Inverse Integrated Assessment of Climate Change: the Guard-rail Approach

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Abstract. The paper provides a comprehensive review of the tolerable windows approach (TWA, also known as the guard-rail approach). The TWA can now be considered mature from a conceptual and methodical point of view. Concerning conceptual aspects, its relationship to the most important competing approaches (e.g., scenario analysis, multi-criteria-analysis, cost-benefit analysis, and cost-effectiveness analysis) is clarified. Methodically, the deterministic variant was recently supplemented by a probabilistic extension.

As part of an illustrative application of the TWA, emissions corridors are derived that constrain the risk of a break-down of the thermohaline circulation (THC) to a prescribed level. In order to achieve this goal, the integrated assessment model *dimrise* is used. This model comprises a globally aggregated multi-gas climate module that is linked to a dynamic THC model. For assessing the monetary costs of climate protection, both components are supplemented by a model of the world economy. A potential instability of the THC is taken into account via subjective probability distributions relating the probability of THC collapse to the change in global mean temperature in 2100. Our results indicate that the point of no return for a possible break-down of the THC with more than 3% probability could be crossed within two decades if a business-as-usual emissions path is followed.

Keywords: integrated assessment, tolerable windows approach, guard-rail approach, cost-benefit analysis, cost-effectiveness analysis, climate change, emissions corridors, thermohaline circulation

Abbreviations: BAU – business-as-usual; IAM – integrated assessment model IPCC – Intergovernmental Panel on Climate Change; THC – thermohaline circulation; TWA – tolerable windows approach

1. Introduction

After more than two decades of intensive research, global climate change nowadays is generally considered to pose a serious threat to the future well-being of mankind (Solomon et al., 2007; Parry et al., 2007). Unfortunately, numerous features of the global climate change problem aggravate the development of an appropriate response strategy (Halsnas and Shukla, 2007): climate change is the result of the development of a complex network of various interacting cause-effect chains with numerous feedbacks. Many of these chains are characterized by nonlinearities and potential irreversibilities (Schneider et al., 2007; Lenton et al., 2008). There is still a huge uncertainty concerning the science of climate change, its potential impacts, and suitable options to mitigate or adapt (Metz et al., 2007). The distribution of potential impacts is inhomogeneous in space and time. Even worse, there is a substantial time lag between causes (greenhouse gas emissions, land-use change, etc.) and effects (climate impacts) ranging from decades to millennia (Meehl and Stocker, 2007). And finally, climate change is a global problem that invites free-riding behavior.

As a result, the design of a responsible climate policy obviously requires scientific advice (Halsnas and Shukla, 2007). In order to capture the aforementioned characteristics, this advice should be based on integrated assessment models (IAM) that are especially designed to take into account the interrelationship between the various subsystems involved (Schellnhuber et al., 2004): the energy and agricultural sectors of the emitting societies, the climate system, and the natural and social systems affected by climate impacts. In general, integrated assessment models are capable of providing a temporally resolved description of the expected evolution of the combined anthroposphere-climate system. Although the majority of the models is still restricted to impacts of gradual climate change (such as changing water availability, modified agricultural yield, sea-level rise, altered frequencies of extreme events, and changing ecosystems), some models nowadays are also capable of assessing the risk of singular events – also referred to as abrupt climate change (Keller et al., 2000; Zickfeld and Bruckner, 2003; Keller et al., 2004; Yohe et al., 2006; McInerney and Keller, 2007; Zickfeld and Bruckner, 2008; Bruckner and Zickfeld, 2008). In addition, first efforts are made to capture parametric uncertainty by using probabilistic distributions of the most important uncertain parameters involved (Zickfeld et al., 2003; Keller et al., 2004; Rahmstorf and Zickfeld, 2005; Yohe et al., 2006; McInerney and Keller, 2007).

Applied as part of a *scenario analysis*, integrated assessment models are used in the so-called *forward mode*. Within that mode, a climate protection strategy is defined and its consequences in terms of (remaining) climate impacts and associated mitigation costs are calculated. Technically seen, the integrated assessment models applied in this case are *simulation models* (Alcamo, 1994; Alcamo and Kreileman, 1996; Alcamo et al., 1998).

A different approach is to define the objective first and to derive the associated climate protection strategy subsequently. Applied in an *inverse mode*, the respective IAM are necessarily *optimization models*. Which objective is used depends on the selected decision-making framework. The most prominent frameworks (and associated objectives) are cost-benefit analysis (maximization of global welfare – cf. Nordhaus, 1992; Nordhaus and Boyer, 2000) and cost-effectiveness analysis (minimization of mitigation costs subject to climate protection goals – such as, for instance, concentration or temperature constraints – cf. Wigley et al., 1996). In the year 1995, the German Advisory Council on Global Change proposed a supplementary approach (WBGU, 1995) – the tolerable windows approach (TWA). In a nutshell, the main idea of the TWA can be described as follows: The TWA starts with an explicit normative definition of constraints (the guardrails) that are intended to exclude both, intolerable climate impacts on the one hand and unacceptable socioeconomic consequences of mitigation measures on the other. Following from this, a scientific analysis of the pertinent causal relationships of the anthroposphere-climate system is carried out in order to investigate the main features of the set of all climate protection strategies that are compatible with the guardrails. In the last ten years, the TWA – nowadays preferably called *guard-rail approach* – has been further developed by a group of researchers mainly associated with the Potsdam Institute for Climate Impact Research (PIK), Potsdam and the Institute for Energy Engineering at the Technical University in Berlin. The paper provides a contemporary review of the current development state of this approach. The review reveals that the approach now can be considered mature in the sense that the main conceptual and methodical problems were solved and interesting application to gradual and abrupt climate change were carried out. In the following, important conceptual and methodical aspects of the guard-rail approach are summarized. In addition, an illustrative application is presented which investigates the stability of the North Atlantic current. Further applications of the TWA are discussed in: Tóth et al. (2002), Tóth et al. (2003a), Tóth et al. (2003b), Zickfeld and Bruckner (2003), Kriegler and Bruckner (2004), and Zickfeld and Bruckner (2008).

2. Conceptual Aspects

From a conceptual point of view, the guard-rail approach comprises three steps: (1) a prescription of explicitly normative guard-rails (constraints) that cover both, intolerable climate impacts and socio-economically unacceptable mitigation costs, (2) a subsequent scientific analysis of the relevant and interconnected elements of the Earth system, including: ecosystems, the climate system, and the global socioeconomic system, (3) a calculation of the set of all policy paths that meet the constraints by applying a suitable integrated assessment model.

Various papers discuss the relationship between the TWA and competing approaches (Petschel-Held et al., 1999; Bruckner et al., 1999; Bruckner et al., 2003b). In order to facilitate climate change decision-making, the TWA seeks to bring together the core elements of various other approaches to assess the implications of long-term climate protection goals: the concept of guardrails is taken from the cost-effectiveness analysis (cf. Wigley et al., 1996) and motivated by the successful application of the critical loads concept to various environmental problems (cf. Hettelingh et al., 1995); the emphasis on different impact categories refers to multi-criteria analysis (Paruccini,1994); and the simultaneous consideration of climate damage and emission mitigation burden is a key element of cost-benefit analysis (Nordhaus, 1994; Nordhaus and Boyer, 2000; Manne et al., 1995). Finally, the burden of normative specifications and final assessments stays with the policy-makers – a feature which is shared with most scenario analyses (Alcamo, 1994; Alcamo et al., 1998).

Despite the aforementioned similarities, the conceptual basis of the TWA differs substantially from the standard policy optimization approach as employed in the context of cost-benefit analysis or cost-effectiveness analysis. Instead of identifying an optimal policy with respect to a particular welfare function, the TWA aims at identifying a policy leeway for prescribed guardrails. This policy guidance approach is motivated by the peculiarities of the climate change issue such as, to name just two of them, the possibility of critical impact levels and the contentious issue of aggregating across time, space and valuation categories to arrive at a scalar utility measure (for a detailed discussion see Helm et al., 1999).

A detailed comparison of the TWA with the cost-benefit analysis (CBA) can be found in (Bruckner et al., 1999). Here we would like to focus on its relationship with the cost-effectiveness analysis as both approaches are very similar. Within the cost-effectiveness approach, mitigation cost are minimized subject to climate protection constraints (e.g., concentration or temperature thresholds). In determining the respective least-cost climate protection path, the integrated assessment model seeks to exploit any opportunity to decrease mitigation costs. Consequently, if meeting the climate protection goal requires a deviation from the business-as-usual (BAU) evolution, then the feasibility domain provided will be completely utilized in the sense that the system will eventually strike at least one climate-related guard-rail. This, however, is not a particularly prudent approach, especially in cases where both the threshold guard-rails and the model calibration parameters are subject to substantial uncertainty. With a view to the potentially irreversible character of climate change, seeking to follow a least-cost emissions path derived from uncertain model results would be a very risky strategy.

Facing the sometimes huge parametric as well as structural uncertainties involved, one might be tempted to reduce CO_2 emissions as far as this 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 tries to capture the concerns of both environmentalists and economic growth advocates by simultaneously placing constraints on environmental impacts and on mitigation costs. Hence the TWA does not adopt the one or the other minimization paradigm described above. Consequently, typical output from TWA applications does not recommend a single emissions path. Instead, the approach provides a bundle of emissions paths within predefined constraints. In this paper, we will present emissions corridors which contain the aforementioned admissible emissions paths. A method that is capable of calculating emissions corridors is discussed in the following.

3. Methodical Aspects

The methodological foundation for the derivation of corridors in the framework of the TWA was presented in (Petschel-Held et al., 1999; Bruckner et al., 1999; Bruckner et al., 2003b). In general, corridors can be calculated for any component of the state vector $\boldsymbol{x}$ (e.g., global mean temperature changes) or control vector $\boldsymbol{u}$ (e.g., annual emission rates) of the coupled anthroposphere-climate system modelled by a set of ordinary differential equations

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}(t), \boldsymbol{u}(t), t) \tag{1}$$

A corridor $\mathrm{Cor}(y, t)$, with y being a particular control or state variable, represents the range of values of y generated by the bundle of *admissible* system futures $(\boldsymbol{x}(\cdot), \boldsymbol{u}(\cdot))$ which observe the predefined guardrails modelled as a set of inequalities

$$\boldsymbol{h}(\boldsymbol{x}(t), \boldsymbol{u}(t), t) \leq 0 \quad \forall\, t\,. \tag{2}$$

An emissions corridor $\mathrm{Cor}(E, t)$ is the picture that we get if we plot all admissible control paths $\boldsymbol{u}(\cdot)$ and their resulting state trajectories $\boldsymbol{x}(\cdot)$ simultaneously, and project this set of points onto the subspace spanned by emissions E and time t . Thus, an emissions corridor comprises the set of all admissible emissions values at any time. However, corridors do not contain information about the dynamics of the system, i.e. which of the admissible points are connected by admissible paths. The loss of information results in the important fact that not every conceivable path lying within the corridor does necessarily observe all guardrails. We can only say for sure that every path leaving the corridor does necessarily violate at least one guardrail. Figure 1 gives an impression of the inner structure of emission corridors (Kriegler and Bruckner, 2004).

If a corridor is simply connected, it has a connected boundary that determines its size and shape. This boundary can be computed for emissions corridors in a rather simple and efficient manner by subsequently maximizing and minimizing the emissions for fixed values in time (Bruckner et al., 2003b; Leimbach and Bruckner, 2001).

$$\text{Maximize (Minimize)} \quad \Phi_{\hat{t}} \equiv u_{\text{Emissions}}\big|_{t=\hat{t}} \tag{3}$$

subject to the dynamical constraint

$$\dot{\boldsymbol{x}}(t) \;=\; \boldsymbol{f}(\boldsymbol{x}(t), \boldsymbol{u}(t), t) \quad \forall t \in [t_o, t_{\text{end}}] \quad ,$$

the initial condition $\boldsymbol{x}(t_o) \;=\; \boldsymbol{x}_o$ and the additional constraints provided by the predefined guardrails

$$\boldsymbol{h}(\boldsymbol{x}(t), \boldsymbol{u}(t), t) \;\leq\; 0 \quad \forall t \in [t_o, t_{\text{end}}] \quad \cdot$$

Eq. 2 secures that the prescribed guard-rails are not violated under any circumstances. Given the still existing uncertainty in key parameter values, e.g. the climate sensitivity which might well exhibit high values

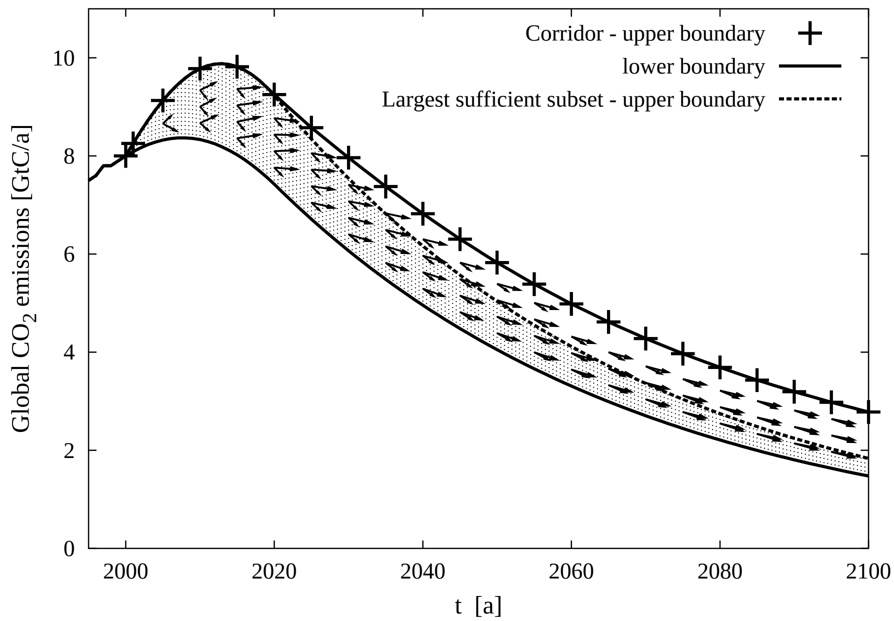

Figure 1. Inner structure of an emissions corridor that observes the following guard-rails: maximum global mean temperature change: 2 °C, maximum emissions reduction rate: 2% per year, minimum transition time to a decarbonizing economy: 20 years. Shown are the largest sufficient subset (dotted area, confined by the two paths minimizing emissions for all points in time and maximizing cumulative anthropogenic emissions in the year 2100) and the tangent cones of admissible emissions paths for several points in the corridor (Kriegler and Bruckner, 2004).

albeit with a low probability (cf. Figure 2), it might not always be able to completely exclude a violation of the guard-rail. In order to take this important aspect into account, a probabilistic version of the TWA was developed (Zickfeld et al., 2003; Rahmstorf and Zickfeld, 2005; Kleinen, 2005; Kleinen et al., 2008).

Within this risk-oriented approach, Eq. 2 is replaced by

$$P(\boldsymbol{h}(\boldsymbol{x}(t), \boldsymbol{u}(t), t) \geq 0) \leq P_{\max} \quad \forall\, t\,, \tag{4}$$

where $P(\boldsymbol{h}(\boldsymbol{x}(t), \boldsymbol{u}(t), t) \geq 0)$ is the probability that the guard-rail is transgressed and $P_{\max}$ is the corresponding maximum admissible violation probability.

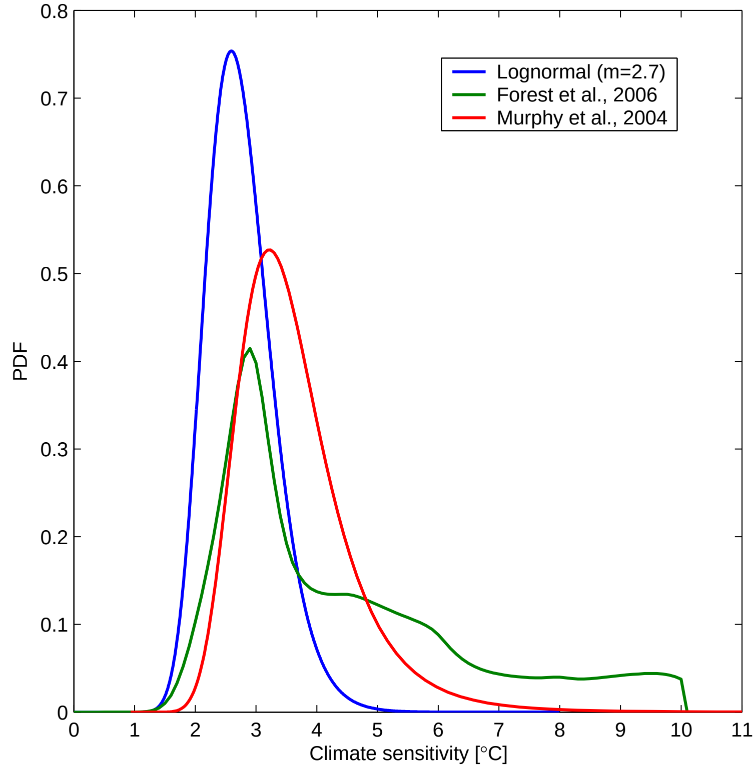

Figure 2. Probability density functions for climate sensitivity.

4. Illustrative Application: Safeguarding the Stability of the Thermohaline Circulation

Since the late 1980s (Broecker, 1987) changes in ocean circulation have increasingly been discussed as a possible risk associated with future anthropogenic climate change (Manabe and Stouffer, 1993; Stocker and Schmittner, 1997; Rahmstorf and Ganopolski, 1999). This discussion has mostly focussed on the Atlantic thermohaline circulation (THC) i.e. that part of the Atlantic ocean circulation which is driven by temperature- and salinity-dependent density gradients. Climate model simulations indicate that perturbation of the surface ocean density through freshening (reduction of salinity due to inflow of freshwater from precipitation, river flow or ice melt) and/or warming in response to anthropogenic climate change have the potential to halt the THC (Manabe and Stouffer, 1993; Stocker and Schmittner, 1997; Rahmstorf and Ganopolski, 1999). Reorganizations of the THC are believed to play an important role in rapid climate changes recorded in Greenland during the last glacial cycle (Dansgaard et al., 1993).

Of the comprehensive climate models used in the Fourth Assessment Report of the IPCC, none showed a complete shutdown of the THC in the 21st century (Meehl and Stocker, 2007). Elicitations of subjective probability distributions from experts, however, indicate higher probabilities of THC collapse than those reported in recent modelling studies (Zickfeld et al., 2007). Fig. 3 displays subjective probabilities that a collapse of the THC will occur or will be irreversibly triggered by the year 2100 given specific changes in global mean temperature. For a temperature increase of 4 K relative to the pre-industrial level, for instance, eight experts assess the probability of triggering a THC collapse as significantly different from zero and three of them as larger than 40%.

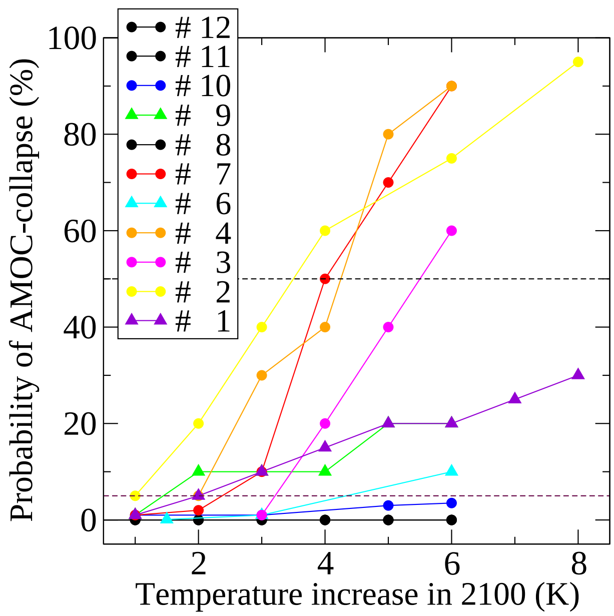

Figure 3. Elicited subjective probabilities "that a collapse of the THC will occur or will be irreversibly triggered" as a function of the global mean temperature increase realized in the year 2100. From Zickfeld et al. (2007).

In the following the TWA will be applied in order to support decision-making processes that intend to safe-guard the future stability of the THC. In order to achieve that goal, an integrated assessment model called *dimrise* (*d*ynamic *i*ntegrated *m*odel of *r*egular climate change *i*mpacts and *s*ingular *e*vents) is applied.

4.1. Model Description

The integrated modelling framework *dimrise* comprises (1) a dynamic model of the Atlantic THC coupled to a (2) reduced-form climate model and (3) a global economy model.

The THC module within *dimrise* is a four-box interhemispheric dynamic extension of the seminal Stommel (1961) model calibrated against results obtained with CLIMBER-2 — a 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 et al., 2004).

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

$$\Delta F(t) = h_2 \Delta T^{\mathrm{NH}}(t) = h_2 p^{\mathrm{NH}} \Delta T^{\mathrm{GL}}(t). \qquad (5)$$

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[1] h_2 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.

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 Meehl and Stocker (2007). For scenarios with higher climate forcing, the overturning 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). The reduced-form THC module itself, its implementation and

[1] 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 et al. (2004).

calibration, the results from transient experiments, and a variety of sensitivity analyses 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), Zickfeld and Bruckner (2008) and Bruckner and Zickfeld (2008).

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. 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).

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. We elected to use the economic relationships contained within the highly aggregated dynamic integrated climate and economy (DICE) model[2], 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.

The globally aggregated economic model DICE is a Ramsey-type optimal growth model.[3] 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 macroeco-

[2] Version DICE-99, see (Nordhaus and Boyer, 2000).
[3] The core model equations are given in (Nordhaus and Boyer, 2000) as Appendix B.

nomic scale, in the presence of exogenous technological change $A(t)$

$$Q(t) = \Omega(t)A(t)K(t)^{\gamma}L(t)^{1-\gamma}, \tag{6}$$

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.[4] 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 $C(t)$

$$Q(t) = I(t) + C(t). \tag{7}$$

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

$$\dot{K}(t) = I(t) - \delta K(t). \tag{8}$$

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

$$E(t) = [1 - \mu(t)]\sigma(t)Q(t). \tag{9}$$

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

$$\Omega(t) = 1 - b_1\mu(t)^{b_2} \tag{10}$$

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

$$W = \int_t R(t)L(t)\log c(t)dt \tag{11}$$

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

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

Due to the still existing uncertainty, we do not try to assess the damages of a potential break-down of the THC in monetary terms. Consequently, we did not carry out a cost-benefit analysis. In contrast, we derive either (constrained) optimal mitigation strategies that obey prescribed bounds on THC weakening or 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.

4.2. Normative Guard-rails

In the following, *dimrise* will be applied in two different settings: a deterministic and a probabilistic framework.

In the *deterministic case*, the prescribed goal of preventing a THC collapse is implemented by constraining the Atlantic overturning flow rate $m(t)$ to remain above a critical value m_{min}

$$m(t) \geq m_{\text{min}} \quad \forall t. \tag{12}$$

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.[5] Here we set the minimum admissible flow rate to 10 Sv in order to accommodate transient effects.

In the *probabilistic case*, the risk of a THC collapse is constrained. In order to achieve this goal, the probability $p(m(t) \leq m_{\text{min}})$ for a weakening of the THC that is below the critical value is not allowed to transgress a prescribed maximum risk level p_{max}:

$$p(m(t) \leq m_{\text{min}}) \leq p_{\text{max}} \quad \forall t. \tag{13}$$

Expectations about a socio-economically unacceptable pace of emissions reductions 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

$$l = \frac{W_{\text{RC}} - W}{W_{\text{RC}}} \leq l_{\text{max}}. \tag{14}$$

[5] 1 Sv (Sverdrup) corresponds to $10^6\ \text{m}^3/\text{s}$.

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

$$0 \leq \dot{\mu}(t) \leq \dot{\mu}_{\max} \tag{15}$$

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

4.3. Standard Model Parameters

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

Table I. Default parameter values. Note that 1 Sv corresponds to 10^6 m^3/s.

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 Sv°C^{-1}
Climate sensitivity	$T_{2\times CO_2}$	2.5 °C
Climate sensitivity probability distribution		lognormal
THC collapse probability distribution following		expert 1
Default normative guard-rail values		
Atlantic overturning flow rate – lower bound	$m_{\min}$	10 Sv
Admissible THC collapse probability – upper bound	$p_{\max}$	5 %
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 cost-effectiveness 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 4 (black solid curve). 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. [6]

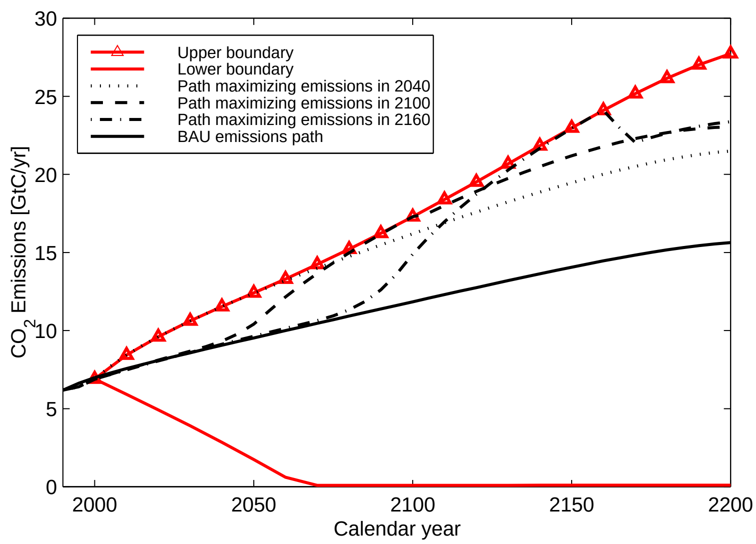

Figure 4. Emissions corridor — being the area between upper and lower boundaries — for standard parameter settings (see Table I). As an illustration of its internal structure, we show paths which maximize acceptable CO_2 emissions in 2040, 2100, and 2160. For comparison, we also display the reference (business-as-usual) emissions path which is the 'no controls baseline' obtained by applying the DICE model without climatic and welfare loss constraints.

[6] It should be emphasized that DICE-99 exhibits considerably lower emissions than the respective emissions paths calculated using earlier DICE variants (Nordhaus, 1994).

5.2. Constrained Optimal Emissions Paths and Emissions Corridors: the Deterministic Case

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 entire 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 4.

Figure 4 also displays the emissions corridor for standard model parameter values (Table I). It is shown that the BAU path lies entirely within the corridor. Also, the constrained optimal emissions path does not deviate noticeably from the DICE BAU path implying that emissions reductions would not be required to safeguard the THC under standard parameter settings. 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, deviation from these unsustainable development paths might well be required.

In order to investigate the overall risk originating from uncertainties in key model parameters influencing the future evolution of the THC, i.e. climate and hydrological sensitivity, a 'climate-related worst-case' is considered in the following. Concerning climate sensitivity, this case adopts the uncertainty band provided by Meehl and Stocker (2007), namely a "likely" climate sensitivity range between 2.0 and 4.5 °C [7]. 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 $T_{2\times CO_2} = 4.5\,^\circ\mathrm{C}$ and $h_2 = 0.05\,\mathrm{Sv}^\circ\mathrm{C}^{-1}$.

Figure 5 shows that the emissions corridor shrinks considerably under 'worst-case' assumptions for climate and hydrological sensitivity

[7] In the IPCC terminology, "likely" defines a probability of 0.66–0.9. This implies a probability of 0.05–0.17 that the climate sensitivity is either lower than 2 °C or higher than 4.5 °C

(corridor delimited by red upper and lower boundaries). The BAU path now transgresses the upper corridor boundary at about 2090. The associated constrained optimal path deviates from the BAU path from the year 2000 on. This implies that an immediate deviation from BAU is required followed by a substantial long lasting emissions reduction in order to avoid – in a manner that minimizes welfare losses due to mitigation efforts – a THC breakdown under worst-case assumptions for 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.

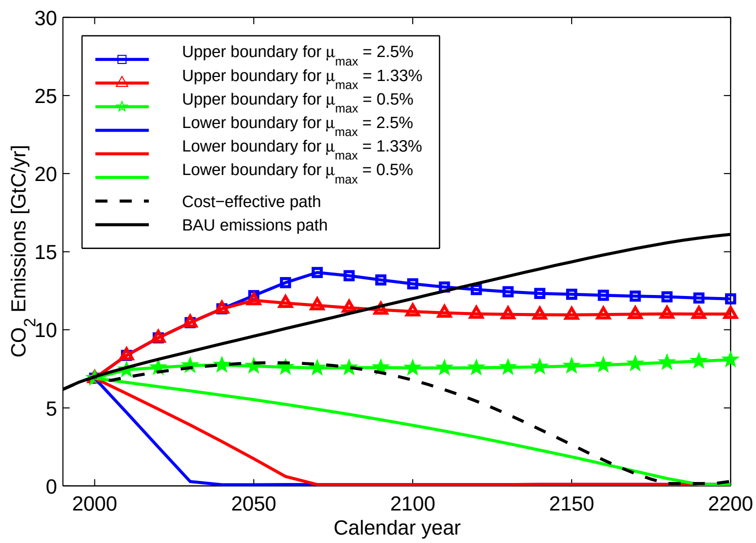

Figure 5. Emissions corridors for different values of the maximum emissions reduction rate $\dot{\mu}_{\max}$ under worst-case conditions $T_{2\times CO_2} = 4.5\,^\circ\mathrm{C}$ and $h_2 = 0.05\,\mathrm{Sv}^\circ\mathrm{C}^{-1}$ (with all other model parameters and guard-rails are held at their standard values).

Figure 5 also depicts the sensitivity of the emissions corridor to changes in the maximum emissions control level. In the climate-related worst-case, the BAU path exceeds the upper corridor boundaries for all admissible emissions reductions rates from the range considered. In all cases, the crossing of boundaries occurs before 2100. If the admissible emissions control level increase $\dot{\mu}$ is restricted to 0.5 %-Points per year the BAU path transgresses the corridor boundary within the next two decades. 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.

On first sight, the results presented here might be considered to contradict the IPCC statement ”It is very unlikely that the MOC [Meridional Overturning Circulation] will undergo a large abrupt transition during the 21^{st} century” (Meehl and Stocker, 2007), page 752. This however, is not the case. As we have shown elsewhere (Zickfeld and Bruckner, 2008), a path that transgresses the corridor boundary within the next few decades would not imply an immediate collapse of the THC: because of the inertia of the ocean, the actual event would occur two centuries after it was triggered. Even in the case of a finally collapsing THC, the initial weakening throughout the 21^{st} century would not exceed more than about 30%.

5.3. Constrained Optimal Emissions Paths and Emissions Corridors: the Probabilistic Case

As demonstrated in the previous section, the deterministic implementation of the TWA is well suited for deriving emissions corridors for best-guess parameter settings and for exploring the sensitivity of the corridors in the face of parametric and normative uncertainty. In the case of potentially high-impact phenomena such as a collapse of the THC, however, a risk assessment approach would be desirable. In the framework of the TWA this can be achieved by complementing the deterministic guardrail with an overshoot probability society is willing to accept (e.g. “avoid a THC collapse with a probability of x%”) in conjunction with a probabilistic algorithm for the computation of emissions corridors. In this section we present an application of the probabilistic version of the TWA. Conceptual and methodical aspects of this extension are discussed in (Kleinen et al., 2008). The numerical derivation of probabilistic emissions corridors uses an idea that was first proposed by H. Held (Held et al., 2008).

Unlike for the deterministic case, the THC is here not taken into account by explicit modelling, but via subjective probability distributions elicited from climate experts[8] (Zickfeld et al., 2007). These distributions relate the probability that a THC collapse is triggered to the change in global mean temperature in the year 2100 (see Fig. 3). Here, we use the distribution of expert 1 which lies in the middle of the

[8] Alternatively one could use the dynamic THC module of *dimrise*. For a probabilistic assessment, however, this would require the specification of uncertain model parameters such as the hydrological sensitivity in terms of probability density functions, which are currently not available. Also, the use of subjective probabilities may be considered superior as these are not based on a single model but synthesize all available evidence, from modelling, observations and paleoclimatic studies.

elicited probability range. Note that the probability for THC collapse, given a specific change in temperature, is conditional on the probability that this temperature change is actually realized. The uncertainty in the temperature response to a given forcing is usually characterized in terms of the climate sensitivity (defined as the equilibrium change in global and annual mean temperature in response to a doubling of atmospheric CO_2 over its pre-industrial value), which enters the climate module of *dimrise* as a parameter. Here, we adopt a lognormal distribution for climate sensitivity with a median of 2.7 K (Figure 2).

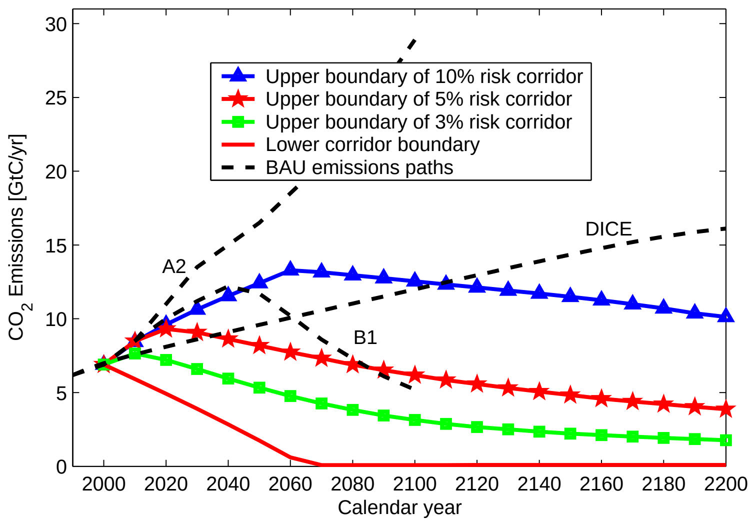

Figure 6. Emissions corridors limiting the probability of THC collapse to 10%, 5% and 3%. These were computed assuming a lognormal distribution for climate sensitivity with a median of 2.7 K (Figure 2) and the subjective probability distribution of expert 1 in Figure 3.

Figure 6 displays emissions corridors that limit the probability of THC collapse to 10%, 5% and 3%. As can be clearly seen, the width of the emissions corridors decreases with decreasing acceptable risk. In the case of the 5% corridor the DICE BAU path transgresses the upper corridor boundary by 2040. This implies that a deviation from BAU would be necessary before 2040 if the risk society is willing to take does not exceed 5%. As mentioned earlier, the BAU path of DICE-99 describes just one possible (non-intervention) scenario for world economic evolution discussed in the literature. If the world economy does initially unfold according to the SRES emissions scenarios B1 or A2, for instance, limiting the risk of THC collapse to 5% requires an immediate deviation from these unsustainable development paths.

If the risk of a THC break-down is restricted to 3%, the point of no return might already be passed within the next two decades.

6. Summary

The tolerable windows approach (TWA, also known as the guard-rail approach) allows the climate policy formulation process to be safeguarded in the following way. First, guardrails are defined in order to exclude intolerable climate change impacts, on the one hand, and unacceptable socioeconomic consequences of climate change mitigation measures, on the other. Second, a scientific analysis is conducted to investigate the features of those emission paths that are compatible with the guardrail constraints.

The TWA now can be considered mature from a conceptual and methodical point of view. Concerning conceptual aspects, its relationship to the most important competing approaches (e.g., scenario analysis, multi-criteria-analysis, cost-benefit analysis and cost-effectiveness analysis) is clarified. Methodically, the deterministic variant recently was supplemented by a probabilistic extension.

As part of an illustrative application of the TWA, emissions corridors are derived that constrain the risk of a break-down of the thermohaline circulation (THC) to a prescribed level. In order to achieve this goal, the fully coupled integrated assessment model *dimrise* (dynamic integrated model of regular climate change impacts and singular events) has been used. The THC module of *dimrise* employs a dynamic four-box interhemispheric extension of the classic Stommel model. The free parameters of this box-model are calibrated to reproduce the THC behavior as shown by CLIMBER-2, a climate model of intermediate complexity developed at the Potsdam Institute for Climate Impact Research. The THC module is driven by the ICLIPS multi-gas climate module, a computationally efficient globally aggregated model that is able to mimic the response of sophisticated carbon cycle and atmosphere-ocean general circulation models. In order to estimate the monetary cost of avoiding a THC breakdown, the THC and climate modules are coupled with a globally aggregated Ramsey-type optimal growth model of the world economy.

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 can be calculated within the framework of the tolerable windows approach. These emissions corridors delineate the sets of all emissions paths that (1) do not endanger the stability of the THC and (2) do not transgress prescribed welfare losses associated with the emission mitigation efforts that are necessary to achieve that goal.

Applications of a conservatively calibrated *dimrise* model variant reveal that the point of no return for a future break-down of the THC could be crossed within two decades if a business-as-usual emissions path is followed. This vulnerable behavior can be readily explained by taking into account both (1) the considerable time-lag between greenhouse gas emissions, associated temperature change, and the resulting response of the ocean circulation, and (2) the cumulative emissions that would arise from two decades of inaction together with the restricted capacity of the world economy to rapidly reduce greenhouse gas emissions thereafter.

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