Low Risk Emissions Corridors for Safeguarding the Atlantic Thermohaline Circulation *

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Abstract. In this paper, we present the integrated assessment model *dimrise* (*d*ynamic *i*ntegrated *m*odel of *r*egular climate change *i*mpacts and *s*ingular *e*vents). This model is designed to investigate the stability of the North Atlantic thermohaline circulation (THC) and to derive related climate policy recommendations. It is written in GAMS and comprises a dynamic model of the Atlantic overturning coupled to a climate model and a global economy model for assessing the monetary cost of climate protection. The THC model is a dynamic four-box interhemispheric extension of the classic Stommel model calibrated against results obtained using the CLIMBER-2 climate model. The reduced-form climate model used to drive the THC model is the ICLIPS multi-gas climate model, which is a computationally efficient, globally aggregated model able to mimic the response of more sophisticated carbon cycle and atmosphere-ocean general circulation models. The THC and climate modules are coupled to a globally aggregated Ramsey-type optimal growth model of the world economy derived from the Nordhaus DICE model. Together, these components create a novel dynamic fully coupled computationally efficient integrated assessment model. Illustrative applications demonstrate that *dimrise* is able to derive cost-effective emissions paths that comply with prescribed bounds on admissible THC weakening, duly imposed in order to avoid an irrevocable break-down. In addition, emissions corridors are presented which contain all possible emissions paths that do not endanger the stability of the North Atlantic circulation and that simultaneously obey restrictions on welfare loss arising from mitigation efforts. The presented results show that, using a conservative calibration of the model, the North Atlantic circulation may be threatened within two decades in the absence of precautionary mitigation.

Keywords: climate change, emissions corridors, sensitivity analysis, thermohaline circulation, tolerable windows approach

Abbreviations: BAU – business-as-usual; IPCC – Intergovernmental Panel on Climate Change; THC – thermohaline circulation; TWA – Tolerable Windows Approach

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1. Introduction

Paleo-reconstructions (Dansgaard et al., 1993) and computer simulations (Manabe and Stouffer, 1993; Stocker and Schmittner, 1997; Rahmstorf and Ganopolski, 1999) have shown the potential for an instability of the thermohaline circulation (THC), i.e. that part of the Atlantic ocean circulation which is driven by temperature- and salinity-dependent density gradients. There is now increasing evidence that weak external forcing has been sufficient to shut down the THC several times in the past and that anthropogenic climate change might well trigger a future collapse.

A complete shutdown would lead to a stagnant deep ocean exhibiting reduced deep-water oxygen levels and lowered carbon uptake, both resulting in potentially severe consequences for marine ecosystems and fisheries (Smith et al., 2001). In addition, as the circulation transports large amounts of heat northward (in the order of 1 PW = 10^{15} W) (Macdonald and Wunsch, 1996), THC breakdown could have a major impact on the climate and consequently on societies in the North Atlantic region. Moreover, changes in ocean circulation could lead to rapid dynamic sea level rise of up to one meter on some Atlantic coasts and create further social and environmental impacts (Levermann et al., 2005). Even worse, the impact of changes in the ocean circulation might not be restricted to this part of the world. As the heat transport to the North is reduced, climate change in the South is expected to become enhanced compared with that already anticipated due to gradual global climate change alone — the resulting 'climate see-saw' effect is well known to paleoclimatologists (Rahmstorf, 2004). Furthermore, paleoclimatic data (Peterson et al., 2000) and climate model investigations (Claussen et al., 2003) both indicate that a change in ocean circulation could shift the intertropical convergence zone (ITCZ) and thereby possibly disrupt tropical precipitation patterns around the globe. Finally, given that the largest uptake of anthropogenic carbon dioxide is associated with deep-water formation in the North Atlantic, a breakdown might also feed back and enhance global climate change to an even greater extent (Sarmiento and Quere, 1996).

As a consequence, potentially unstable features of the THC have been attracting increasing scientific and public attention. In recent years, the majority of the scientific investigations have focused on the *physical* stability of the North Atlantic current. According to the results obtained by Stocker and Schmittner (1997), the THC is not only sensitive to the atmospheric CO_2 concentration level but also to the rate of associated temperature change. In addition, multi model comparison studies (Cubasch and Meehl, 2001) have shown that, for a given CO_2

emissions trajectory, the projected evolution of the THC is strongly dependent on uncertain parameters including the climate sensitivity, the North Atlantic hydrological sensitivity (the amount of freshwater input in the North Atlantic for a given global mean temperature change), and the pre-industrial rate of Atlantic overturning (because an already weak circulation is more likely to fail). Hence, a reliable integrated assessment of the THC stability issue and its implications for global climate policy should take into account both the dynamic features and the substantial uncertainties involved. As a minimum standard, integrated assessment models designed to support climate policy formulation should therefore (1) include a fully dynamic representation of the Atlantic thermohaline circulation and (2) allow an extensive sensitivity analysis to be conducted with respect to the uncertain parameters listed earlier.

Although projects have been introduced to address this gap in knowledge (Rahmstorf et al., 2003), thus far little is known quantitatively about (1) the potential consequences of a partial or complete collapse of the THC on marine and terrestrial ecosystems, human societies in general, and economies in particular and (2) the probability of such an event. THC failure depends on the probability functions of the underlying calibration parameters which are either heavily debated (in the case of climate sensitivity) or still to be assessed (in the remaining two cases).

Due to the existing ignorance about the exact consequences of THC failure, we abstained from framing the climate change decision problem in terms of an overarching cost-benefit analysis or — more specifically, given that parameter uncertainty plays a major role as well — in terms of expected utility. Instead, least-cost emissions paths and emissions corridors were calculated that obey a prescribed bound on THC weakening, chosen to reflect the likely onset of THC instability.

In order to achieve that goal, a novel computationally efficient integrated assessment model called *dimrise* (*d*ynamic *i*ntegrated *m*odel of *r*egular climate change *i*mpacts and *s*ingular *e*vents) has been developed. *dimrise* includes (1) a dynamic model of the Atlantic THC coupled to (2) a reduced-form climate model and (3) a global economy model for assessing the monetary cost of climate protection.

This model, discussed in detail in Section 2, extends previous approaches[1] to integrated assessment of THC stability. Because the dynamics of THC strength change is modelled explicitly, the limiting threshold used in cost-effectiveness analyzes can be defined with respect to the actual THC strength. Lacking a dynamic THC component, other

[1] A contemporary overview of integrated assessment models used to address the THC issue is provided in a series of papers in *Climatic Change* **56**, 245–289 (2003). These papers focus on catastrophic events and stochastic cost-benefit analysis.

integrated assessment models (Nordhaus, 2000; Keller et al., 2000; Tóth et al., 1998) were forced to use proxy indicators to specify a presumed THC stability limit, including CO_2 concentration, temperature change and — for more advanced studies — the rate of temperature change. So while Mastrandrea and Schneider (2001) address the incorporation of ocean circulation changes in a fully dynamic way, our approach differs in that we have integrated all components (the THC, climate, and economic modules) to obtain a single fully coupled GAMS program [2] with endogenized treatment of the THC. By contrast, Mastrandrea and Schneider instead opt to run two independent models — DICE for the economic component and SCD (simple climate demonstrator) for representing climate and THC changes — and to iterate between these models until consistency is achieved via mutual result data exchange. Compared with our earlier models used to derive emissions corridors (Tóth et al., 1998; Zickfeld and Bruckner, 2003), we have now replaced a simplified treatment of the economic aspects by a fully dynamic representation of the economy obtained from the DICE model (Nordhaus, 2000).

The novel integrated assessment model so obtained is capable of determining cost-effective greenhouse gas emissions paths that do not result in a level of North Atlantic ocean overturning below a prescribed lower bound. In addition, emissions corridors will be presented comprising all admissible CO_2 emissions paths that secure the stability of the THC and, simultaneously, do not pose an unacceptable mitigation burden on societies. In order to reflect the substantial uncertainties involved, the sensitivity of our results on key physical and socio-economic parameters is discussed in Section 5.

2. Model Description

As indicated in Section 1, the integrated modeling framework *dim-rise* comprises (1) a dynamic model of the Atlantic THC coupled to a (2) reduced-form climate model and (3) a global economy model. These various model components (or modules) are discussed further in Sections 2.1–2.3. Section 4.1 specifies the threshold values selected to indicate (1) the likely onset of THC instability and (2) the bounds placed by societies on any emissions mitigation burden.

[2] GAMS (Brooke et al., 1992) is a computer language and modeling environment primarily intended for solving optimization problems.

2.1. Dynamic THC Module

The THC module within *dimrise* is a dynamic reduced-form model of the THC distinguished by several features that make it well suited for inclusion in an integrated assessment model. This module (1) is physically based, (2) is computationally efficient, (3) facilitates comprehensive uncertainty analysis, and (4) can be readily linked to the output from *globally aggregated* climate models. From a physical point of view, the model is a four-box interhemispheric dynamic extension of the seminal Stommel (1961) model calibrated against results obtained with CLIMBER-2 — a state-of-the-art climate model of intermediate complexity (Petoukhov et al., 2000; Ganopolski et al., 2001). The THC module is driven by global mean temperature change which is then translated into corresponding transient fluxes of heat and freshwater into the North Atlantic circulation through an appropriate downscaling procedure (Zickfeld and Bruckner, 2003).

Under this approach, the change of freshwater flux $\Delta F(t)$ into the Atlantic north of 50° N is proportional to the atmospheric temperature change in the northern hemisphere ΔT^{NH} which is itself proportional to the global mean temperature change ΔT^{GL}. Thus

$$\Delta F(t) = h_2 \Delta T^{\mathrm{NH}}(t) = h_2 p^{\mathrm{NH}} \Delta T^{\mathrm{GL}}(t). \tag{1}$$

The global-to-regional temperature scaling constant $p^{\mathrm{NH}} = 1.07$ is derived from greenhouse gas simulation experiments using CLIMBER-2 (Zickfeld et al., 2004). The (North Atlantic) hydrological sensitivity h_2 (see [3]) denotes the magnitude of changes in freshwater flux into the North Atlantic in terms of the temperature change experienced in that region. Thus, h_2 summarizes evaporation, precipitation, river discharge, and meltwater changes in the North Atlantic catchment area — and is one of the main uncertainties in predicting the fate of the THC. Consequently, this parameter will be investigated in detail in later sensitivity analyzes.

Although highly simplified when compared with comprehensive, coupled atmosphere-ocean circulation models, the dynamic THC box model satisfactorily reproduces their key characteristics. In response to moderate climate change scenarios, for example, the box model shows that circulation first weakens and then, as soon as the additional climate forcing is stabilized, recovers. This behavior is consistent with the majority of comprehensive climate models as summarized by Houghton et al. (2001). For scenarios with higher climate forcing, the overturning

[3] The subscript 2 is used to distinguish this constant from h_1 which represents the equivalent parameter for the southern hemisphere. We retain this subscript to facilitate comparisons with Zickfeld and Bruckner (2003).

collapses due to the presence of a threshold value in the freshwater perturbation beyond which circulation cannot be sustained. The latter regime is similar to the behavior discussed by Manabe and Stouffer (1994), Stocker and Schmittner (1997), and Rahmstorf and Ganopolski (1999). Furthermore, the box model convincingly reproduces the results obtained by Stocker and Schmittner (1997), who demonstrate that the stability of the THC is also dependent upon the rate of climate change. This rate-sensitive response implies that the ultimate temperature increase that can be reached without inducing a collapse of the THC is higher for slower rates of temperature rise. Due to this feature, a dynamic model is therefore indispensable for appropriate THC risk assessment. In order to show the rate-dependency of THC stability, Schmittner and Stocker (1999) use a collection of different CO_2 concentration paths with the same underlying structure, namely an exponential increase in the equivalent carbon dioxide concentration followed by an abrupt stabilization once the selected maximum concentration is achieved. This somewhat peculiar choice of concentration path gave Schmittner and Stocker the opportunity to summarize the results of their sensitivity investigations in the form of stability diagrams. This, however, implies that the threshold information contained in these stability diagrams is bound to the specific structure of the concentration paths employed. It would therefore be unwise to apply this information to concentration (and corresponding emissions) paths exhibiting a different structure. Although cost-effective concentration paths that obey THC stability thresholds might have a structure similar to that investigated by Schmittner and Stocker, the set of emissions paths delineated by the boundaries of emissions corridors might equally contain any number of paths with a very different structure. Early emissions corridor studies (Tóth et al., 1998) based solely on the stability information provided by Schmittner and Stocker must therefore be considered as a first step toward a more comprehensive investigation. Armed with the dynamic THC model just described, we are now able to investigate the transient influence of arbitrary emissions and concentration profiles on THC overturning and failure. This capability facilitates the derivation of realistic yet complying emissions corridors considerably.

The reduced-form THC module itself, its implementation and calibration, the results from transient experiments, and a variety of sensitivity analyzes are discussed in detail in Zickfeld et al. (2004). The application of this module to derive emissions corridors is reported in Zickfeld and Bruckner (2003).

2.2. Climate Module

In order to estimate future global mean temperatures, we apply the ICLIPS multi-gas climate model (ICM) (Bruckner et al., 2003a) from the ICLIPS suite (Tóth et al., 2003a). ICM is a computationally efficient, globally aggregated model able to reproduce the response of sophisticated carbon-cycle and atmosphere-ocean general circulation models fairly well. The model translates anthropogenic emissions of CO_2, CH_4, N_2O, halocarbons, SF_6, and SO_2 into time-dependent paths (time-series) covering atmospheric concentrations, radiative forcing, and global mean temperature change.

The carbon cycle module of ICM (Hooss et al., 2001) was developed at the Max Planck Institute for Meteorology, Hamburg, and consists of (1) a differential impulse-response representation of the 3-dimensional Hamburg Model of the Ocean Carbon Cycle (HAMOCC), extended into the nonlinear high-CO_2 domain by an explicit treatment of the chemistry governing CO_2 uptake through the ocean surface and (2) a nonlinear differential impulse-response model of terrestrial biosphere CO_2 fertilization effects.

In order to allow for the explicit consideration of climate sensitivities, ICM, as presented in Bruckner et al. (2003a), has been extended by replacing the original temperature impulse response function model (Hooss et al., 2001) with a box-diffusion model analog (Kriegler, 2001).

2.3. Economic Module

In order to assess the social mitigation burden associated with time-dependent emissions mitigation efforts, a dynamic model of the world economy was added to the THC and climate modules. During the past decade, various models of the world economy have been developed to assess the economic consequences of the Kyoto Protocol or, alternatively, to determine mitigation costs associated with differing CO_2 concentration stabilization efforts. A contemporary overview of some of the most prominent results of these economic and integrated assessment models is provided by, among others, (Metz et al., 2001).

We elected to use the economic relationships contained within the highly aggregated dynamic integrated climate and economy (DICE) model, developed by W. Nordhaus (Nordhaus, 1992; Nordhaus and Boyer, 2000), for inclusion in *dimrise*. Our reasons are as follows. DICE is computationally fast, already implemented in GAMS, and well known and widely used by the integrated assessment community — and, moreover, its features have been investigated for more than a decade now. Due to the relative simplicity and transparency of DICE, the complex interplay between the dynamics of the THC, the climate system, and the economic system can be readily investigated with reference to the results obtained using DICE alone. DICE, therefore, was our economic model of choice for the proof-of-concept development of a fully dynamic THC-climate-economy model.

This, however, does not imply that DICE is necessarily the most appropriate representation of the economic sphere. Since its creation, DICE and the underlying social cost-benefit methodology have been widely disputed in the literature. In order to pursue the sensitivity analysis of coupled THC-climate-economy dynamics, future investigations must move beyond the parameter sensitivity studies (as presented here) and confront the issue of competing representations of the economic domain. Potential substitutes for DICE include, among others, RICE (Nordhaus, 2000) — the regionalized version of DICE, MERGE (Manne et al., 1995), the economic module from the ICLIPS suite (Leimbach and Tóth, 2003), and other models discussed in Metz et al. (2001). In addition, economic models that embed endogenous technological progress should be considered as these have shown substantially lower mitigation costs when compared to the traditional models cited above (Edenhofer et al., 2006).

The globally aggregated economic model DICE is a Ramsey-type optimal growth model.[4] DICE describes the essential elements of the long-term economic development process — the investment and capital accumulation cycle — in an endogenous way. A single Cobb-Douglas production function characterizes the transformation of the factor inputs, capital $K(t)$ and labor $L(t)$, into gross product $Q(t)$, at the macroeconomic scale, in the presence of exogenous technological change $A(t)$

$$Q(t) = \Omega(t)A(t)K(t)^{\gamma}L(t)^{1-\gamma}, \tag{2}$$

where γ denotes the elasticity of output with respect to capital and $\Omega(t) \leq 1$ is applied to reduce economic output where mitigation costs occur.[5] Labor availability $L(t)$ is derived from exogenous demographic scenarios.

The gross product (often simply called 'output') $Q(t)$ can be devoted to either investment $I(t)$ or consumption $C(t)$

$$Q(t) = I(t) + C(t). \tag{3}$$

[4] The core model equations are given in (Nordhaus and Boyer, 2000) as Appendix B.

[5] In contrast to the original DICE formulation, climate change damages are not taken into account via their influence on global output. Instead, thresholds are set to restrict global climate change.

Investment is used to increase the capital stock, which depreciates with a rate δ

$$\dot{K}(t) = I(t) - \delta K(t). \tag{4}$$

Reference case industrial CO_2 emissions — that is, in the absence of explicit abatement — are given by the product of a prescribed carbon-intensity factor $\sigma(t)$ and the prevailing gross product. In the case of controlled emissions, the percentage reduction in CO_2 emissions is specified by the emissions control level $\mu(t)$— one of the control variables available to mitigate annual global industrial CO_2 emissions $E(t)$ — such that

$$E(t) = [1 - \mu(t)]\sigma(t)Q(t). \tag{5}$$

The increase in marginal mitigation cost — as typically exhibited by abatement cost curves — is modelled by the following power law

$$\Omega(t) = 1 - b_1\mu(t)^{b_2} \tag{6}$$

with calibration constants b_1 and b_2.

In the original version of DICE, a globally aggregated intertemporal social welfare function W is maximized in order to derive reference case optimal economic growth (neglecting climate damages and mitigation costs) and optimal climate change abatement (taking these effects into account), respectively. W is modelled according to a Bernoullian utility function approach

$$W = \int_t R(t)L(t)\log c(t)dt \tag{7}$$

with $R(t)$ being the social time preference discount factor and $c(t)$ the *per capita* consumption, suitably derived from $C(t)$.

As pointed out in Section 1, our current knowledge does not allow a meaningful estimate of the cost of a breakdown in the Atlantic THC. Therefore, we do not carry out a cost-benefit analysis in relation to global climate change. Instead, we derive either (1) least-cost mitigation strategies that obey prescribed bounds on THC weakening or (2) emissions corridors delineating the set of all emissions paths that do not violate elected constraints on admissible climate change and acceptable mitigation costs. In the first case, W will be maximized subject to the prescribed bounds. In the second case, W acts as a diagnostic variable which indicates welfare losses compared to the reference case of zero dedicated abatement.

The DICE code used is an adapted extract from DICE-99. DICE-99 is very similar in structure to earlier versions (Nordhaus, 1994), but has been re-calibrated in order to reproduce the results from RICE-99 (Nordhaus and Boyer, 2000). RICE-99 is an updated regionalized variant of DICE with a more representative economic structure — one which uses a three-factor production function covering capital, labor and carbon-energy and which contains explicit modeling of fossil fuel exhaustion. Note that due to the re-calibration, DICE-99 shows considerably lower CO_2 reference emissions over the next century than earlier DICE and RICE models — mainly because of slower projected economic growth and a higher rate of autonomous decarbonization within the world economy (Nordhaus and Boyer, 2000, p. 6).

The programming modifications required to transfer the underlying DICE-99 equations to *dimrise* are discussed in detail in Keitsch (2003). For instance, DICE-99 sometimes relaxes (replaces) equality constraints by inequality constraints in the knowledge that these constraints will necessarily bind on optimization. This strategy, which improves numerical stability, is only valid if welfare maximization is the objective (function). Use of DICE in a diagnostic mode therefore requires a thorough reconsideration of the entire codebase. In addition, for numerical reasons, the continuous combined evolution of the THC-climate-economy system described in Eq. 4 needs to be converted to a difference equation. A time-step of 5 years is adopted, in line with that used by ICM.

3. Overarching Methodological Issues and Model Application Schemes

3.1. Cost-effectiveness Analysis

The dynamic model *dimrise* described thus far is suitable for determining least-cost emissions mitigation scenarios that obey prescribed bounds on the weakening of the THC. In order to achieve the goal of least-cost, the percentage welfare loss l relative to the reference case (which is obtained by intentionally neglecting both global climate change and mitigation efforts completely) is used as the objective function. Minimizing l (defined in Eq. 10.) delivers time-paths for both control variables contained in the model: investment $I(t)$ and emissions control level $\mu(t)$. $I(t)$ governs capital accumulation and indirectly determines, via Eq. 2, the evolution of economic output. As the time-dependent carbon intensity factor $\sigma(t)$ is prescribed, the only other additional opportunity to influence emissions is provided by the emissions control level variable $\mu(t)$.

3.2. Tolerable Windows Approach

In determining the least-cost emissions path, the coupled THC-climate-economy systems seeks to exploit any opportunity to decrease discounted mitigation costs. Consequently, if maintaining the THC threshold requires a deviation from the business-as-usual (BAU) evolution, then the feasibility domain provided will, no doubt, be utilized to the fullest extent. This implies that, in such cases, the system will eventually strike at least one guard-rail. This, however, is not a particularly prudent approach, given that both the threshold guard-rails and the model calibration parameters are subject to substantial uncertainty. With a view to the potentially irreversible character of a THC breakdown, seeking to follow cost-effective emissions paths derived from uncertain model results is analogous to "dancing on the rim of a volcano".

Faced with the huge uncertainties involved and adopting the precautionary principle, one might be tempted to reduce CO_2 emissions as far as is technically possible — or, at least, as far as this does not imply, of itself, an intolerable mitigation burden. Whereas the cost-effectiveness approach seeks to minimize mitigation costs subject to climate constraints, this alternate approach seeks to minimize climate change subject to mitigation cost constraints. Both approaches (which also map to key positions in the political arena) are extreme in the sense that they tend to overemphasize a single aspect, namely environmental concern or economic development. Rather these aspects deserve to be considered on an equal footing if one's higher aim is sustainable development.

In order to establish an area of compromise, the Tolerable Windows Approach (TWA) tries to capture the concerns of both environmentalists and economic growth advocates by simultaneously placing constraints on environmental impacts and on mitigation costs. Hence, in order to avoid a single criteria fixation, the TWA does not adopt one or other minimization paradigm. Consequently, typical output from TWA applications does not recommend a single emissions path. Instead, the approach provides a bundle of emissions paths within these predefined constraints. In this study, we determine emissions corridors which contain all admissible emissions paths. These emissions corridors display a necessary condition for the admissibility of emissions paths with respect to the set of normative constraints – the guard-rails. Every path which leaves the corridor is clearly not admissible. Conversely, due to the presence of internal restrictions, not every arbitrary path remaining within the corridor is necessarily admissible. The TWA was proposed by the German Advisory Council on Global Change in 1995 (WBGU, 1995). Methodology-oriented publications include: Petschel-Held et al. (1999), Bruckner et al. (1999), and Bruckner et al. (2003b). Illustrative applications of the TWA are discussed in: Tóth et al. (2002), Tóth et al. (2003a), Tóth et al. (2003b), Zickfeld and Bruckner (2003), and Kriegler and Bruckner (2004).

In order to derive a numerical approximation for the upper (or lower) boundary of an emissions corridor for a given guard-rail set, annual emissions are maximized (or minimized) subject to this set of constraints subsequently for every year over the nominated time-horizon and in accordance with the chosen discretization scheme. Usually, the relevant optimization is repeated every 10 years (Bruckner et al., 2003b). In order to depict this procedure, exemplary emissions paths which maximize annual emissions for selected years (2040, 2100, 2160) are shown in Figure 1. The entire upper boundary depicted is the envelope of all emissions paths which maximize emissions at some point in time. In order to be admissible, it is not sufficient for these emissions paths to fulfill the prescribed constraints at the year chosen for maximization. Rather, the emissions paths must obey all constraints during the entire time horizon. Finally, the time span for which emissions corridors are depicted ends at the year 2200, although the actual model runs terminate in 2400. The latter value is sufficiently large to account for the temperature response (time constant) of the oceans and sufficiently small to hold the model numerically tractable.

In a Ramsey-type optimal growth model, welfare maximization determines capital stock evolution and output generation. Eq. 2 remains valid in order to calculate output for given inputs of capital and labor in a diagnostic way, but the overall economic evolution might show an artificial behavior if welfare optimization is replaced in favor of minimizing mitigation costs or maximizing annual emissions at specific points in time, as is done as part of the corridor calculation scheme. The economic equations contained in DICE, therefore, had to be supplemented by additional restrictions to guarantee a meaningful economic development path. In order to avoid wildly fluctuating capital stocks and strongly varying capital/labor ratios, the following restrictions were imposed on the evolution of capital stock within the economy:

$$\dot{K}(t) \geq 0, \ \ \ddot{K}(t) \geq 0. \tag{8}$$

As a result, capital stock is forced to increase with a positive curvature. For instance, both exponential growth and linear growth (the latter as a limiting case) would comply. Hence, the model is not allowed to artificially increase capital stock in order to maximize emissions at a specific point in time and to rapidly reduce capital stock thereafter in order to collapse emissions.

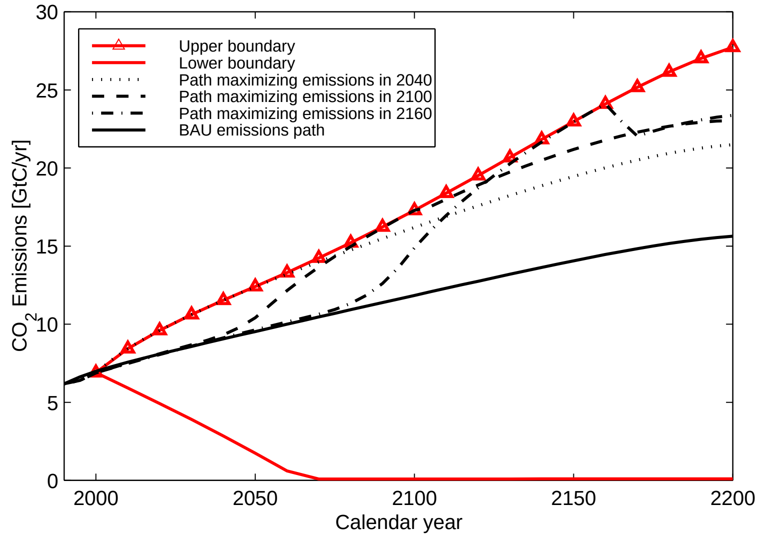

Figure 1. Emissions corridors — being the area between upper and lower boundaries — for standard parameter settings (see Table I). As an illustration of its internal structure, we show paths which maximize acceptable CO_2 emissions in 2040, 2100, and 2160. For comparison, we also display the reference (business-as-usual) emissions path which is the 'no controls baseline' obtained by applying the DICE model without climatic and welfare loss constraints.

4. Normative Guard-rails and Model Calibration

4.1. Normative Guard-rails

Various climate change and climate change impact indicators (including global mean temperature change, rate of temperature change, CO_2 concentrations, sea level rise, loss of protected areas, and loss in agricultural yield) have been used in different applications of the TWA applied in order to constrain the impacts of gradual global climate change (cf. Tóth et al.,2002).

In order to improve development transparency, our study focuses on one indicator only for use as a climate-related guard-rail — namely, THC stability. The prescribed goal of preventing THC collapse is implemented by constraining the Atlantic overturning flow rate $m(t)$ to remain above a critical value $m_{\min}$

$$m(t) \geq m_{\min} \quad \forall t. \tag{9}$$

Under equilibrium (steady-state conditions) $m_{\min}$ corresponds to half of the initial overturning (cf. Rahmstorf, 1996) and is given as 11.4 Sv in our box model.[6] Here we set the minimum admissible flow rate to 10 Sv in order to accommodate transient effects.

Popular expectations about a socio-economically acceptable pace of emissions reductions efforts are expressed by two conditions constraining (1) welfare losses and (2) the rate of increase of emissions reduction control, as follows.

An economic indicator l is used to constrain mitigation costs. It is defined by the associated percentage welfare losses measured relative to welfare W_{RC} in the reference case

$$l = \frac{W_{\mathrm{RC}} - W}{W_{\mathrm{RC}}} \leq l_{\max}. \tag{10}$$

Later sensitivity investigations use values of $l_{\max}$ between 0.2–4.0 %.

Consideration of the economic equations within *dimrise* reveals that capital invested in the energy sector is not modelled explicitly. Consequently, any premature decommissioning of energy sector capital (asset stranding) due to the rapid transition to an economy with considerably less CO_2 emissions and any associated costs (or benefits) of this transformation are not included in the economic module. In addition, other obstacles, for instance restricted uptake rates on new technologies, are likewise not directly taken into account.

In order to represent these effects in an admittedly somewhat *ad hoc* manner, the emissions control level $\mu(t)$ is not allowed to increase faster than some prescribed value

$$0 \leq \dot{\mu}(t) \leq \dot{\mu}_{\max} \tag{11}$$

Furthermore, in order to avoid artificial oscillations in the emissions control level, $\mu(t)$ is not allowed to decline.

The last decade of the 20^{th} century brought a rapid decline in CO_2 emissions for Germany (Ziesing, 2003). Initially, this was due to a reduction of output within the former East Germany (sometimes called "wall fall profits"). Later, the emissions levels were further reduced by massive investments in energy sector infrastructure. These events then raise the question of just how much of the (temperature adjusted) emissions reduction of 15.7 % in 2002 relative to the 1990 baseline was due to autonomous improvements in economy-wide carbon intensity and how much can be attributable to purposeful policy intervention.

[6] 1 Sv (Sverdrup) corresponds to 10^6 m^3/s.

This question cannot be easily resolved. In order to obtain a rough estimate of how fast $\mu(t)$ might grow, we will, as a 'Gedankenexperiment', assume that the observed emissions reductions were achieved by intentional mitigation effort. The capability of German society to reduce emissions via active mitigation thus derived might well be overestimated and hence act as an upper bound to similar efforts in other parts of the world. Neglecting the increase of gross domestic product between 1990 and 2002, $\mu(t)$ increased by 1.33 %-Points per year on average and, taking output growth into account, by 2.40 %-Points per year. In the sensitivity analysis presented, the maximum admissible growth rate $\dot{\mu}_{\max}$ will be varied between 0.5 and 2.5 %-Points per year.

4.2. Standard Model Parameters

The standard model calibration parameters and the default guard-rail values are summarized in Table I.

Table I. Standard and default parameter values. Note that 1 Sv corresponds to $10^6\,m^3/s$.

Parameters		
Standard model calibration parameter values		
Initial THC overturning (historical)	m_{init}	22.8 Sv
Regional temperature constant (northern)	p^{NH}	1.07
Hydrological sensitivity (North Atlantic)	h_2	$0.03\,\text{Sv}^\circ\text{C}^{-1}$
Climate sensitivity	$T_{2\times CO_2}$	2.5 °C
Default normative guard-rail values		
Atlantic overturning flow rate – lower bound	$m_{\min}$	10 Sv
Overall welfare loss – upper bound	$l_{\max}$	2.0 %
Emissions control rate of change – upper bound	$\dot{\mu}_{\max}$	1.33 %-Pts/year

In all least-cost emissions path and emissions corridor computations, CO_2 emissions from land-use change and emissions of non-CO_2 greenhouse gases are assumed to follow the average of the four SRES marker scenarios (i.e. the average of A1, A2, B1, B2) (Nakićenović and Swart, 2000) until 2100, and then plateau. SO_2 emissions are linked to industrial CO_2 emissions (i.e. the control variable) assuming a global average desulfurization rate of 1.5% per year.

5. Results

5.1. Reference Case

The business-as-usual (BAU) reference case emissions path is depicted in Figure 1. In this case, the issue of global climate change is simply not considered — meaning that neither the impact of climate change on world gross product nor any mitigation costs are taken into account during the relevant *dimrise* run. This is achieved by disabling the appropriate elements within the model. Due to the modifications required to port the DICE equations to *dimrise* (see Sections 2.3), the BAU emissions path obtained is very similar, but not identical, to the reference (no controls) emissions path of DICE-99. It should be emphasized that DICE-99 exhibits considerably lower emissions than the respective emissions paths calculated using earlier DICE variants (Nordhaus, 1994, p. 87).

5.2. Least-cost Emissions Paths

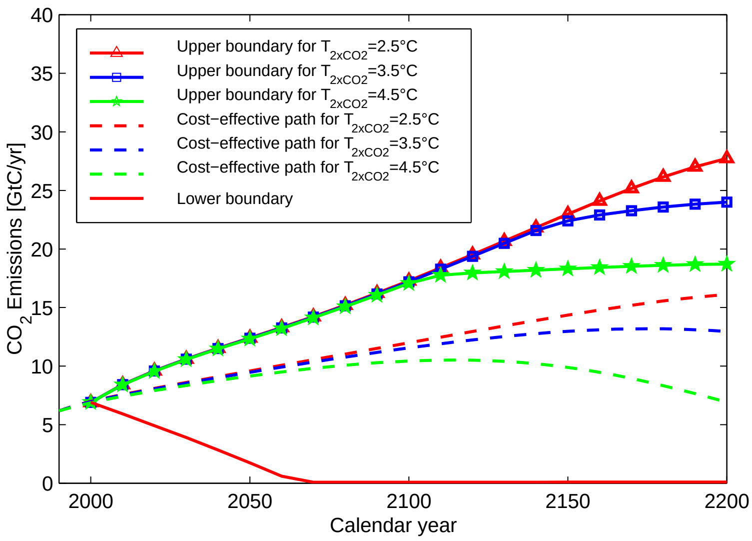

Figure 2. Emissions corridors for different values of climate sensitivity $T_{2\times CO_2}$ (with all other model parameters and guard-rails held at their standard values). The lower corridor boundary is the same for all values of $T_{2\times CO_2}$, as this is solely determined by the maximum emissions reduction rate.

Cost-effective emissions paths determined for $m_{\min} = 10\,\mathrm{Sv}$ and their sensitivity to different assumptions about climate sensitivity and hydrological sensitivity are shown in Figures 2 and 3, respectively.

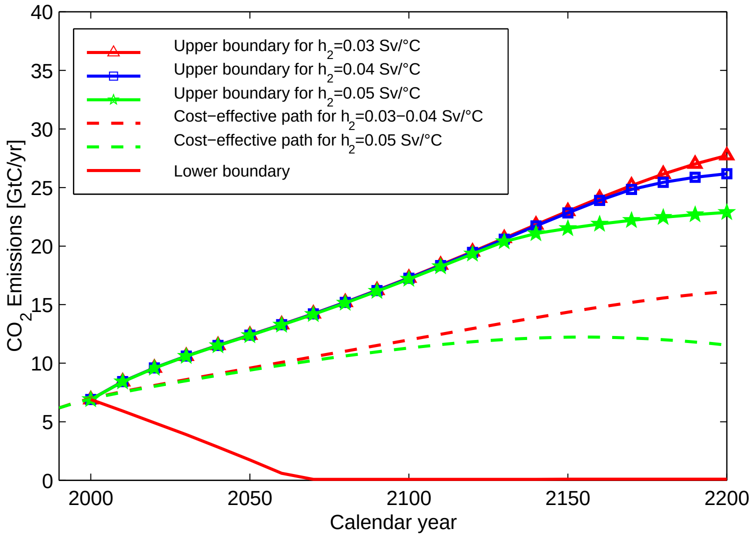

Figure 3. Emissions corridors for different values of the North Atlantic hydrological sensitivity h_2 (with all other model parameters and guard-rails held at their standard values). The lower corridor boundary is the same for all values of h_2, as it is solely determined by the maximum emissions reduction rate.

For standard model parameter values (see Table I), the cost-effective emissions path which maintains the THC does not deviate noticeable from the BAU emissions path — also used as the reference case. This same statement holds true for the lower climate sensitivity of $T_{2\times CO_2} = 1.5\,°C$ and hydrological sensitivities h_2 in the range between 0.01 and $0.04\,Sv°C^{-1}$.

For climate sensitivities higher than 2.5 °C, a moderate and a substantial deviation is observed for values of 3.5 °C and 4.5 °C, respectively. The moderate emissions control level of about 20 % in 2200 is in contrast to Keller et al. (2000), who determined an emissions control of more than 60% for the same climate sensitivity of 3.5 °C. This discrepancy results mainly from the fact that Keller et al. used an earlier version of DICE, namely DICE-95, which, under reference case conditions, shows considerably higher emissions than DICE-99 (Nordhaus, 1994, p. 87). Considering the magnitude of the actual emissions (expressed in GtC), both studies are in reasonable agreement.

The Keller et al. study indicates that CO_2 concentrations will reach their maximum admissible value of about 800 ppm within 100 years and remain largely constant thereafter. In our analysis, CO_2 concentrations increase linearly until 2300, peaking at approximately 1000 ppm, and gradually decline thereafter. The observed difference of about 200 ppm in the CO_2 maximum concentration level can be explained by the rate

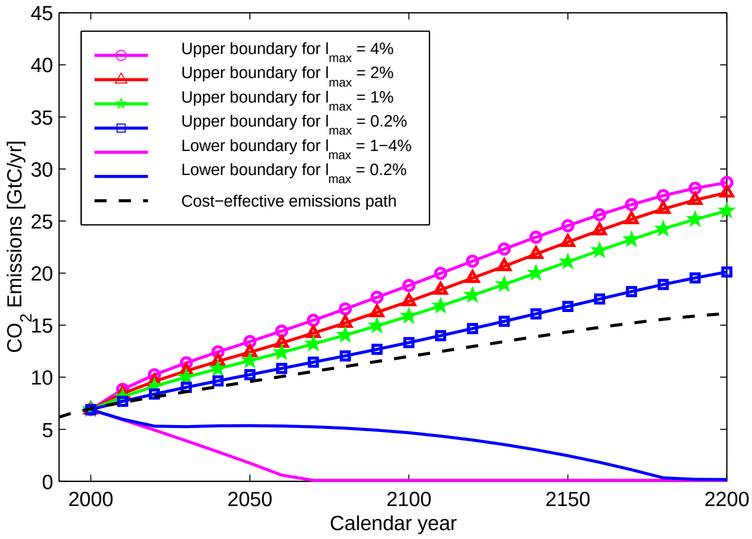

Figure 4. Emissions corridors for different values of the maximum admissible welfare loss $l_{\max}$ (with all other parameters and guard-rails held at their standard values).

dependency of the THC stability. As Stocker and Schmittner have shown (Stocker and Schmittner, 1997), the THC appears less stable under faster perturbations. As already pointed out, the Keller et al. study shows high initial (business-as-usual) emissions and an associated high initial rate of the CO_2 concentration increase. This then results in a lower final absolute CO_2 concentration limit compared to our maximum CO_2 concentration level. Although both approaches try to model the rate dependent behavior of the THC, they are technically quite different. Keller et al. use a rate dependent concentration ceiling derived from the Stocker and Schmittner study. In contrast, the dynamic THC module allows us to express the stability limit in terms of the maximum admissible THC weakening directly. This threshold is translated into a corresponding upper bound on global mean temperature change and further into a peaking concentration profile that observes the temperature bound. Earlier integrated assessment models that lack a fully dynamic representation of the THC are not capable to reflect this interesting aspect of cost-effective concentration trajectories.

5.3. Emissions Corridors

Emissions corridors calculated along the conceptual and methodological lines of the TWA (see Section 3.2) are presented in Figures 1 to 7.

As long as emissions control is not applied, emissions can exceed BAU emissions only where the capital stock grows faster than it would

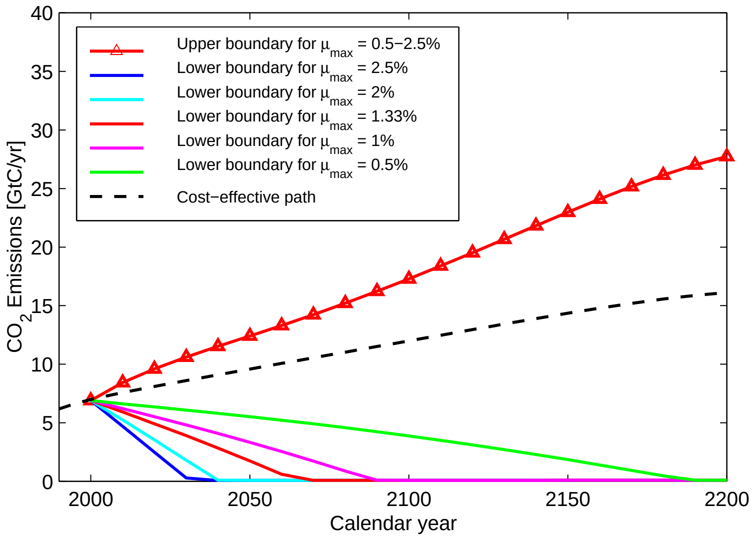

Figure 5. Emissions corridors for different values of the maximum emissions reduction rate $\dot{\mu}_{\max}$ (with all other model parameters and guard-rails held at their standard values).

with BAU. As output can only be spent once, more investment implies less consumption resulting in less utility and reduced welfare. The upper boundary of the emissions corridor depicted in Figure 1, which exceeds the BAU emissions path, is consequently a direct result of the welfare loss constraint specified for the standard case ($l \leq 2.0\,\%$). The lower boundary, in contrast, reflects the imposed maximum admissible increase in the emissions control level ($\dot{\mu} \leq$1.33 %-Points per year).

The sensitivity (all other parameters and guard-rails being held at their standard values) of the upper and lower boundary to changes in the admissible welfare loss are depicted in Figure 4. The influence of varying the maximum emissions control level increase is shown in Figure 5. As can be seen, decreasing $\dot{\mu}_{\max}$ has a significant influence on the lower corridor boundary. In the range considered, the upper boundary does not change. For high values of climate and hydrological sensitivities (cf. Figure 7), however, the upper boundary exhibits a significant influence of the admissible increase in the emissions control level.

The implications of alternative expectations concerning the climate sensitivity $T_{2\times CO_2}$ and hydrological sensitivity h_2 are depicted in Figures 2 and 3. Increasing $T_{2\times CO_2}$ from 2.5 to 4.5 °C considerably reduces the size of the emissions corridor in the 22^{nd} century. A relaxation of $T_{2\times CO_2}$ to 1.5 °C does not alter the emissions corridor. This indicates that the upper boundary in the standard case is effectively defined by economic constraints only. The influence of changing h_2 in the range considered is qualitatively comparable, but quantitatively less pronounced. In the range between 0.01 and $0.03\,\mathrm{Sv}°\mathrm{C}^{-1}$, no difference to the emissions corridor relative to the standard case can be detected.

Relative to an earlier study by the authors (Zickfeld and Bruckner, 2003), the emissions corridors are considerably narrower — particularly during the first decades of the 21st century. The reason for this is that the present study embeds a more realistic representation of the socio-economic sphere which prevents emissions from rising too sharply. The maximum welfare loss guard-rail now limits the rate of capital accumulation because a proportion of economic output has to be consumed rather than invested.

5.4. Low Risk Least-Cost Emissions Paths and Emissions Corridors

The sensitivity analyzes presented thus far modified one parameter whilst keeping all other parameters at their standard values (see Table I). In order to investigate the risks associated with *combined* uncertainties, a 'climate-related worst-case' was formulated. Concerning climate sensitivity, this case adopts the uncertainty band currently provided by the IPCC, namely a climate sensitivity range between 1.5 and 4.5 °C (Cubasch and Meehl, 2001). With respect to the hydrological sensitivity, a range between 0.01 and 0.05 Sv/°C provided by Rahmstorf and Ganopolski (1999) is taken into account. Our climate-related worst-case is thus characterized by the setting $T_{2\times\mathrm{CO}_2} = 4.5\,°\mathrm{C}$ and $h_2 = 0.05\,\mathrm{Sv}°\mathrm{C}^{-1}$. Staying within the emissions corridors determined for the worst-case reduces the risk of an anthropogenically induced THC breakdown considerably. It must be emphasized, however, that recent estimates exist, where the uncertainty range for climate sensitivity is extended considerably towards higher values (e.g., Forest et al., 2002; Andronova and Schlesinger, 2001).

The sensitivity of the climate-related worst-case least-cost emissions path and emissions corridor to changes in the mitigation guard-rails, namely acceptable welfare loss and maximum emissions control level increase, are depicted in Figures 6 and 7, respectively.

In contrast to the least-cost emissions paths calculated for best guess sensitivities ($T_{2\times\mathrm{CO}_2} = 2.5\,°\mathrm{C}$ and $h_2 = 0.03\,\mathrm{Sv}°\mathrm{C}^{-1}$, see Figure 2), the worst-case least-cost path (see Figures 6 and 7, noting that this particular time-path is identical) does not allow one to follow the BAU path over the next two centuries. Instead, an immediate deviation from BAU is required followed by a substantial long lasting emissions reduction in order to avoid, in a cost-effective manner, a THC breakdown for high

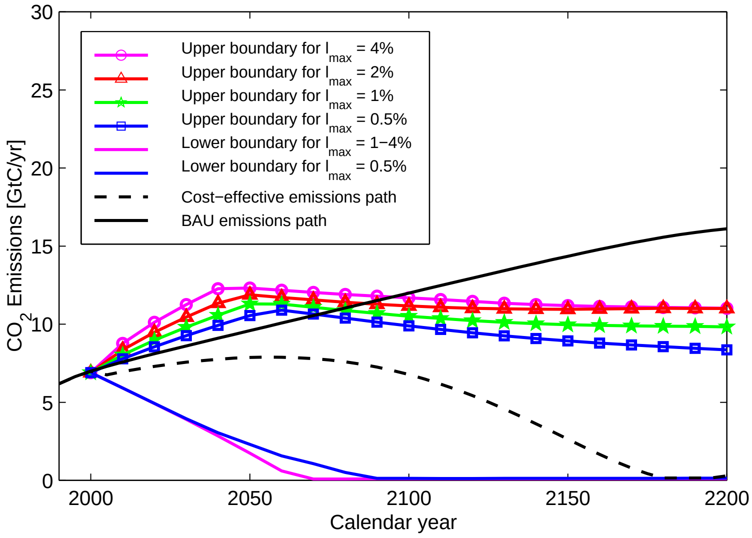

Figure 6. Least-cost emissions paths and emissions corridors for different values of the maximum admissible welfare loss $l_{\max}$ under worst-case conditions $T_{2\times CO_2} = 4.5\,^{\circ}\mathrm{C}$ and $h_2 = 0.05\,\mathrm{Sv}^{\circ}\mathrm{C}^{-1}$ (with all other model parameters and guard-rails are held at their standard values).

values of the climate and hydrological sensitivity. In that case, global emissions are not allowed to increase significantly beyond current levels and must finally drop to zero after a transition time of about 175 years.

In the climate-related worst-case, the BAU path exceeds the upper corridor boundaries for all admissible welfare losses from the range considered (see Figure 6). In all cases, the crossing of boundaries occurs before 2100, implying that — while taking the underlying restrictions into account — under BAU conditions a complete shut down of the THC might well be irrevocably triggered within the next 100 years. Notwithstanding, the consequences of this event might not be visible within that time frame due to inertia within the climate system.

It should be emphasized that the BAU path of DICE-99 (and correspondingly of *dimrise*) describes just one possible (non-intervention) scenario for world economic evolution discussed in the literature. Other, equally plausible business-as-usual scenarios including, for instance, the SRES (Special Report on Emissions Scenarios, Nakićenović and Swart, 2000) scenarios A1B, A1FI, A2, and B2, substantially exceed the moderate DICE-99 BAU emissions scenario — with some (A1FI and A2) exhibiting twice the emissions value of the DICE-99 BAU path in 2100. If world economy does initially unfold according to these high emissions scenarios, a preservation of the THC might well require an effective emission reduction already within the next 20 to 30 years.

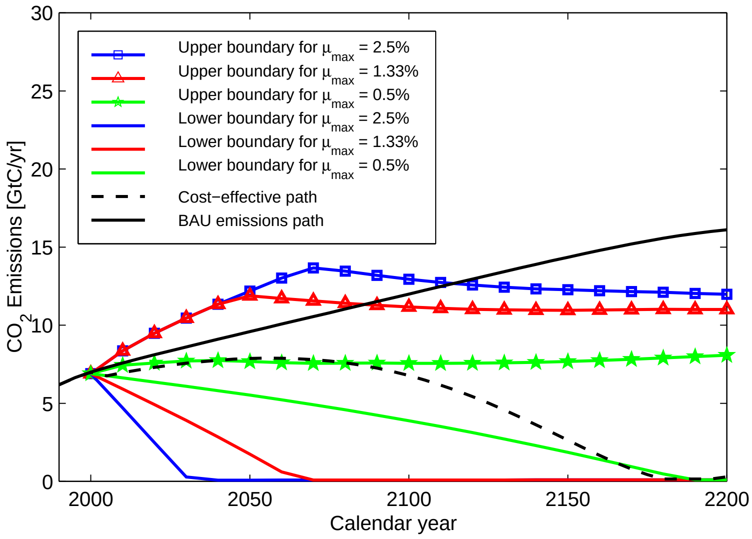

Figure 7. Emissions corridors for different values of the maximum emissions reduction rate $\dot{\mu}_{\max}$ under worst-case conditions $T_{2\times CO_2} = 4.5\,^{\circ}\mathrm{C}$ and $h_2 = 0.05\,\mathrm{Sv}^{\circ}\mathrm{C}^{-1}$ (with all other model parameters and guard-rails are held at their standard values).

Moreover, under climate-related worst-case conditions, even the moderate BAU path determined by *dimrise* transgresses the corridor boundary within the next two decades, if the admissible emissions control level increase $\dot{\mu}$ is restricted to 0.5 %-Points per year (see Figure 7). In accordance with the concept of the TWA, this does not mean that, in this case, a breakdown of the THC is inescapable due to the inertia of the climate system solely. After some decades without effective climate protection, the restricted mitigation capabilities of societies (expressed in our analysis in terms of maximum admissible welfare loss and maximum emissions control level increase) simply might not allow to decrease emissions fast enough to prevent a THC break-down.

A comparison of Figures 6 and 7 shows clearly that — for the economic guard-rail ranges considered — the overall sensitivity of the upper corridor boundary to changes in the admissible welfare loss $l_{\max}$ is small compared to changes in the admissible rate of emissions reduction $\dot{\mu}_{\max}$. The admissible welfare loss reflects normative decisions concerning the amount that societies (in aggregate) are 'willing-to-pay' to protect the THC, whereas the upper bound on the rate of emissions control increase is a result of both willingness to reduce emissions fast and the technical ability to do so. Both aspects are influenced, in turn, by social processes and technical progress, which may both well change or accelerate in light of new information on the level of threat posed by global climate change.

Enhancing the capability of societies to realize high emissions reduction rates, for instance $\dot{\mu}$ =2.5 %-Points per year, considerably broadens the worst-case emissions corridors (see Figure 7). Consequently, broadening of the technological options at hand to achieve this goal might prove to be a cornerstone of any precautionary effort to safeguard the stability of the THC.

6. Summary and Outlook

Simulation studies reveal that the Atlantic THC is sensitive not only to atmospheric CO_2 concentrations, but also to the rate of associated temperature change. For a given CO_2 emissions trajectory, the future evolution of the THC depends strongly on uncertain parameters including the climate sensitivity, the North Atlantic hydrological sensitivity, and the pre-industrial rate of Atlantic overturning. Due to the complexity of the phenomenon involved and the difficulty of making accurate characterizations, and despite the importance of the THC for climate change policy-making, established integrated assessment models rarely include a fully dynamic representation of the Atlantic thermohaline circulation capable of investigating THC stability issues.

The presented integrated modeling framework *dimrise* (*d*ynamic *i*ntegrated *m*odel of *r*egular climate change *i*mpacts and *s*ingular *e*vents) comprises (1) a dynamic model of the Atlantic THC coupled to (2) a reduced-form climate model and (3) a global economy model for assessing the monetary cost of climate protection. The THC model is a dynamic four-box interhemispheric extension of the classic Stommel model — a conceptual model that has been successfully applied to the investigation of THC stability. This reduced-form box model was calibrated using results from the climate model CLIMBER-2 — a model of intermediate complexity that is suitable for investigating the dynamic behavior of the THC. The aggregated climate model used to drive the THC model is the ICLIPS multi-gas climate model — a computationally efficient, globally aggregated model able to mimic the response of more sophisticated carbon cycle and atmosphere-ocean general circulation models. The THC and climate modules are coupled with a globally aggregated Ramsey-type optimal growth model of the world economy derived from the Nordhaus DICE model. Together, these components create a novel computationally efficient integrated assessment model. Consequently, the overall model is well suited to undertake an extensive uncertainty analysis investigating both, the strength of the THC and the associated mitigation costs.

All three components are written in GAMS. The resulting optimization model identifies cost-effective greenhouse gas emissions paths that satisfy a prescribed minimum rate of Atlantic overturning. In addition, emissions corridors are presented that delineate the set of all admissible CO_2 emissions paths that do not endanger the stability of the THC and, simultaneously, do not transgress prescribed (normative) bounds on welfare loss originating from the associated emissions mitigation burden.

For current best-guess values of climate and hydrological sensitivity, the least-cost emissions path safeguarding the THC would not be forced to deviate from the business-as-usual emissions path. Considering higher but still plausible values of the climate and hydrological sensitivities indicates that a substantial long-term emissions reduction is required in order to preserve the THC in a cost-effective manner. Under these worst-case conditions, the (relatively moderate) business-as-usual emissions path would leave the emissions corridor within the next two decades (assuming worldwide mitigation capabilities remain low). And although a THC breakdown would not be observed immediately, this event may well be inescapable due to a combination of climate system inertia and insufficient emissions mitigation capabilities. Improving mitigation capability can broaden the emissions corridor considerably. Hence, increased efforts to enhance the worldwide mitigation potential should be a cornerstone of any strategy to safeguard the Atlantic thermohaline circulation specifically and global climate processes more generally.

With a view to the complexity of the THC issue and our ignorance about its many aspects, the analysis presented should be interpreted as a first step towards a comprehensive sensitivity analysis of the THC stability issue which covers both the inertia and nonlinear character of the climate system and the restricted flexibility of the economic system. As such, the results are subject to numerous caveats.

For example, we have not discussed the sensitivity of the results to different assumptions regarding the initial strength of the THC overturning. Also, we have limited our sensitivity analysis to the range of climate sensitivities proposed by the IPCC, although recent studies suggest that this range could be much broader (Forest et al., 2002; Andronova and Schlesinger, 2001). Given the uncertainty in parameter values which might lead to abrupt and potentially irreversible climate change, a risk management approach whereby the THC guard-rail is expressed in probabilistic terms ("limit the risk of a THC collapse to x %") could prove useful . We are currently developing a probabilistic version of the Tolerable Windows Approach that is able to output the respective emissions corridors on the basis of probability density functions for the key parameters (climate sensitivity, hydrological sensitivity, and the initial strength of the THC). Preliminary investigations using just climate sensitivity suggest that the emissions corridors become very narrow if only low breakdown probabilities are sought (Zickfeld et al., 2003; Rahmstorf and Zickfeld, 2005).

The Innovation Modelling Comparison Project (ICMP) has recently shown that the costs of climate protection might have been substantially overestimated by economic models that do not embed endogenous technological learning (Edenhofer et al., 2006). Furthermore, the combination of large-scale bioenergy usage with carbon capture and sequestration (BECS) is attracting increasing attention as a promising mean of enhancing world wide emissions mitigation capacity (Read and Lermit, 2005; Obersteiner et al., 2001). In order to provide robust policy recommendations, instead of the proof-of-concept application presented here, future applications of *dimrise* will therefore need to take into account both technological learning and the potential of negative emissions using BECS technologies.

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