Kyoto and the long-term climate stabilization

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Abstract

This paper provides a brief overview of recent results from a modeling approach to integrated assessment of climate change. Our focus is on a new concept, the Tolerable Windows Approach (TWA), as it is adopted in a research project called Integrated Assessment of Climate Protection Strategies (ICLIPS) at PIK. This approach is based on an inverse modeling concept that derives climate protection strategies from perceived unacceptable impacts of climate change as well as from intolerable socioeconomic implications of mitigation measures and produces complete sets of permitted emission paths. The TWA seeks to investigate implications of and trade-offs among several constraints related to different domains in the climate-society system.

The paper puts the pre-Kyoto proposals for near-term greenhouse gas emissions reductions and the Kyoto Protocol’s target for 2010 in the context of long-term environmental objectives. It is demonstrated that differences in near-term emissions targets do not matter much with a view to reaching the ultimate (but yet unspecified) climate stabilization objective. Yet they can make a difference if rates of change in different climatic attributes turn out to be a serious concern. These results are very sensitive to assumptions about future SO_x emissions and the associated removal of the aerosol mask from the atmosphere. Moreover, the paper provides insight in one of the potential climate-related surprises. Based on recent results in modeling the response of the thermohaline circulation to human-induced climate change forcing, we conclude that a plausible set of combinations of magnitudes and rates of global warming might disrupt the circulation system. This is not an immediate danger but it is worth considering in long-term studies because of the immense inertia characterizing the underlying geophysical processes.

Keywords:
tolerable windows approach, climate windows, catastrophic climate change, aerosols

After signing the Kyoto protocol on climate change, the world is approximately at the same stage of managing the global warming problem at which European nations were after they completed the first sulfur protocol in dealing with the acid rain problem. There are some broad, largely across the board emission reduction targets for Annex I countries, while there are none to that part of the world which will produce increasing fractions of global greenhouse gas (GHG) emissions. Many research groups are trying to find the least expensive ways to achieve those emission targets. Models and analyses presented in this volume are extremely important to find the answers to these multi-billion-dollar questions.

The ultimate dilemma, however, is still open. This utmost question is: at what level wants mankind stabilize the Earth's climate? Are there ultimate limits to anthropogenic interference with the climate system? If yes, where are they and how to find them? The project on Integrated Assessment of Climate Protection Strategies (ICLIPS) at PIK seeks to help find answers to these questions. We maintain that while looking at cost-effective strategies to implement existing international agreements is a fundamental research task, it is equally important to pursue inquiries into this broader issue. This is all the more important as model calculations show that the Kyoto emission targets are only remotely related to the ultimate objectives of stabilizing the atmosphere and climate.

The rest of this paper is organized as follows: we first present the background and objectives of the ICLIPS project together with its central concept, the tolerable windows approach (TWA) in Section 1. This is followed by a concise outline of the inverse approach that serves to derive the domain of permitted emission paths from any pre-defined tolerable climate window. Section 3 explores the implications of assigning emission rights on a per capita basis as well as consequences of delaying effective emission reductions by a decade. Long-term repercussions of the most prominent pre-Kyoto proposals and the actual outcome (Section 4) as well as the sensitivity of results to assumptions about atmospheric aerosols (Section 5) are assessed. Section 6 presents preliminary results from modeling one of the conceivably dramatic changes induced by global change, the possible shut-down of the North Atlantic thermohaline circulation. Section 7 offers a concise summary of our conclusions.

1. The concept of TWA

An increasing number of research projects have been addressing the global climate change problem by developing Integrated Assessment models (IAMs). These models apply all or at least a subset of the following components: scenarios of socioeconomic development, including assumptions about population growth, economic development, technological change and fossil fuel availability; emission of greenhouse gases (mainly CO_2) associated with alternative development paths; a simple atmosphere-climate model to compute atmospheric concentrations of those GHGs, the resulting radiative forcing and global or regional climate change; and finally, impacts of the estimated climate change on various natural systems (forests, ecosystems, water resources) and socioeconomic sectors (agriculture, health, energy use). Some of these models follow the analytical path we just outlined and calculate implications of alternative development and emission paths end-to-end. Others organize individual components of this system into a cost-benefit framework. Yet others stipulate alternative emissions or concentration targets and derive cost-effective strategies to reach them (Manne and Richels, 1996).

The ICLIPS project has been conceived in the vein of this last approach: we try to identify the ultimate reasons for climate protection and derive targets from the direct impacts of climate change on society or the indirect impacts via changes induced in ecosystems. In both cases, our attempt is to provide information necessary for recognizing implications which are conceived to be unacceptable for social actors or their designated representatives, the policymakers. In this sense the TWA is based on a generalized version of the critical load concept. A schematic outline of the tolerable windows concept is presented in Figure 1.

The analysis starts with a series of climate impact response functions that synthesize the best available information from the sectoral and regional climate impact studies (impacts space). These response functions should support policymakers and social actors in making their judgments about “tolerable impacts”. Given their knowledge about and experience with managing climate sensitive economic sectors and natural systems, the basic question is what are the speed and magnitudes of changes in different climatic attributes which they conceive to pose severe risks for their region or impact sector. This information is then used, partly filtered by some biogeophysical relationships, to define tolerable climate windows (climate space). These windows reflect maximum permitted changes in climate characteristics, such as temperature change, rate of temperature change, precipitation change, rate of precipitation change, sea-level rise, rate of sea-level rise, and others.

The above climate constraints serve as input to a GHG emission-climate model. The objective is to produce a large set of permitted emission paths that keep the climate system within the climate window derived from the use of the response functions (emission space). At this point, there are several possibilities for further analysis: one can define additional normative principles (proposed or agreed international allocation of emission quotas - quota space) and check the feasibility of the associated decisions. Alternatively, one can adapt a set of criteria to select among the paths. This would turn the problem into a multi-criteria analysis. As yet another option, one can adopt an appropriate economic model and search for cost-effective paths by testing different policy instruments (instrument space). Some initial results from following this latter direction have been presented in Toth et al. (1998c).

Figure 1 also shows that TWA as implemented for climate change here, provides the possibility to clearly separate scientific-analytical issues (despite all the uncertainties and unknowns involved) from the normative decision problems which are dominated by individual and social perceptions, political power, economic capacity, and numerous other subjective and value-laden factors. A mathematical treatise of the inverse translation strategy is presented in Petschel-Held and Schellnhuber (1997).

2. From tolerable climate windows to emissions

As explained in the previous section, the starting point for an analysis using the TWA concept is a set of climate impact response functions. Best available information from sectoral and regional climate impact assessments are synthesized in these functions. Impact sectors include socioeconomic areas and components of the natural environment which are highly valued by humans and assumed to be sensitive to changes in climate. Response functions indicate how these systems might react to climate change. They contain simple representations of highly aggregated information and are usually derived from detailed impact assessment studies.

Two main types of response functions are distinguished. Most human-managed systems seem to respond smoothly to small and gradual changes in climate attributes within a reasonable interval around prevailing values. (A typical example is crop-yield curves.) The second type of response functions would characterize large geophysical systems that might react abruptly if changes in certain climate attributes exceed a critical point. An example of such a discontinuous response function is the possibility to turn off the North-Atlantic deep-water formation and the associated decreasing intensity of the North-Atlantic heat conveyor belt as a consequence of climate change (see Section 6).

The social decision problem in the first case is to define tolerable impacts as perceived by social actors, i.e., what would they consider to be “acceptable losses” as a result of changing climate. The basic question in the discontinuous case is whether societies wish to avoid those critical points beyond which a phase transition and a different qualitative behavior of the underlying geophysical system could be expected. Our climate response functions are intended to help social actors make these decisions. The outcome will determine attributes of an acceptable climate window.

Developing and testing climate response functions for agriculture, human health, water resources, sea-level rise and natural ecosystems are underway. Concurrently, we have completed first experiments with calculating emission corridors from pre-defined climate windows.

Climate change constraints derived with the help of response functions serve as input to our carbon cycle and climate module (developed in cooperation with Klaus Hasselmann and his team at the Max Planck Institute in Hamburg). The model is based on an extended version of the impulse-response model (Meier-Reimer and Hasselmann, 1987, Hasselmann et. al, 1996). A detailed description of this model is presented in Toth et al. (1998b). This formulation of the climate problem can be used in either of the following two ways. The forward mode follows the traditional direction: GHG emission trajectories are provided as input, and the model calculates atmospheric concentrations and climate change. In the inverse mode, one would specify the rates and magnitudes of permitted changes in climate attributes and would seek to derive emission paths that comply with those constraints. This becomes a control problem in which climate attributes and atmospheric properties represent the state variables {x(t) in X(t)}, emissions are the control variables {u(t) in U(x(t),t)} and the problem also involves possible constraints on the rate of change of state variables {x'(t) in F(x(t), u(t), t)}. The tolerable window is then defined as restrictions on emissions (x) in a domain defined by the intersection of all tolerable windows.

In the problem defined above, F(x) becomes a set-valued function. Mathematically speaking, it is multi-valued differential equation called differential inclusion. This is not the appropriate place to go into the mathematical beauties of this problem. We refer the reader to Bruckner and Petschel-Held (1997) who show that “nice” solution exists. It provides a multi-dimensional tube of all admissible solutions that we call a funnel. In order to visualize the results, we need to project the funnel onto various state and control variables, such as emissions, cumulative emissions, concentration, global mean temperature, sea-level rise, etc.

It is important to note that the funnel and the projected corridors represent necessary conditions only. Each admissible emission path lies within the tube (or the projected corridor) but not every arbitrary emission path within the tube is admissible. Thus it is important to emphasize that the results do not represent “safe” corridors in their full breadths. In order to derive sufficient conditions for the emission paths, one would need to describe all admissible policy paths. This is equivalent to the need of investigating the internal structure of the funnel. One possible solution to this problem is to parameterize possible control functions, i.e., pre-define some simple but plausible characteristics for the emission paths. This approach has been followed and results presented in Toth et al. (1998a).

3. Emission rights and impacts of delayed emissions reduction

Until operational versions of the climate response functions become available to derive and specify tolerable climate windows from the impact space, a series of experiments have been conducted with the atmosphere-climate model. Beyond the obvious need to test the inverse approach, this modeling exercise has also been motivated by the work of the German Advisory Council on Global Change (WBGU) in its preparation for the Kyoto Conference of the Parties to the Framework Convention on Climate Change (WBGU, 1997).

The Council has derived a tolerable global climate window in terms of magnitude and rate of global mean temperature increase. The Council argued that most of the present-day ecosystems and living natural resources on which mankind has evolved and developed was created during the late Quaternary period. According to this argument, leaving the climate domain prevailing during this evolutionary period might create environmental risks of the magnitude that should be avoided, especially if one considers the precautionary principle. The Council therefore declared that the increase in global mean temperature (relative to the pre-industrial level) should not exceed 2°C and the rate of temperature increase should not exceed 0.2°C/decade. These two constraints for a global climate window are supplemented by a provisional assumption related to the rate of change in the control variable. Based on studies conducted by the RWI (Rhine-Westphalian Institute for Economic Research in Essen, Germany), the Council assumed that reducing GHG emissions at a rate faster than 4% per year would be economically too painful to implement. As we can see later, this assumption does influence the shape of the emission corridors, but can be easily replaced by better-grounded constraints once the climate model and the economy model are coupled.

Results presented in this section are based on an extended atmospheric chemistry-climate model. In addition to CO_2, the model also includes CH_4, N_2O, CFCs and aerosols. One simplifying assumption (to be resolved at a later stage) is that all GHG emissions are reduced at the same rate, except for CFCs that follow the IS92a paths. For simplicity and according to the interest of this workshop, energy-related global CO_2 emissions are presented in the next few figures.

Figure 2a presents the basic emission corridor for the Council window. We recall that at least one permitted emission path passes through any arbitrary point in the corridor. However, not any arbitrary path within the corridor is necessarily a permitted path. If emissions follow the upper boundary of the corridor in the first few decades after 1995, for example, this would entail a sharp turn-around and persistent emission reductions at the maximum annual rate (4% per year) for many decades to come.

How near-term emissions affect the remaining room to maneuver over the long-term? This is shown by the scenario presented in Figure 2b. Here we have simply assumed that CO_2 emissions follow the business-as-usual path according to the IPCC IS92a scenario until 2015. The result is a much narrower corridor: it implies that the likelihood of a fast turn-around of emissions and persistent reductions at relatively higher rates (3-4% per year) is significantly higher. Recent debates among modeling groups (Wigley et al., 1996 on the on hand, Grubb et al., 1995, on the other) revolve to a large extent around the question whether it is at all plausible and, if so, how strong a signal to economic agents should be given so that they start developing the necessary low-carbon/non-carbon technologies that will permit implementation of those relatively ambitious reduction requirements at an acceptable social cost.

The next analysis illustrates implications of a fairness principle for the emission corridor. In this case, it has to be explicitly emphasized that this is just a thought experiment. It should under no circumstances be treated as a proposal for or even a very realistic assumption about how equity consideration should shape allocation of GHG emission rights. It has been simply assumed that GHG emissions by non-Annex I countries follow the business-as-usual path and these countries start emission reductions only when their per capita emissions reach Annex I levels on the basis of their 1992 populations. If we allocate these emission rights to non-Annex I countries and deduct the corresponding amount of the total emission budget, we get the Annex I corridor as presented in Figure 2c. Obviously, the result is a relatively narrow corridor.

Figure 2d shows the resulting emission corridor if we combine the previous two assumptions about future emissions. This implies that the world community is following the business-as-usual emission path until 2015 and reduction obligations will be distributed between the Annex I and non-Annex I countries according to the case in Figure 2c. The result for Annex I countries emissions through the first half of the 21st century looks like a straightjacket rather than an emission corridor with ample choice.

It is important to point out that Annex I corridors in Figures 2c and 2d reflect rigid implementation of emission quotas resulting from the specified equity principle. No cost divergence is considered between Annex I and non-Annex I. The difference between the 2a and 2b corridors indicates the huge potential for reducing abatement costs if Annex I countries are allowed to “buy” part of the non-Annex I corridor. The economic value of this transaction is the subject of many detailed energy-economic models these days. Political scientists and economists are obsessed with designing a politically feasible and over the long term sustainable international agreement.

We have to emphasize that all these emission corridors are associated with the global climate window as specified by the Council. It is beyond the scope of our analysis to discuss arguments for and against whether the 2°C increase in global mean temperature above pre-industrial level and the rate of temperature increase at no more than 0.2°C/decade is a preferred or realistic proposition. Our objective here is to provide an assessment framework that can help test any climate protection proposal formulated through selected climate attributes.

The computed emission corridors, nevertheless, can assist in deciding about the magnitude and urgency of policy measures associated with them, on the one hand, and/or trigger rethinking the originally proposed climate change targets, on the other. Eventually, the exercise will turn into a judgmental cost-benefit analysis in which the users' perceptions of risks associated with climate change are balanced against their perceptions about the flexibility/rigidity and costs of turning around emission trends in a relatively short period of time.

4. Pre-Kyoto proposals and the outcome

The year 1997 has been characterized by a sort of "numbers' war" in the process of international negotiations to establish a climate protocol. The second assessment report of IPCC has confirmed a "discernable" human influence on the atmosphere due to the emission of greenhouse gases. This statement called for action to manage the anthropogenic GHG problem. The most important action is to give a signal to social actors and decision makers of the emerging need to reduce GHG emissions and to restructure activities and capital stocks accordingly. A near-term emission target was meant to be the appropriate signal. Single countries and various country groups fiercely debated in the pre-Kyoto phase just how strong this signal needs to be.

Many analysts have pointed out that, from the perspectives of stabilizing atmospheric concentrations of GHGs, that is stabilizing the climate system with respect to anthropogenic interference, differences in short-term emission targets make little difference. We look at this issue in this section by using the Council window as the normative climate change target and the ICLIPS atmosphere-climate model.

Originating in the Rio Framework Convention and reconfirmed by the Berlin Mandate accepted at the first Conference of the Parties, countries listed in Annex I are obliged to undertake emission reductions. Accordingly, non-Annex I countries are assumed to follow the IPCC IS92a scenarios up to 2010. Annex I country emissions are specified according to the various proposals. As it is well-known, the Untied States proposed a return to the 1990 level, Japan recommended a 5% reduction below the 1990 level, the European Union argued for a 15% reduction, while the Alliance of Small Island States (AOSIS) thought 20% below 1990 emissions would be the appropriate target for 2010. Given the differentiated Annex I targets and the actual basket of GHGs, the Kyoto outcome for 2010 is rather close to the original Japanese proposal.

In this analysis, emissions of CO_2, N_2O and CH_4 follow the same trajectories while CFC emissions are assumed to follow the path defined by the Montreal Protocol and its amendments. The highest rate of annual emission reductions is specified at 2%. SO_2 emissions are also assumed to go in tandem with CO_2 emissions.

Figure 3 presents the corridors for energy-related global CO_2 emissions as specified by the four pre-Kyoto proposals. The starting points for all four corridors in 2010 differ according to the proposed reduction targets. Each proposal offers some room to maneuver in the emissions space to keep the climate system within the Council window. It is striking how little the corridors differ, especially in terms of their long-term implications. The difference in the time when global GHG emissions will need to embark on a persistent reduction path is more significant. The less ambitious the near-term target is, the sooner the turning point arrives at which emissions will have to be reduced by the maximum permitted rate (in this case 2%/year). For the US proposal, it is around 2020, while a 2010 AOSIS target would permit a turning point almost a decade later.

A sensitivity test of the above analysis involving a smaller climate window is presented in Figure 4. We have kept all the assumptions and specifications unchanged except for the upper limit on the rate of temperature change. We have set this at 0.15°C/decade. According to Figure 4, the near-term (2010) targets proposed by Japan and the US make it impossible to keep the climate system within this smaller window. For the AOSIS and EU proposals, corridors still exist. However, understandably, global emission peaks are lower and the date of embarking an absolute global reduction path is sooner than for the previous window. This case offers several useful insights.

First, although stabilizing the climate system is clearly a long-term management task, relatively small differences in near-term targets can make a difference for some attributes. Especially rates of change in certain system attributes (rate of temperature change, rate of sea-level rise) are sensitive to changes in the rate of near-term emissions.

Second, there is a broad consensus among energy economy modelers that the more ambitious the near-term emission reductions are, the more expensive they will be. This means that small differences in near-term targets might result in large differences in the cost of implementation.

Third, considering the previous two points, it seems to be extremely important and an economically most rewarding task to specify the climate sensitivity and tolerance levels of various impact sectors as precisely as possible. If there are systems for which a rate of temperature change higher than 0.15°C/decade poses utmost danger, decision makers may want to set the target window at this level.

Fourth, the analysis also shows a caveat of the TWA in its current form. It is difficult to conceive even a highly sensitive ecosystem that would thrive at a rate of temperature change of 0.14°C/decade, but would collapse and decay if the rate was 0.15°C/decade. Additional work will be required to soften these sharp constraints and extend the analysis by using fuzzy techniques to include uncertainties in our analysis.

5. The role of the aerosol mask

In all analysis we presented so far, SO_x emissions have been assumed to change in the same direction at the same rate as CO_2. Recently, analysts and policymakers have increasingly argued that this is an unrealistic assumption, especially over the long term. SO_2 emissions are likely to be reduced mainly through end-of-pipe technologies due to increasing concerns over local and regional air pollution and increasing damages caused by acid deposition. Considering the relatively short atmospheric residence time of sulfate aerosols (on the order of hours to a few days), this would imply a fast attenuation and eventual removal of the aerosol mask from the climate system. The warming disguised so far by the mask would become apparent. This would make staying within the same climate window even more difficult. This section presents results of a sensitivity analysis. Throughout this section, SO_x emissions are assumed to decline at 2% per year starting 2000. Moreover, Annex I countries are taken to implement the Kyoto target by 2010.

We have defined three different windows. Our central case is the original Council window: 2.0°C global mean temperature increase, 0.2°C/decade rate of temperature increase.(See Toth et al., 1998a for details of the window specification, especially the procedure to exclude combinations of large temperature change and high rates of temperature change by rounding off the corresponding corner of the climate window.) A small window is characterized by 1.5°C temperature increase and an upper limit of 0.15°C/decade for the rate. Finally, a large window would imply a maximum increase in global mean temperature of 3°C, at a maximum rate of 0.3°C/decade.

We have also tested the sensitivity of the corridors with respect to the maximum annual rate of GHG emission reductions. We look at 1%, 2% and 4% per year respectively for each climate window.

No open corridor exists under the specified conditions for the small window. This suggests that a climate change involving either the 1.5°C temperature increase, or the 0.15°C/decade rate of temperature increase is already in the atmospheric system if we start removing the aerosol mask at the rate implied by an SO_x reduction of 2% starting in 2000.

Under the originally specified circumstances, there was no solution for the Council window either. Additional assumptions had to be specified in order to get an open corridor. Only if we freeze non-Annex I emissions in the year 2000, would it be possible to obtain some space for flexibility for the long-term emission pathways beyond 2010. The other possibility is that Annex I countries reduce emissions below the Kyoto target by 2010. Figure 5 presents the resulting corridors. In terms of political feasibility, fulfilling this additional assumption is next to impossible. This makes implementation of the WBGU window most questionable.

Finally, Figure 6 presents the global emission corridors for the large window. Relaxing the temperature change limit, but especially easing the rate of temperature change constraint seems to provide a reasonable amount of medium-term flexibility to control GHG emissions. This insight underlines the importance of the rate of temperature change yet again. Climate impact research will need to provide better information in order to help define (in)tolerable limits for this climate attribute.

6. Threshold windows

Evidence has been accumulating over the past few years that some of the large geophysical systems strongly linked to climate might be characterized by unstable behavior or multiple equilibria. Subjected to a gradual forcing of temperature change, for example, and the resulting changes this may cause to large scale regional biogeophysical attributes like albedo, air pressure, precipitation patterns, etc., these systems might undergo a sudden change. At a given threshold, systems with multiple equilibria might exhibit a fast transition from one equilibrium state to another.

The potential for large discontinuities has been explored in various geophysical systems. A short list includes the potential shifts in the South Asia monsoon system, melting down of the West Antarctic ice-shield, changing pattern and intensity of the El-Niño southern oscillation, and others. In this section, preliminary results of analyzing the thresholds for the North Atlantic thermohaline circulation are presented. This system has been shown to have multiple equilibria.

Temporal variation of the intensity of the thermohaline circulation in the North Atlantic has been subject of study in geological history and possible future impacts of anthropogenic climate change as well. In a seminal paper using the GFDL climate model, Manabe and Stouffer (1993) have shown that a 2×CO_2 equivalent concentration climate would substantially reduce the intensity of the circulation but the system would recover once the forcing is removed. In contrast, a climate associated with a 4×CO_2 concentration would lead to permanent shut-down of the circulation system. This indicates that between 2×CO_2 and 4×CO_2 there is a threshold beyond which the thermohaline circulation flips to a different stable equilibrium state.

Geohistorical research and specially targeted modeling activities provided additional insights into this phenomenon. In this section, we take the analysis by Stocker and Schmittner (1997a) as our starting point and rely heavily on contributions by Rahmstorf (1996; 1997) and recent results provided by the CLIMBER model (Ganopolski et al., 1998a; 1998b; Ganopolski, 1998).

Stocker and Schmittner have shown that the North Atlantic thermohaline circulation is sensitive not only to the final level of atmospheric CO_2 concentration but also to the rate of change at which any specific CO2 concentration level will be reached. According to their model, reaching a 750 ppm CO_2 concentration in hundred years time would lead to a permanent shut-down of the circulation system, while reaching the same 750 ppm concentration level at a lower rate would lead to a slow-down-recovery behavior. Similarly, reaching 650 ppm concentration at a faster rate by increasing concentrations at 2% per year would lead to a permanent shut down, while reaching the same 650 ppm slower, by going at 1% per year, would again result in a slow-down-recovery pattern.

In a follow-up to discussions with members of the ICLIPS team, Stocker and Schmittner (1997b) have mapped their results from the concentration and rate of concentration increase space to a climate space including temperature change and the rate of temperature change. The corresponding threshold curve is presented in Figure 7. The figure shows that a fast transition to a 4.5 degrees increase in global mean temperature (the upper limit assumed for a 2×CO_2 concentration in terms of climate sensitivity) at a fast rate involving 0.5°C/decade would take us dangerously close to the threshold curve. Moreover, the climate change path involving 0.2-0.25°C/decade rates of change (rather plausible according to most non-intervention scenarios) would imply crossing the thermohaline threshold if the equilibrium temperature change would reach about 5.0-5.5°C. The marked point in the figure illustrates that even optimum emission paths based on cost-benefit optimization not including catastrophic climate change might take humanity beyond this threshold.

We took the original Stocker-Schmittner relationships and extended them further to include emissions. We have specified upper limits of global annual growth of emissions for the next 150 years and calculated the time-dependent limit according to Stocker and Schmittner. We have then computed the time when the specified limit will be exceeded. The resulting threshold boundary is shown in Figure 8. The figure shows that increasing emissions at the rate of 3.5% per year could lead to a breakdown of the thermohaline circulation in the mid next century. Even continuing emissions at the current rate of about 2% per year might lead to crossing the collapse threshold by the end of the 21st century. These results suggest that there is a non-negligible risk of causing a major geophysical disturbance through anthropogenic GHG emissions.

It is important to note that these results are very sensitive to several assumptions and parameter values characterized by large uncertainties. One key parameter value is the relationship between the $2\times CO_2$ climate sensitivity and the CO_2 equivalent concentration target beyond which the thermohaline circulation might collapse.

In addition to climate sensitivity, the other key parameter affecting the stability of the thermohaline circulation is hydrological sensitivity. It determines the change (increase) in freshwater input to the North Atlantic region. The freshwater input is closely related to and can be described as a function of temperature change in the Northern hemisphere. Hydrological sensitivity is a highly uncertain parameter as well. Climate models spread across a broad range. For this analysis, the CLIMBER model (Ganopolski et al., 1998a) was used to develop threshold curves for the thermohaline circulation in a temperature change-rate of temperature change climate window. For comparison, we have also depicted the original Stocker and Schmittner threshold curve. To the left, the threshold computed by assuming a high hydrological sensitivity is shown. The uppermost curve, in contrast, shows the threshold curve for assuming a low hydrological sensitivity. Taking these values as extremes in terms hydrological sensitivity, three domains are identified in Figure 9. The area below the high hydrological sensitivity line is the case when the probability of breakdown of the thermohaline circulation is low. At the other extreme, the area above the low hydrological sensitivity threshold is identified as a high probability area for the collapse of the circulation system. The domain in between is the medium probability zone. For comparison, the figure also shows the WBGU climate window. As can be clearly seen, keeping the climate system within this window would not raise a serious risk of interfering with the conveyor belt according to our knowledge today.

What does this mean in terms of emissions? Figure 10 shows the necessary emission corridor corresponding to the high hydrological sensitivity case. The corridor has been computed by assuming a maximum rate of annual emission reduction of 2% and a scenario for SO_2 emission reduction at the rate of 2% per year starting in 2000. The underlying global GHG emissions are bound from above by the IS92e scenario. Recall that all emission paths that prevent crossing the thermohaline threshold lie within this corridor, but not every arbitrary emission path is necessarily a permitted one (see Toth et al, 1998a for possible techniques to explore the internal structure of the corridor). To allow comparison in the emission space as well, the necessary emission corridor specified by the WBGU climate window is also depicted in the figure. This reconfirms our earlier observation that preserving the stability of the thermohaline circulation is not of immediate concern but it is a real long-term risk. Given the magnitude of economic losses and human inconvenience that might be caused by an eventual collapse, improved understanding and more precise assessment of the phenomenon is necessary.

At this stage, it is important to point out that the corridors presented in this section are obtained by making some drastic simplifying assumptions. For example, we assume that the instability curve depicted in Figure 9 imposes restrictions on the transient rate of temperature change and the actual magnitude of temperature change rather than on the long-term average rate of change and the equilibrium temperature change, respectively, although the latter climate parameters were used for deriving the instability curve. Future enhancements of emission corridor calculations therefore will need to rely on a fully dynamic reduced-form thermohaline circulation model which will be included in the ICLIPS model.

7. Summary and conclusions

Inverse approaches to analyzing the issue of stabilizing the atmosphere and climate systems with respect to human influence have become increasingly important to provide the information necessary to set the appropriate targets under Article 2 of the FCCC. One key objective of the ICLIPS project at PIK is to provide clues to establish environmental targets in the climate change domain by developing climate impact response functions in various impact areas. This paper has used climate change targets directly. Our central climate window has been specified by an Advisory Board to the German Government and it involves a maximum permitted increase in global mean temperature of 2°C at a rate not faster than 0.2°C/decade. One important result of our analysis is that if rates of climate change (the rates of temperature change, precipitation change, sea-level rise, etc) matter, and an increasing number of climate impact assessments show that in some cases they do, then they should be included in the target. The ICLIPS project is using the TWA to derive emission corridors necessary to keep the climate system within a pre-specified window.

By analyzing three different target climate change windows, we have shown that some are already impossible. About 1.5°C temperature increase or 0.15°C/decade rate of increase is already in the system. Somewhat more relaxed climate windows will be possible to attain only with an early involvement of developing countries if costs of drastic near-term Annex I emissions reductions turn out to be very high. For the large window (3°C, 0.3°C/decade), no additional constraint on non-Annex I emissions is required before the middle of the next century.

Emission corridors are very sensitive to assumptions about future SO_2 emissions. This is mainly due to the constraint on the rate of temperature change, because a fast removal of the aerosol mask would make so far hidden climate change visible and thus would increase the rate of warming. Our analysis shows that for the same climate change window, feasible emission corridor exists if CO_2 and SO_2 emissions are assumed to go in tandem. Corridors vanish, however, if an independent reduction of SO_2 emissions is assumed at 2% per year starting in 2000. It is important to note that the aerosol effect is to a large extent regional. Its treatment in a global model involves some drastic simplifying assumptions. Moreover, the SO_2-aerosol case is plagued by numerous uncertainties both in terms of their future emissions as well as their precise atmospheric and radiative role.

One special area in climate impact research is preoccupied with searching for thresholds in large-scale geophysical systems potentially characterized by discontinuous behavior. Adopting recent results by researchers dealing with the thermohaline circulation, we have concluded that there is no sign of immediate danger to shut down the circulation system through anthropogenic interference. However, such a drastic change cannot be excluded over the long term. This is yet another area with immense uncertainties and potentially high consequence events.

The Kyoto Protocol provides a short-term signal to social actors that future reductions in GHG emissions, especially CO_2, might be required to prevent unpleasantly drastic magnitudes or rates of climate change. To a large extent, the pre-Kyoto debate has revolved around how strong this signal should be. Depending to a large extent on their near-term interests and to some extent on the perceived balance between near-term costs and the strength of the signal required to draw attention and induce action, nations have argued for near-term emission targets across a broad spectrum. Neither the pre-Kyoto proposals nor the actual outcome, however, imply anything for stabilizing global emissions, yet alone atmospheric concentrations of GHGs and thus the climate system. The Kyoto Protocol leaves these long-term questions open.

Finding politically feasible instruments that provide the largest possible degree of flexibility and foster implementation of near-term emission targets in a cost-effective way can make a difference of many billions of dollars in the costs. Choosing the right target for long-term climate stabilization, in comparison, might involve losses or gains on the order of trillions. Increased research over the coming years will be required to provide policymakers with improved information to make the right choices on both of those issues.

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References:

Bruckner, T. and G. Petschel-Held, 1997, Applications of differential inclusions in environmental sciences. To be submitted.

Ganopolski, A., S. Rahmstorf, V. Petoukhov, M. Claussen, 1998a, Simulation of modern and glacial climates with a coupled global model of intermediate complexity, *Nature* **391**:351-356.

Ganopolski, A., C. Kubatzki, M. Claussen, V. Brovkin, V. Petoukhov, 1998b, The influence of vegetation-atmosphere-ocean interaction on climate during the Mid-Holocene, *Science* **280**:1916-1919.

Ganopolski, A., 1998, Personal communication.

Grubb, M., T. Chapius and M.H. Doung, 1995, The economics of changing course, implications of adaptability and inertia for optimal climate policy, *Energy Policy* **23**(4):417-432.

Hasselmann, K., S. Hasselmann, R. Giering, V. Ocana, H. von Storch, 1996, Optimization of CO_2 emissions using coupled integral climate response and simplified cost models: A sensitivity study, pp. 349-398 in N. Nakicenovic, W.D. Nordhaus, R. Richels and F.L. Toth (eds.) *Climate Change: Integrating Science, Economics, and Policy*, CP-96-1, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Manabe, S. and R.J. Stouffer, 1993, Century -scale effects of increased atmospheric CO_2 on the ocean-atmosphere system, *Nature* **364**:215-218.

Manne, A.S. and R.G. Richels, 1996, The Berlin Mandate: The costs of meeting post-2000 targets and timetables, *Energy Policy* **24**(3):205-210.

Meier-Reimer, E. and K.F. Hasselmann, 1987, Transport and storage of CO_2 in the ocean - an inorganic ocean-circulation carbon cycle model, *Climate Dynamics* **2**:63-90.

Nordhaus, W.D. and Z. Yang, 1996, A regional dynamic general-equilibrium model of alternative climate-change strategies, *The American Economic Review* **86**(4):741-765.

Petschel-Held, G. and H.J. Schellnhuber, 1997, The Tolerable Windows Approach (TWA) to climate control: Optimization, risks, and perspectives. pp. 121-139 in F.L. Toth (ed.) *Cost-Benefit Analyses of Climate Change*, Birkhauser, Basel.

Rahmstorf, S., 1996, On the freshwater forcing and transport of the Atlantic thermohaline circulation, *Climate Dynamics* **12:**799-811.

Rahmstorf, S., 1997, Risk of sea-change in the Atlantic, *Nature* **388**:825-826.

Stocker, T.F., and A. Schmittner, 1997a, Influence of CO_2 emission rates on the stability of the thermohaline circulation, *Nature* **388**:862-865.

Stocker, T.F., and A. Schmittner, 1997b, Personal communication.

Toth, F.L., T. Bruckner, H.-M. Füssel, M. Leimbach, G. Petschel-Held and H.-J. Schellnhuber, 1998a, The tolerable windows approach to integrated assessments. pp. 403-430 in: O.K. Cameron, K. Fukuwatari and T. Morita (eds) Climate Change and Integrated Assessment Models [IAMs] - Bridging the Gaps, Proceedings of the IPCC Asia-Pacific Workshop on Integrated Assessment Models, Center for Global Environmental Research, Tsukuba, Japan.

Toth, F.L., G. Petschel-Held and T. Bruckner, 1998b, Climate change and integrated assessment: The tolerable windows approach, Forthcoming in: J. Hacker (ed.) *Goals and Economic Instruments for Achievement of Global Warming Mitigation in Europe*. Kluwer, Dordrecht, The

Netherlands.

Toth, F.L., M. Leimbach, T. Bruckner, G. Petschel-Held, 1998c, Tolerable climate windows and emission corridors: New results with the ICLIPS model. Forthcoming in the Proceedings of the workshop "Energy Models for Decision Support - New Challenges and Possible Solutions", May 4-5, 1998, Berlin, Germany.

WBGU (German Advisory Council on Global Change), 1997, *Targets for Climate Protection, 1997.* WBGU, Bremerhaven.

Wigley, T.M.L., R.G. Richels and J.A. Edmonds, 1996, Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations, *Nature* **379**:240-243.

Figure 1: **ICLIPS: Inverse translation strategy**

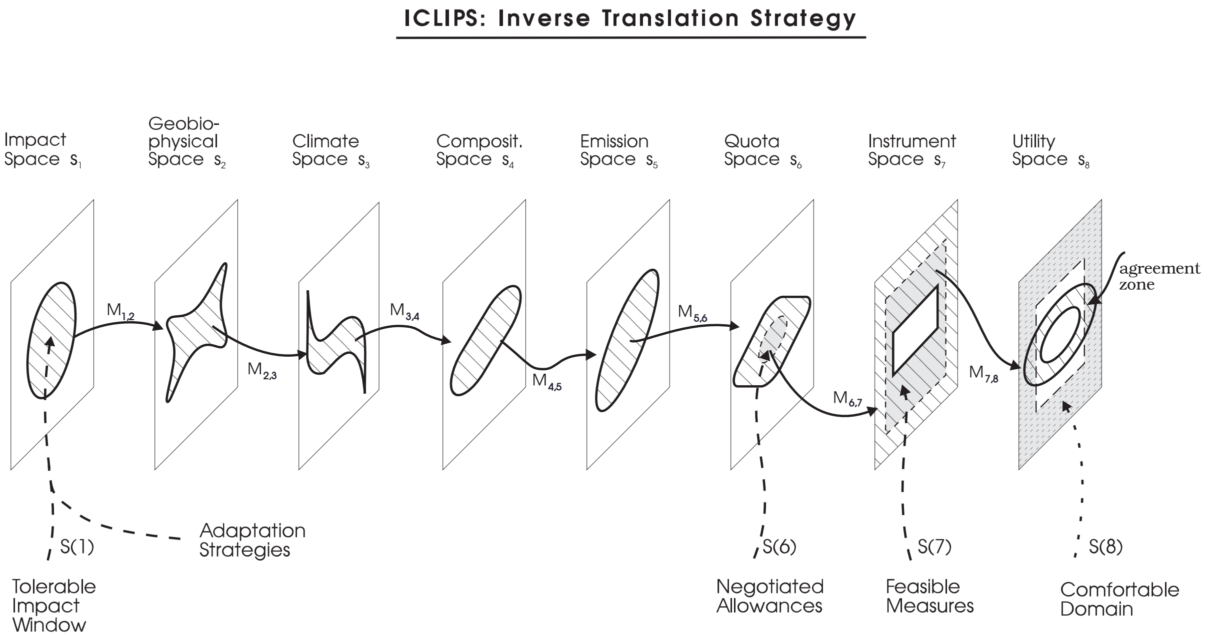

Figure 2: **Emission corridors under different assumptions on delaying reduction measures and equity principles**

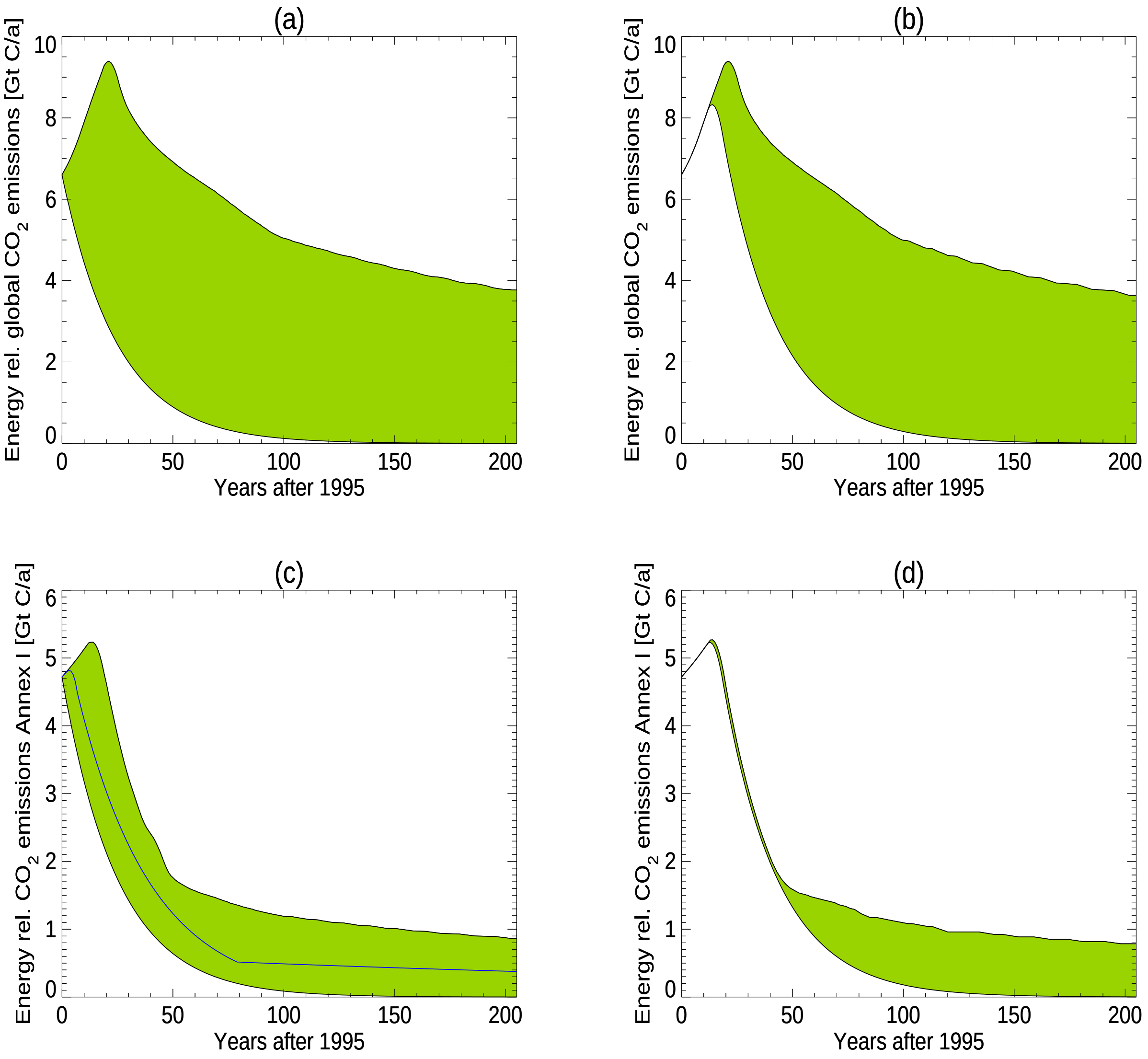

Figure 3: **Necessary emission corridors for the various pre-Kyoto proposals for the WBGU climate window**

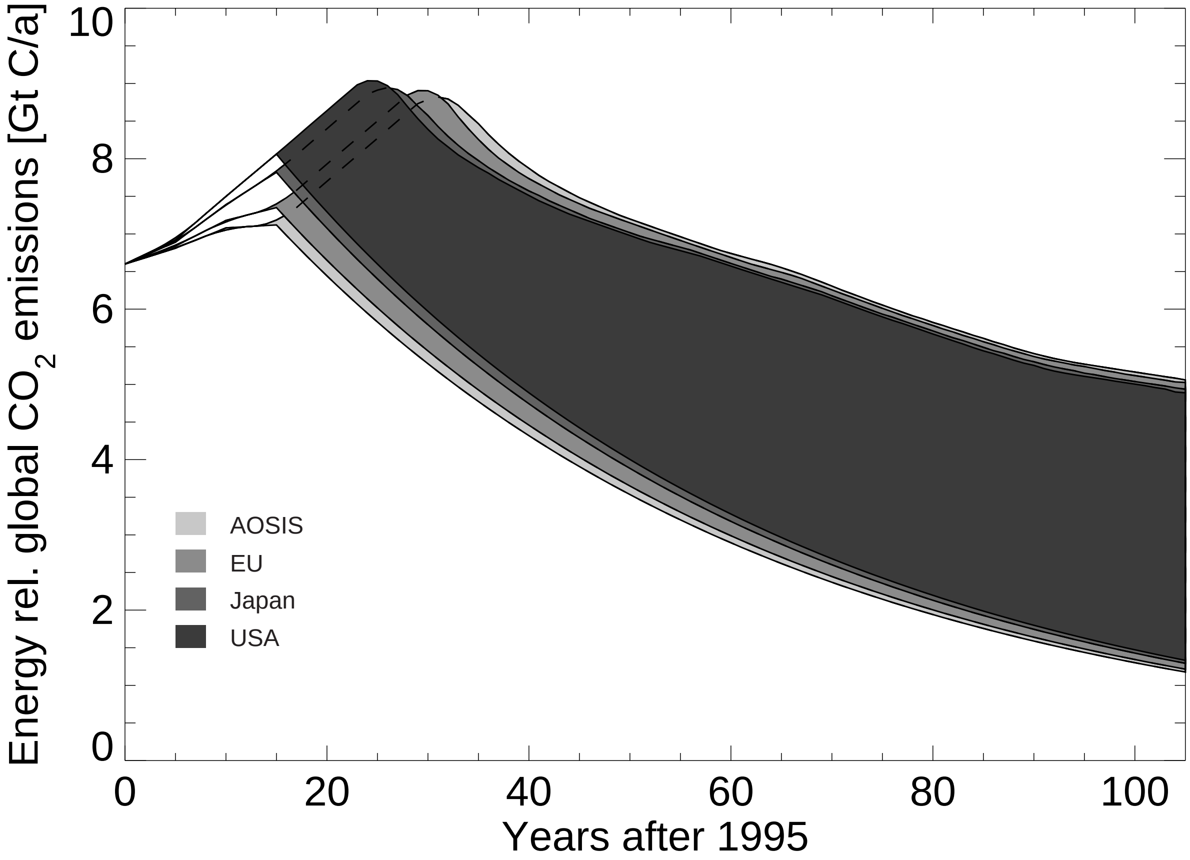

Figure 4: **Necessary emission corridors for the various pre-Kyoto proposals for the small climate window (permitted rate warming is not more than 0.15°C/decade)**

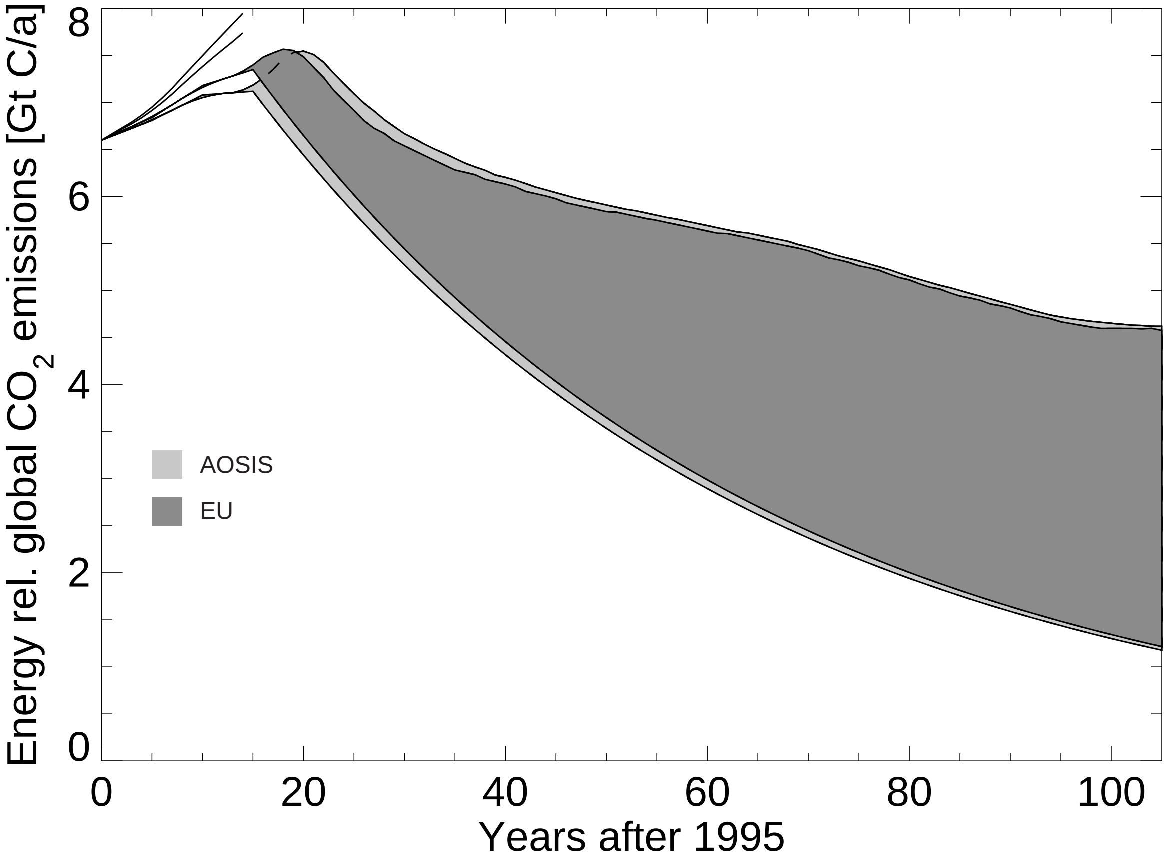

Figure 5: **Necessary emission corridors under the Kyoto Protocol and a fast removal of the aerosol mask – WBGU climate window**

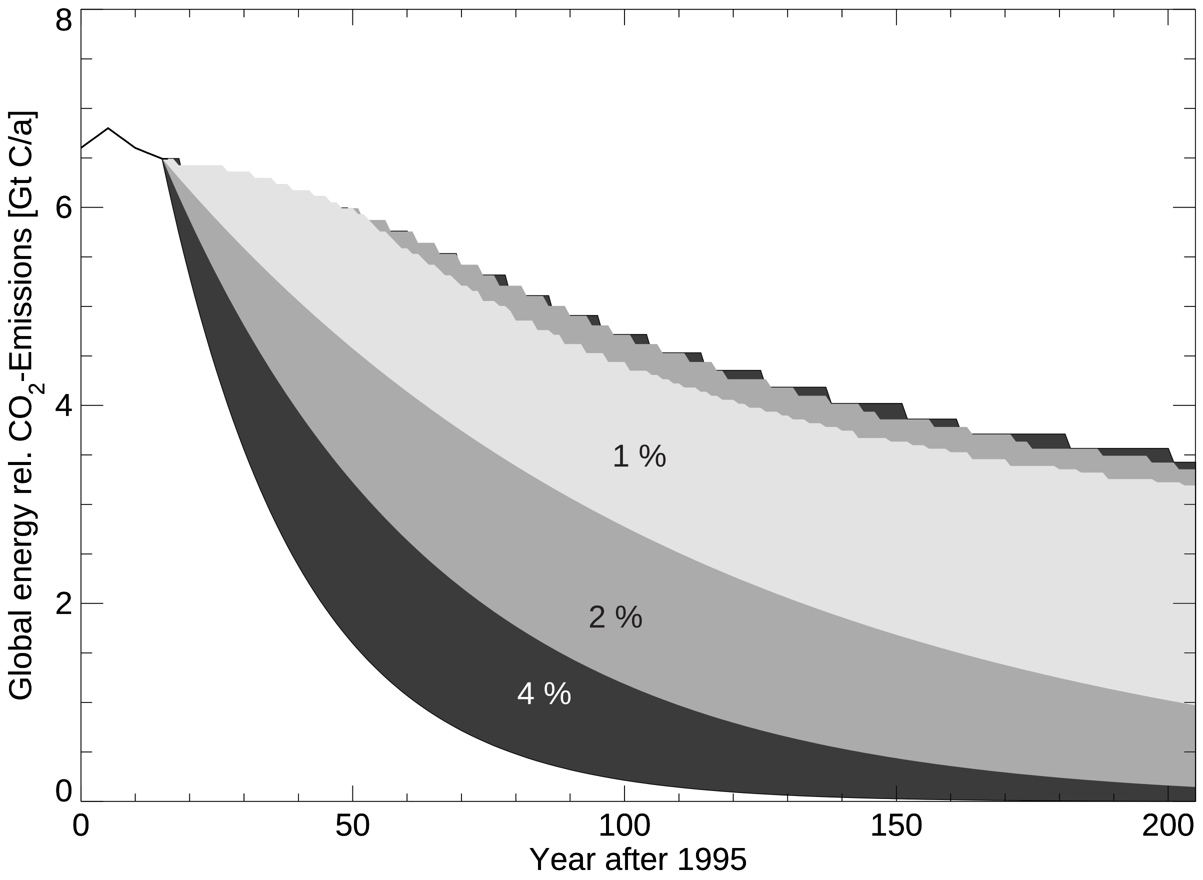

Figure 6: **Necessary emission corridors under the Kyoto Protocol and a fast removal of the aerosol mask – Large climate window (3°C, 0.3°C/decade)**

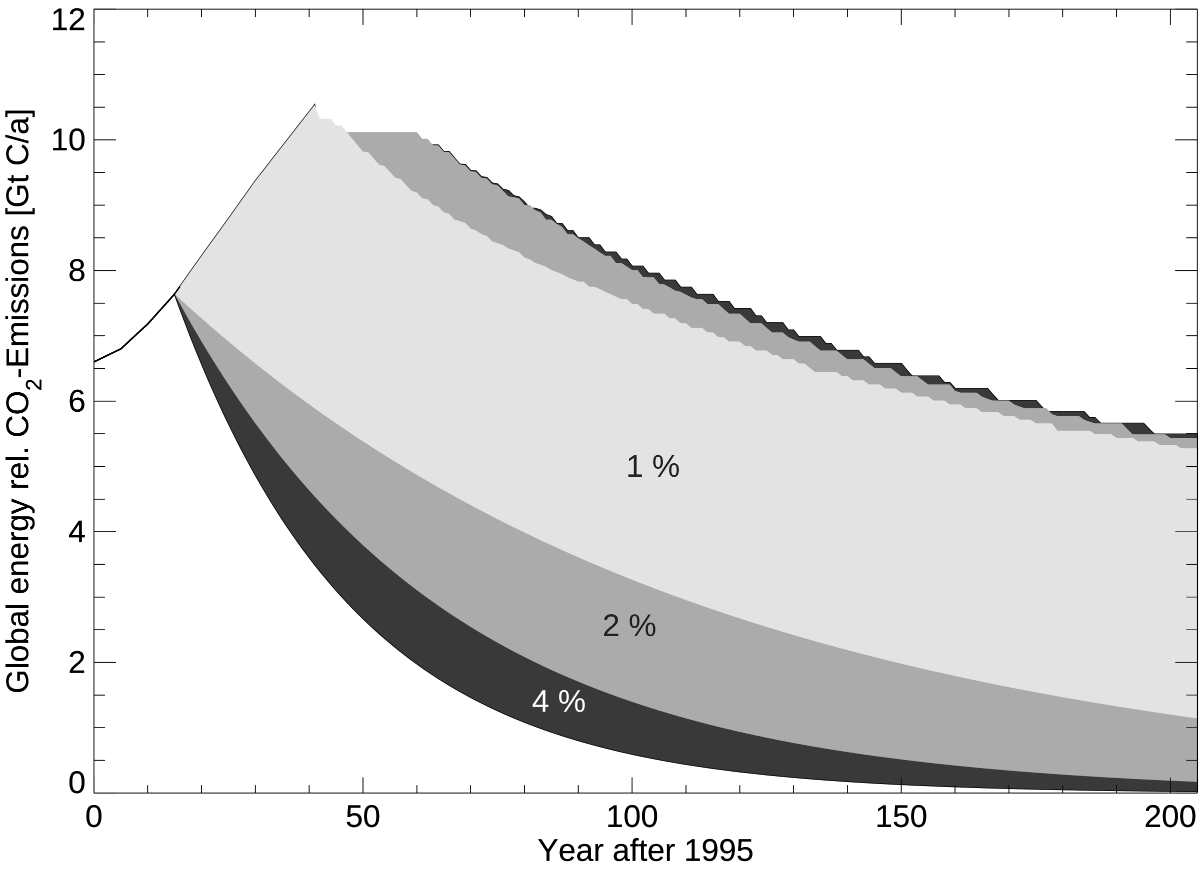

Figure 7: **Stability of thermohaline circulation according to Stocker and Schmittner (1997a; 1997b) and the optimal climate change trajectory in the RICE model (Nordhaus and Yang, 1996)**

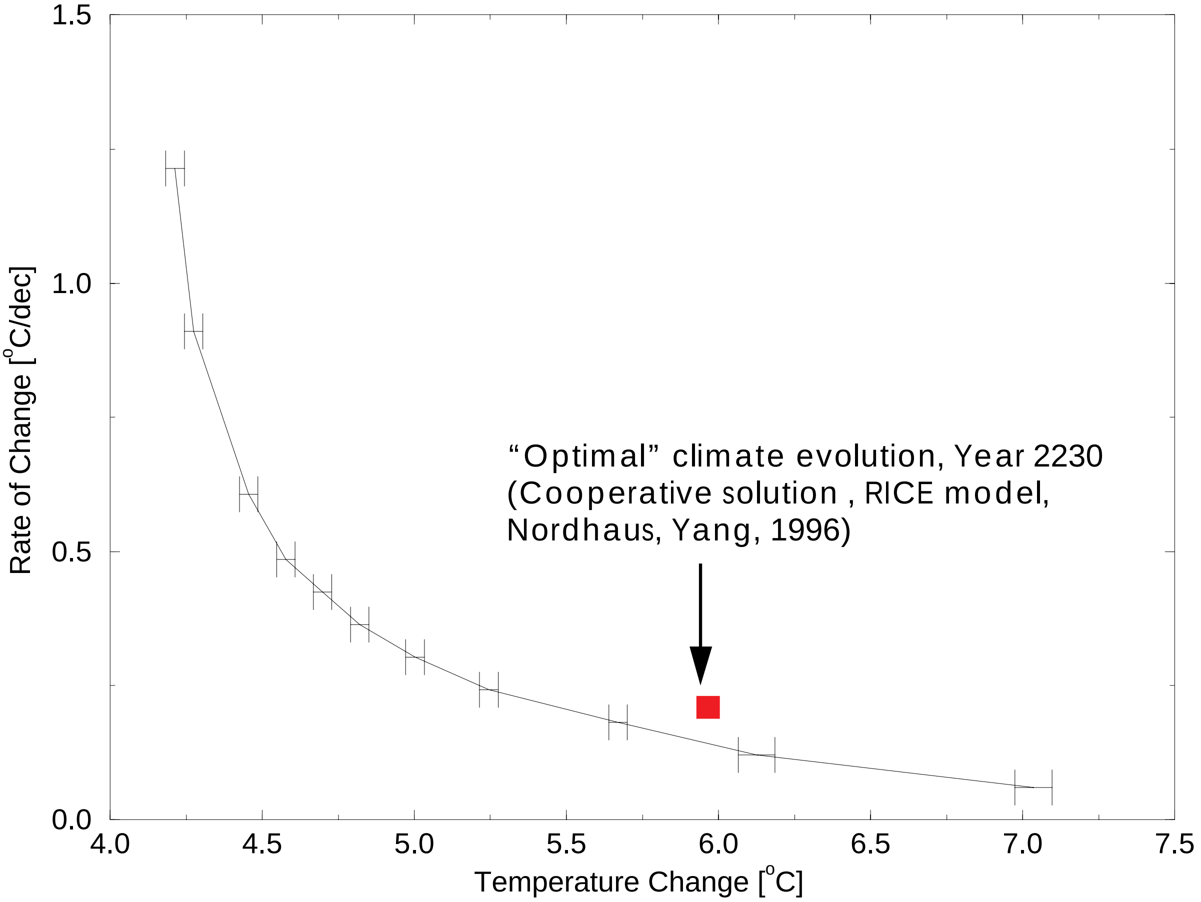

Figure 8: **Threshold curve for the thermohaline circulation as a function of the rate of GHG emission increase**

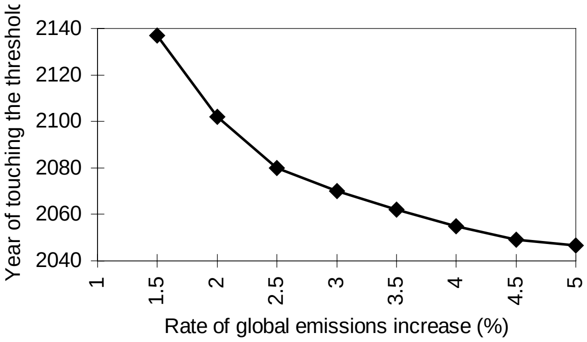

Figure 9: **Threshold curves for the thermohaline circulation in the climate window under different hydrological sensitivity assumptions**

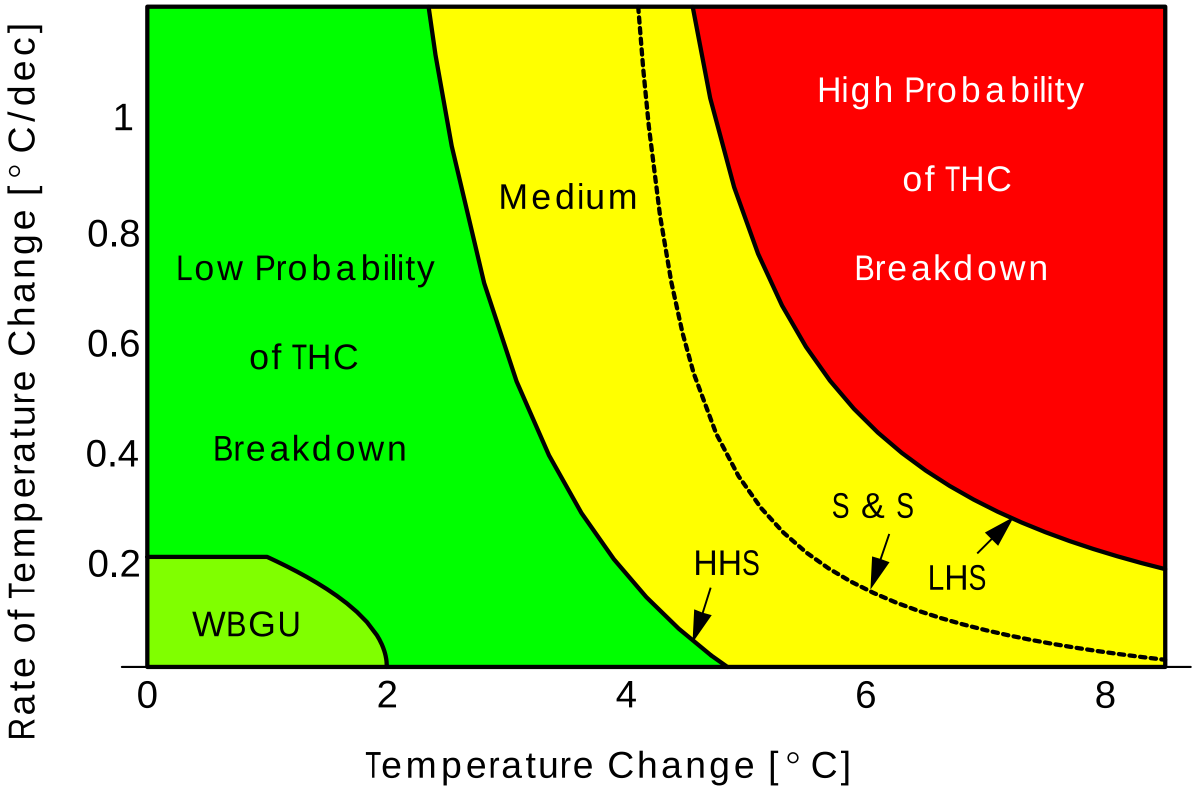

Figure 10: **Necessary emission corridors (i) for not crossing the thermohaline circulation threshold under the high hydrological sensitivity assumption and (ii) for the WBGU climate window**