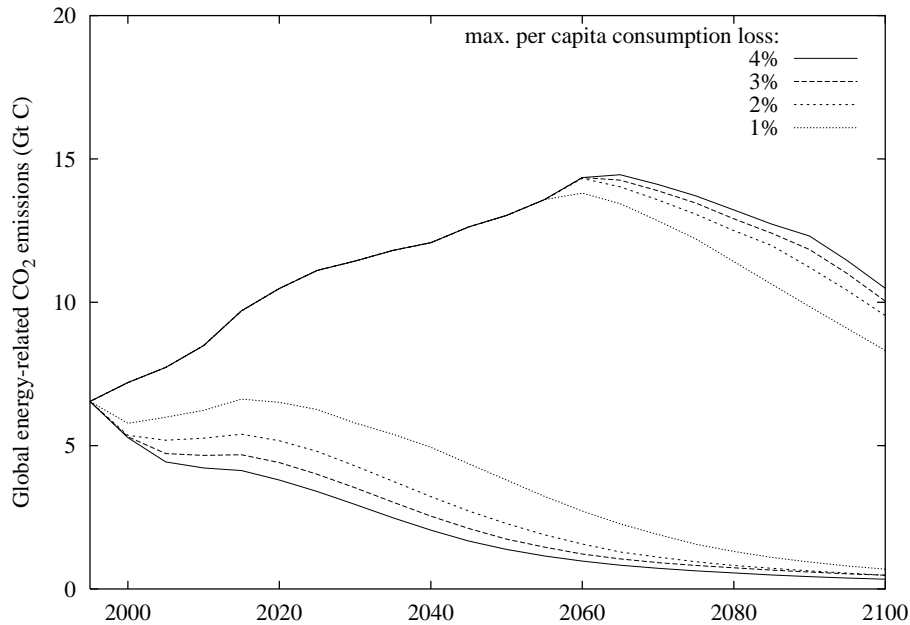


Figure 5. The influence of the per-capita consumption loss constraint on the shape of the emission corridor.

change ($0.25^{\circ}\text{C}/\text{decade}$) does not cause much difference in the magnitude and schedule of CO_2 mitigation. Reducing the permitted rate of temperature change to $0.15^{\circ}\text{C}/\text{decade}$, in contrast, narrows the emission corridor dramatically and calls for action within the next decade or so. Finally, not a single emission path could limit the rate of temperature change to $0.1^{\circ}\text{C}/\text{decade}$. The reasons are similar to those mentioned in the case of absolute temperature change: due to the inertia in the system and the fast lifting of the aerosol mask with ambitious near-term CO_2 reductions, at least $0.1^{\circ}\text{C}/\text{decade}$ warming seems to be unavoidable.

The next series of model runs explores the implications of varying the societies' willingness to pay for climate protection. For the purposes of the present analysis, we take the strong equality of different generations as our ethical principle. It means that, instead of defining regional willingness-to-pay values in terms of discounted present value utility losses, we specify that per capita consumption in any region, in any time period should not fall below the baseline consumption levels by more than the percentage values specified in the permitted welfare loss line of Table I, with 2% being the default limit to consumption loss. The resulting emission corridors are presented in Figure 5.

The bad news is that no corridor exists for energy-related CO_2 emissions under the default climate change constraints that would not cause a consumption loss of at least 0.5% for at least one region in at least one five-year time period of the model

time horizon. In contrast, a consumption loss of 1% below the baseline would allow a relatively comfortable emission corridor. It is interesting to note that increasing the willingness-to-pay in terms of losses in current consumption of the present or any future generations will widen the lower part of the corridor in the short term but does not lead to significantly higher emission possibilities in the second half of the century. Nevertheless, the 1% consumption loss associated with the default climate window is a heavy price tag when we compare it to the current outlays on all environmental protection activities in the OECD countries being at the level of around 0.7 to 2.0% of their GDP.

Another set of model runs demonstrate that the Coase theorem remains valid in the inverse modeling framework as well. (The theorem states that externalities, such as pollution, do not lead to inefficient resource allocation if property rights are clearly defined and there are no transaction costs. The interested parties would find the transactions leading to efficient resource allocation irrespective of the original assignment of the property rights.) The UNFCCC speaks of the common but differentiated responsibility of all countries in climate protection. The Kyoto Protocol exempts developing countries from taking any binding near-term emission reduction commitments. The Kyoto Protocol also adopts historical emissions as the principle of commitment allocation for developed countries by taking 1990 as the reference point. This represents a strange mixture of grandfathering and intragenerational equity principles. One possible way forward might be the involvement of all countries into a global agreement based on a universally acceptable equity principle. This principle could be, for example, the equal right of each individual to use a scarce open access resource (the global atmosphere) and would call for an equal per capita allocation of emission rights. The political implementation could be a negotiated agreement concerning the transition period in which the allocation of emission rights would gradually shift from the historical values (grandfathering) to a per capita-based allocation (one possible equity principle).

The ICLIPS model offers the opportunity to define the time point by which this transition should be completed. Corridors are computed that illustrate the implications for the emission corridor of the differences in time by which the transition is completed (by 2025, 2050, 2075, or 2100). The resulting corridors are presented in Figure 6.

It may come as a surprise to some that this rather drastic change in the adopted emission rights allocation principle leaves the emission corridors virtually unaffected. For economists, however, there is a trivial explanation. Since the model assumes perfect and global trading of emission permits and sets no effective constraints for regional exports and imports of such permits, the initial allocation of emission rights does not influence the global emission opportunities under the given environmental constraint. However, the permit prices, the amount of emission permits traded internationally, and the regional mitigation costs differ drastically as we vary the transition time between 25 and 100 years.

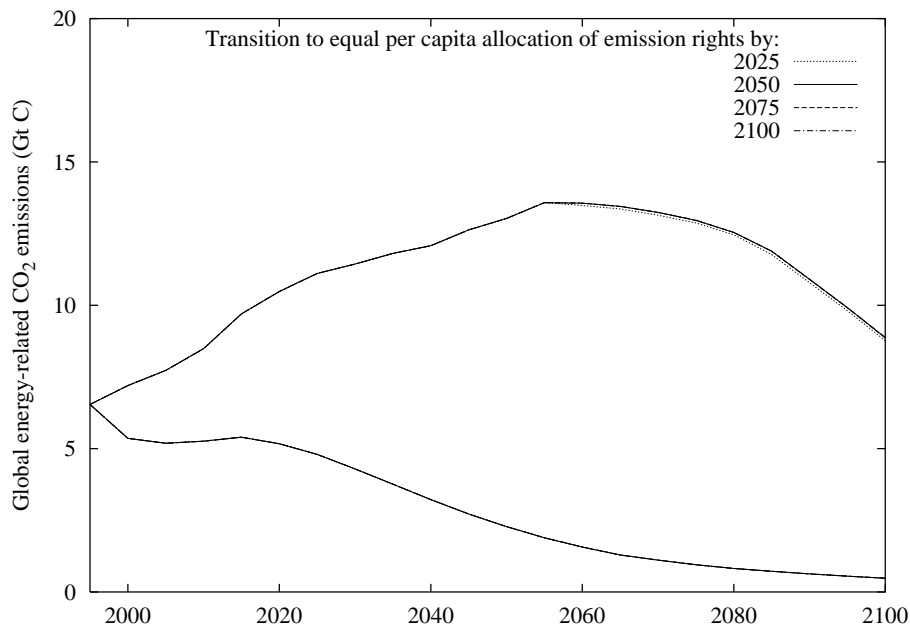


Figure 6. The influence of the transition time for shifting emission rights allocation from grandfathering to per-capita basis on the shape of the emission corridor.

The sensitivity of individual components (aggregated economy model, reduced-form climate model) and of the integrated model to scientific uncertainties is also tested. The results are similar to the experience of other integrated assessment modelers. It is worth noting that the formulation of the inverse model establishes an interesting relationship between a key decision variable (the permitted maximum increase in the global mean temperature) and a fundamental model parameter (the climate sensitivity parameter indicating the equilibrium increase in the global mean temperature as a result of doubling CO₂-equivalent GHG concentrations relative to pre-industrial levels). Varying the climate sensitivity of the ICLIPS Climate Model from its central value of 2.5 °C has the same magnitude but opposite direction effect for the resulting emission corridor as changing the acceptable magnitude of climate change: lowering the climate sensitivity *ceteris paribus* widens the emission corridor while increasing the climate sensitivity parameter leads to progressively narrower corridors until it vanishes altogether.

The final set of model runs investigates the influence of different aerosol emission scenarios on the shape of the CO₂ emission corridors. We recall the default assumption (see Table I) that SO₂ emission decreases at the same rate as CO₂ emission when the latter is mitigated. As we have seen in the uncertainty analysis of the corridors with respect to the limitations for the magnitude and rate of temperature change, this in itself causes trouble for climate change mitigation

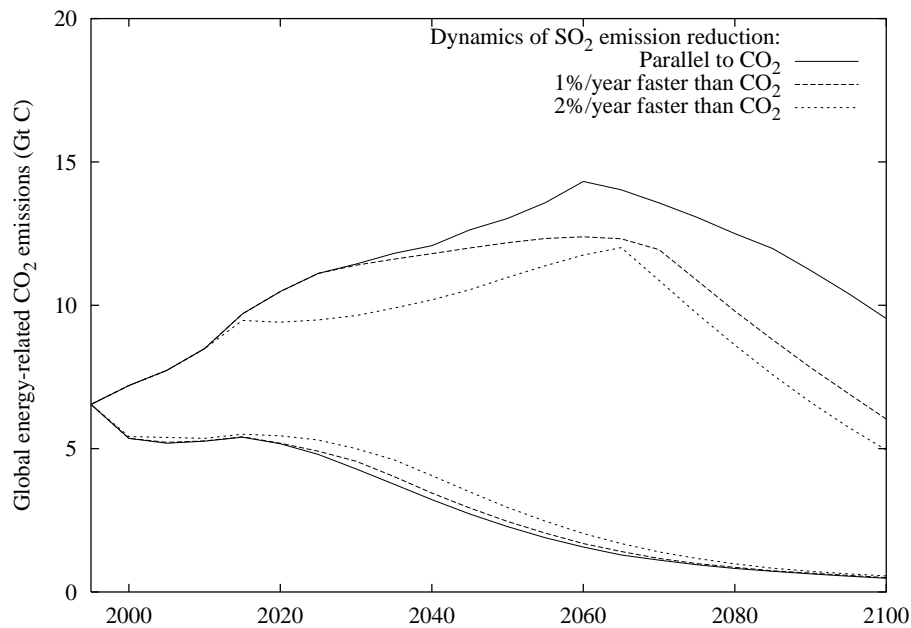


Figure 7. The influence of the SO₂ emission scenario on the shape of the CO₂ emission corridor.

due to the virtually negligible residence time of aerosols in the atmosphere in comparison to CO₂. This is aggravated by the fact that CO₂ is mixing globally and its unfavorable impacts come decades or centuries later. In contrast, SO₂ is a regional nuisance causing tangible economic, ecological, and health damages in several regions today. Historical evidence shows that beyond a medium level of affluence (between 5 and 10 thousand dollars per capita GDP at purchasing power parity) societies are increasingly willing to pay for controlling SO₂ emissions. In the context of climate policy, it is more than appropriate to raise the question: how different aerosol control scenarios affect the CO₂ emission corridor for given climate change targets and carbon control costs. Figure 7 shows the results.

The widest corridor in Figure 7 is the default case when SO₂ is controlled parallel to CO₂ emissions. If SO₂ emissions are reduced by 1 or 2%/year faster than carbon emissions, this leads to drastically narrower CO₂ emission corridors. Aerosol control at rates exceeding carbon mitigation by 3% or more are plausible due to the availability of relatively mature and inexpensive end-of-pipe technologies. Yet, for the default climate change limit, the CO₂ emission corridor vanishes already in the case when SO₂ emission is reduced at a rate of 3% faster than CO₂. Although the resolution of the ICLIPS atmospheric chemistry and climate modules are far too coarse to support precise values, the sensitivity of the CO₂ emission corridor to SO₂ control is an important issue to highlight.

4. Summary and conclusions

The Tolerable Windows Approach (also known as the inverse approach) presented in this paper links tolerable levels and rates of climate change as well as acceptable mitigation costs to permitted long-term CO₂ emission corridors. Conceived in the spirit of Article 2 of the UNFCCC, it makes explicit the importance of perceived tolerable levels and rates of climate change. The inverse approach helps to distinguish clearly between normative judgments and social decisions about managing the climate change risk on the one hand, and scientific analysis of the climate system and the climate-society interactions on the other. It thus helps to disentangle the perception- and choice-related uncertainties of climate policy from scientific uncertainties.

The inverse approach provides a flexible framework for exploring the implications of normative judgments about changes in valued environmental attributes (such as changes in ecosystems or climate), and about the socioeconomic impacts of mitigation (such as costs and emission rights allocation). Monetary valuation of impacts and the discounting of future damages and costs to estimate their net present values are possible but not indispensable. For decision makers, the inverse approach can also help explore implications of different kinds of uncertainties on long-term climate policy options.

The uncertainty analysis presented in this paper demonstrates that if rates of climate change (rates of temperature and precipitation changes and the pace of sea-level rise) matter then they should be included explicitly among the environmental targets for policymaking. The ICLIPS IAM provides both the conceptual framework and the numerical tools to do just that. It can also be used to explore the implications of uncertainties regarding the acceptable rates of change in these attributes with respect to the long-term CO₂ emission corridors.

Looking at the climate change targets, some narrow targets seem already impossible to reach. An increase of 2°C in global mean temperatures without controlling non-CO₂ GHG emissions (in addition to controlling carbon at the maximum rate permitted by the specified acceptable social cost) seems unavoidable. According to the ICLIPS IAM, approximately 1.5°C warming is already in the atmosphere and cannot be avoided even by mitigating non-CO₂ GHGs. This implies that it is important to improve our understanding of the mitigation options of non-CO₂ gases. We know relatively little about their current and future abatement costs and the timing of their control. Reducing SO₂ emissions significantly faster than those of CO₂ might induce a higher rate of temperature increase for several decades. There appears to be a non-trivial trade-off between acidification-related stresses due to SO₂ emissions and high rates of climate change due to the fast reduction of such emissions.

The uncertainty analysis conducted with the ICLIPS IAM also helps reveal major gaps in knowledge that have crucial implications for the long-term options in emission control. Concentrating research efforts in these areas might yield the nec-

essary information needed for environmentally effective and economically efficient climate policies.

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