Sensitivity analysis of emissions corridors for the 21^{st} century

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Abstract.

We investigate the sensitivity of emissions corridors for the 21^{st} century to various factors currently under debate in the climate change arena. Emissions corridors represent the range of admissible emissions futures that observe some predefined guardrails on the future development of the human-climate system. They are calculated on the conceptual and methodological basis of the tolerable windows approach. We assess the sensitivity of the corridors to the choice of time-resolved as well as intertemporally aggregated guardrails that exclude an intolerable amount of climate change on the one hand, and unbearable mitgation burdens on the other. In addition, we investigate the influence of climate sensitivity on the corridors.

Results show a large dependence of emissions corridors on the choice of guardrails and the value of climate sensitivity T_{2CO_2}. If the guardrail on climate change is specified in terms of a maximum admissible global mean temperature increase T_{max} to be observed at any time, the size of the corridors is predominantly determined by a climate impact resilience parameter $\kappa = T_{max}/T_{2CO_2}$. As κ is varied from values below 0.5 to values above 1.5, we move from cases, where no emissions profile whatsoever can observe all guardrails, to cases, where no significant emissions reduction seems necessary given the range of emissions scenarios for the 21^{st} century. The limits on admissible mitigation efforts influence predominantly the timing and the economic viability of emissions reductions. A large mitigation flexibility allows for 'wait then run' emissions paths, while low flexibility asks for a significantly more prudent approach.

Keywords: climate change, tolerable windows approach, guardrail approach, emissions corridors, sensitivity analysis, climate sensitivity, climate impact resilience

1. Introduction

The aim of this paper is to analyze the sensitivity of emissions corridors for the 21^{st} century to various factors that are pertinent to shaping a

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future climate policy regime. We have taken on a broad, thus necessarily coarsened perspective in choosing these factors from the numerous issues currently under debate in the climate change arena. We focus the sensitivity analysis on three stylized limits, so called *guardrails*, to exclude an intolerable magnitude of climate change on the one hand and an unacceptable amount of mitigation efforts on the other. The particular choice of the guardrails is a normative and political rather than a scientific issue. Thus, this sensitivity analysis compares the implications of different political commitments for the future emissions leeway of humankind.

To exclude climate impacts that are deemed intolerable, we consider a time-resolved as well as a time-aggregated guardrail formulation (section 2.3, 2.4). In both cases, we use the increase in global mean temperature T_{max} since preindustrial times as the indicator to express an expectation of the vulnerability of human-environment systems to climate change (cf. WBGU, 1995). In the latter case, we also consider different discount rates for the aggregation of damage costs in time. The two mitigation guardrails are captured in terms of a maximum admissible CO_2 reduction rate r, expressing an expectation of the socio-economically acceptable amount of CO_2 mitigation measures in the long run, and a minimum transition time t_{trans} required for the decoupling of economic growth and CO_2 emissions (section 2.5). In addition we consider a major uncertainty in the assessment of climate change policies, namely the magnitude of the climate response to an increase in atmospheric CO_2 levels expressed in terms of the climate sensitivity T_{2CO_2} (cf. Dowlatabadi and Kandlikar, 1995).

We condense the normative as well as scientific uncertainty that is inherent in the choice of any guardrail by considering highly aggregated indicators for both impact and mitigation guardrails. If we were to specify the guardrails on the resolved level of impact categories (sea level rise, agriculture, human health, etc.) and socio-economic drivers of anthropogenic emissions (population, economic growth, energy intensity, fuel mix, etc.) we would end up with a huge set of parameters rendering a broad sensitivity analysis infeasible. Thus, the focus on aggregated guardrails reduces the information to an extent that allows us to restrict the analysis to a limited set of different 'macroscopic' perspectives on vulnerability and mitigation capabilities.

The sensitivity analysis is embedded in the framework of the *tolerable windows approach* (TWA, also called *guardrail approach*; Tóth et al., 1997, Petschel-Held et al., 1999, Bruckner et al., 1999). Its objective is to translate constraints (guardrails) on the future development of a dynamic system (climate-economy model) into the bundle of admissible control paths (climate policies) that lead to system trajectories which observe the given set of guardrails. In this way the TWA allows us to formalize the notion of a *leeway* or *maneuvering space* for action. This is illustrated in particular by the concept of *emissions corridors*, which was introduced in the context of the safe landing analysis (Alcamo and Kreileman, 1996). Emissions corridors constitute the projection of the bundle of admissible emissions paths onto the subspace spanned by emissions and time.

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 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, 1994a; Manne et al., 1995; Tol, 1997). Finally, the burden of normative specifications and final assessments stays with the policy-makers - a feature which is shared with most scenario analyses (cf. Alcamo and Kreileman, 1996, Alcamo et al., 1998).

Despite the aforementioned similarities, the conceptual basis of the TWA differs substantially from the standard policy optimization approach as it is 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).

As the guardrails can be imposed on different valuation categories, the TWA constitutes a valid tool for a multi-criteria analysis. Each guardrail divides the set of policy options into two disjoint domains, the set of admissible policies complying with the specific guardrail and the set of inadmissible policies leading to a violation of this guardrail. Such a coarse 'boolean' classification within each category allows an uncontroversial aggregation procedure of admissible (inadmissible) sets. The aggregated admissible (inadmissible) set of policies is simply the intersection (union) of the admissible (inadmissible) sets for each valuation category.

A sensible application of the TWA to real world decision making problems requires a proper interpretation of the guardrails. As Fig. 1

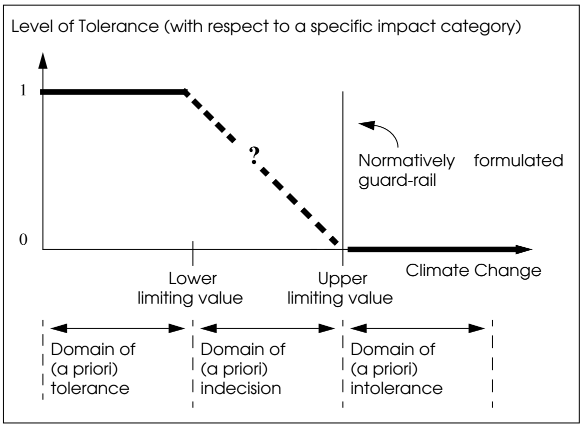

Figure 1. The interpretation of guardrails as intolerability limits on the continuum of climate change (Bruckner et al., 1999).

indicates, it is generally not possible to draw a sharp boundary between tolerability and intolerability in real world applications. It is more appropriate to allow for a grey zone between a stringent tolerability limit, enclosing the 'safe' domain, and a lean intolerability limit delineating the last frontier to an unbearable regime. In this analysis we interprete the guardrails as specifying intolerability limits. We therefore insist that the admissible policies yielding non-intolerable outcomes are not necessarily 'safe' strategies, but only successful in observing the last frontiers to intolerability. If a particular policy is to be chosen from the corridors, safety margins on the guardrails and/or additional qualifiers will be needed to assess the tolerability of the strategy.

The interpretation of the guardrails as laid out above renders the TWA a robust tool for a multi-criteria analysis, since the specification of inadmissible policies is rather insensitive to an incomplete assessment of valuation categories. An action classified as intolerable on the grounds of the valuations incorporated so far will not lose its status if additional valuations are considered. In contrast, a specification of 'safe' policies would require a comprehensive assessment of the tolerability limits across all pertinent valuation categories - an exercise that is doomed in the face of climate change and our limited knowledge about it.

Table I. Important concepts and definitions used in this paper

Concept	Description
TWA (guardrail approach, tolerable windows approach)	translates guardrails into the bundle of admissible paths
(intolerability) guardrail	exludes intolerable domain of future development
time-resolved climate impact guardrail	specifies maximum admissible global mean temperature rise at any time
time-aggregated climate damage guardrail	specifies maximum admissible intertemporally aggregated climate damage
mitigation guardrails	restrict future emissions by (local) constraints on the change of emissions
resilience parameters	T_{max}, T_{2CO_2}
economic parameters	r, t_{trans}
admissible path	system trajectory observing all guardrails
emissions corridor	area covered by the bundle of admissible emissions path
sufficient subset	contains only emissions paths that observe the climate guardrails
tangent cone	cone of slopes of admissible emissions paths at a point $E(t)$
climate impact resilience parameter	$\kappa = \frac{T_{max}}{T_{2CO_2}}$, measure of resilience against increase in atmospheric CO_2
MACE	maximum admissible cumulative emissions in the period 2000-2100

2. Methods

Section 2.1 describes the derivation and interpretation of emissions corridors. Special emphasis is put on adding information about the inner structure of the corridors. Section 2.2 presents the simple carbon cycle and climate model that is used for this analysis. Section 2.3 and 2.4 specify the time-resolved climate impact guardrails and the intertemporally aggregated climate damage guardrails considered here. Section 2.5 motivates the guardrails on the mitigation capability of the socio-economic system. The scope of the sensitivity analysis and its numerical implementation is summarized in section 2.6.

2.1. Calculation of emissions corridors

The methodological groundwork for the derivation of corridors in the framework of the TWA was presented in Petschel-Held et al. (1999) and Bruckner et al. (1999, 2003a). Here, we recapitulate only some basic definitions and concepts which are necessary for the understanding of what follows. In general, corridors can be calculated for any state variable x or control variable u of a dynamical system modeled by a set of ordinary differential equations

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

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

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

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 observes all guardrails. We can only say for sure that every path leaving the corridor violates at least one guardrail.

If a corridor is simply connected, it has a connected boundary that determines its size and shape. A discrete approximation of 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 (Leimbach and Bruckner, 2001; Bruckner et al., 2003a). The resulting optimization task for a finite time horizon and a fixed time $\hat{t}$ can be solved with well established methods of optimal control (Papageorgiou, 1991, Chap. 14.7.2, pg. 227):

$$\text{Maximize (Minimize)} \quad \Phi_{\hat{t}} \equiv u_{\text{Emissions}}\,\big|_{t=\hat{t}} \tag{1}$$

subject to the dynamical constraint

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

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

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

Fig. 2 illustrates the algorithm by showing three admissible emissions paths maximizing anthropogenic carbon dioxide emissions in the years 2025, 2050 and 2075. The entire upper boundary is put up by such emissions paths.

Emissions corridors have several properties that are important for the assessment of the information they offer. Since the corridors integrate over the bundle of all admissible paths, they pose only a necessary condition on the admissibility of a particular path. Thus, it is possible to construct infinitely many emission paths within the corridor which do not observe the guardrails. Fig. 2 shows clearly that, for instance, the upper boundary of the corridor is not an admissible path itself. Therefore, it is desirable to recover some information about the inner structure of emissions corridors. We are particularly interested in identifying *sufficient subsets* of corridors. These are sets, for which all conceivable emissions paths contained within the set observe any guardrail that is specified as global state constraint $\boldsymbol{x}(\boldsymbol{u},t) \leq \boldsymbol{x}_{\max}(t)$ and $\boldsymbol{x}(\boldsymbol{u},t) \geq \boldsymbol{x}_{\min}(t)$, respectively.

Sufficient subsets can be calculated quite easily for a special type of underlying dynamical model, namely for systems of ordinary linear differential equations with a 'directed', 'positive' cause-effect chain. 'Directed' means in this context a cause-effect chain without feedbacks. 'Positive' denotes the property that the change to the cause and the resulting change in the effect always have the same sign. Defining a partial ordering relation $\boldsymbol{x} < \boldsymbol{y}$ on $\boldsymbol{R}^n$ by $x_i < y_i \quad \forall\, 1 \leq i \leq n$, the following property connecting state trajectories and control paths holds true in such dynamical systems:

$$\begin{aligned} \forall\, t \;\; \boldsymbol{x}(\hat{\boldsymbol{u}},t) \leq \boldsymbol{x}_{\max}(t) \,\wedge\, \tilde{\boldsymbol{u}}(t) \leq \hat{\boldsymbol{u}}(t) \quad &\Rightarrow \quad \forall\, t \;\; \boldsymbol{x}(\tilde{\boldsymbol{u}},t) \leq \boldsymbol{x}_{\max}(t) \\ \forall\, t \;\; \boldsymbol{x}(\hat{\boldsymbol{u}},t) \geq \boldsymbol{x}_{\min}(t) \,\wedge\, \bar{\boldsymbol{u}}(t) \geq \hat{\boldsymbol{u}}(t) \quad &\Rightarrow \quad \forall\, t \;\; \boldsymbol{x}(\bar{\boldsymbol{u}},t) \geq \boldsymbol{x}_{\min}(t) \end{aligned} \tag{2}$$

Property (2) has important implications for emissions corridors that are derived from models with a positive, directed cause-effect chain. The present analysis is concerned with such emissions corridors, since the simple climate model used here belongs to this special class of models (see section 2.2).

If property (2) holds, every subset of a corridor confined by admissible paths is a sufficient subset in the sense that every path lying completely within the subset observes the global state constraints. Property (2) also implies that any sufficient subset of an emissions corridor is densely covered by admissible paths as long as the set of possible controls $\mathcal{U}(\boldsymbol{x}(t),t)$ is convex. In this case the emissions corridor is simply connected, and its boundary can be computed by the algorithm developed in Leimbach and Bruckner (2001) and sketched above.

Figure 2 shows an example of a sufficient subset, which is confined by the two admisible paths maximizing emissions in the year 2050 and minimizing emissions for all points in time. Since there are infinitely many such sufficient subsets for each emissions corridor, we have to identify a particularly suitable subset to add new information to the

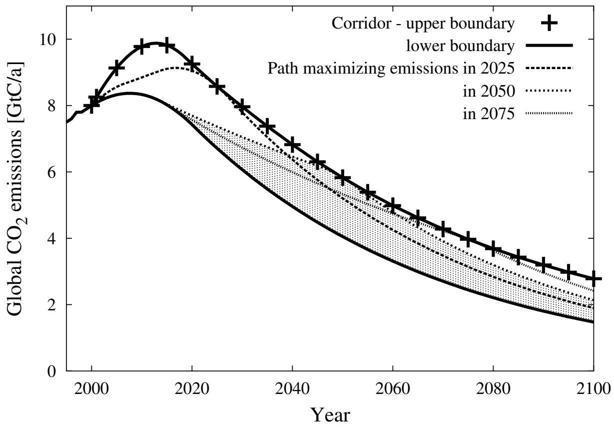

Figure 2. Calculation of an emissions corridor. The maximum emissions values on the upper boundary (crosses) are put up by admissible paths maximizing emissions for fixed points in time. We show the admissible paths reaching the upper boundary of the corridor in the years 2025, 2050 and 2075. The lower boundary is determined by a single minimum emissions path. An example for a sufficient subset of the corridor is indicated by the dotted area. Note that it is *not* the largest sufficient subset of the corridor shown in Fig. 3. The corridor was calculated for the parameter constellation $(\mathrm{T_{max}}, \mathrm{T_{2CO_2}}, \mathrm{r}, \mathrm{t_{trans}}) = (2\,^\circ\mathrm{C},\ 3.5\,^\circ\mathrm{C},\ 0.02\ \mathrm{a}^{-1},\ 20\,\mathrm{a})$.

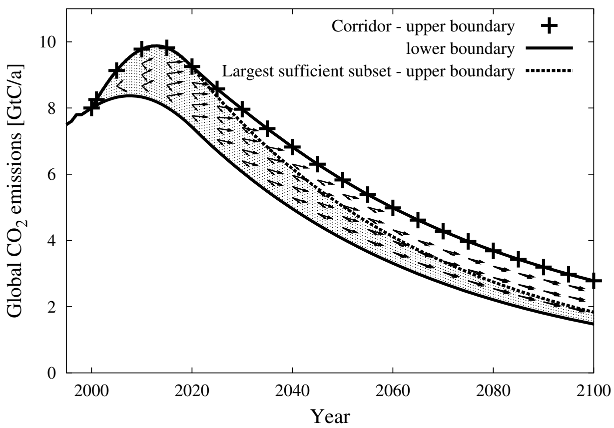

Figure 3. Inner structure of the emissions corridor introduced in Fig. 2. Shown are the largest sufficient subset (dotted area) and the tangent cones of admissible emissions paths for several points in the corridor.

presentation of the corridor. We have chosen the sufficient subset with the largest fractional area of the corridor for this purpose. The difference in size between the whole emissions corridor and its *largest sufficient subset* yields important information about the emissions paths within the corridor that violate at least one guardrail. Such emissions paths, although contained in the corridor, are not contained in any sufficient subset. The smaller the fraction of the corridor covered by its largest sufficient subset, the easier it is to select such an inadmissible emissions path from the corridor. If we had chosen another sufficient subset, the information about the admissibility of paths within the corridor would be more obscure, since we would have gained no indication on how large a sufficient subset can be compared to the corridor. In our specific case, the largest sufficient subset is confined by two admissible paths: a single minimum emissions path connecting the lowest admissible emissions values for all points in time, and an emissions path that maximizes the cumulative anthropogenic emissions in the year 2100 (see Fig. 3).

Every path in the sufficient subset observes the global state constraints. However, to be admissible it also has to comply with the mitigation guardrails directly imposed on the emissions behavior (see section 2.5). Since these guardrails are specified in terms of derivatives of the emissions path (growth rate, change in growth rate), they constitute *local constraints* on the emissions behavior, i.e. they depend only on the emissions in an ε-area around time t. The information about such local constraints can be included in the presentation, at least partly, by drawing *tangent cones* at several points (E, t). The upper and lower arrow of each cone denote the maximum and minimum slope, respectively, that an admissible emissions path can have when reaching the corresponding point (E, t). Thus, a tangent cone depicts the maximum range of possible continuations of admissible emissions paths at the point (E, t). Fig. 3 shows a quite comprehensive and still comprehensible way to present some aspects of the inner structure of emissions corridors.

2.2. Climate model

We use a simple model (Petschel-Held et al., 1999) to describe the response of the globally averaged climate to anthropogenic forcing (see Table II for the definitions of variables and parameters).

$$\dot{F} = E \tag{3}$$

$$\dot{C} = \beta E + \mathrm{B}F - \sigma C \tag{4}$$

$$\dot{T} = \mu \ln c - \alpha T \quad \text{with } c = \frac{C + C_{pi}}{C_{pi}} \tag{5}$$

Table II. State variables and parameters of the climate model.

	Variables
E	anthropogenic CO_2 emissions per year [GtC a^{-1}]
F	cumulative anthropogenic CO_2 emissions [GtC]
C	atmospheric CO_2 concentration anomaly relative to preindustrial level [ppmv]
T	global mean temperature anomaly relative to preindustrial level [$^\circ$C]

Preindustrial values	Initial conditions (year 1995)
$E_{pi} = 0$ GtC a^{-1}	$E_o = 7.5$ GtC a^{-1}
$F_{pi} = 0$ GtC	$F_o = 426$ GtC
$C_{pi} = 280$ ppmv	$C_o + C_{pi} = 360$ ppmv $\Rightarrow$ $c_o = 1.286$
$T_{pi} \approx 14.6\,^\circ$C	$T_o + T_{pi} = (0.31 \ln \mathrm{T}_{2\mathrm{CO}_2} + 0.29)\,^\circ\mathrm{C} +\ T_{pi}$

Parameters	
$\beta = 0.47$ ppmv GtC^{-1}	CO_2 emission to concentration conversion factor
$\sigma = 0.0215$ a^{-1}	carbon cycle response parameter
$\mathrm{B}/(\beta\sigma) = 0.15$	atmospheric retention factor $\Rightarrow$ $\mathrm{B} = 1.51 \cdot 10^{-3}$ ppmv GtC^{-1}a^{-1}
$\mathrm{T}_{2\mathrm{CO}_2} \in [1.5\,^\circ\mathrm{C}, 4.5\,^\circ\mathrm{C}]$	climate sensitivity
$\mathrm{Q}_{2\mathrm{CO}_2} = 3.7$ Wm^{-2}	radiative forcing for a doubling of atmospheric CO_2
$\mathrm{c}_{\mathrm{oc}} = 61.4$ Wa m$^{-2}\,^\circ$C^{-1}	effective ocean heat capacity

The model simulates the first order deviation of global mean temperature (GMT) from a presumed preindustrial equilibrium climate caused by anthropogenic emissions of carbon dioxide alone. Due to the quasi-linear approximation of the climate response, equations (3)-(5) can capture solely a regular climate change, thereby ignoring possible climate instabilities. This observation does not transfer to the entire analysis presented here, since the consideration of climate impact guardrails can be motivated, among other things, by the objective to avoid an instable and irregular climate regime.

The carbon cycle equation (4) represents the differential analogue of a simplified impulse-response model (Hasselmann et al., 1997) that can be derived from three-dimensional carbon cycle simulations. In contrast to more sophisticated impulse-response models (Maier-Reimer, 1993), equation (4) captures only one time scale and the atmospheric retention factor. For a given finite input F of CO_2 into the atmosphere, with vanishing emissions $E = 0$ after some finite time, the asymptotic equilibrium solution of equation (4) is given by $C = \mathrm{B}F/\sigma$. Thus, the atmospheric retention factor is $\mathrm{B}/\beta\sigma$, while the equilibrium uptake fraction of the land-ocean reservoir is $1 - \mathrm{B}/(\beta\sigma)$ (cf. Petschel-Held et al., 1999).

Since equation (4) assumes only one time scale to unload the atmospheric reservoir, it will underestimate the fast response of the land biosphere. In addition, it will overestimate the carbon dioxide uptake in the long run by neglecting the comparatively long time scales of the deep ocean as well as nonlinear effects like the decreasing solubility of CO_2 in seawater. Fig. 4 compares the response of equation (4) to several IS92 CO_2 emissions scenarios (Leggett et al., 1992) with corresponding projections in the IPCC Second Assessment Report (SAR, Schimel et al., 1996). The deviations from the more sophisticated carbon-cycle models used in SAR show the expected behavior. Their magnitude however is sufficiently small for the purpose of this study (see Fig. 5). With regard to the linearization limit of equation (4) we focus this sensitivity analysis on cases where the triple of the preindustrial CO_2 concentration is not exceeded at any time ($C(t) + C_{pi} \leq 840$ ppmv).

The temperature equation (5) represents the differential analogue of an impulse-response function that can be derived from atmosphere-ocean general circulation model (AOGCM) simulations of the climate response to increasing levels of atmospheric CO_2 (Hasselmann et al., 1997). The climate sensitivity, which is defined as the equilibrium GMT increase for a doubling of atmospheric CO_2 relative to preindustrial times, can be directly calculated from equation (5) by considering the case $\dot{T} = 0$, $c = 2$:

$$\mathrm{T}_{2\mathrm{CO}_2} = \frac{\mu}{\alpha} \ln 2$$

In order to model climate responses governed by different values of the climate sensitivity, it is necessary to attempt a physical interpretation of equation (5). This can be achieved in the framework of energy balance models (EBMs; cf. Harvey, 2000). In this framework the net radiative flux into the system at the tropopause (after stratospheric readjustments) is set equal to the oceanic heat uptake. Thus, the temperature of the atmosphere-ocean surface layer-compound is described by (Dutton, 1995; Watterson, 2000):

$$\frac{d}{dt}\, \mathrm{c}_{\mathrm{oc}}(t)\, T(t) = \mathrm{Q}_{2\mathrm{CO}_2} \frac{\ln c(t)}{\ln 2} - \lambda(t)\, T(t)$$

c_{oc} effective ocean heat capacity
Q_{2CO_2} radiative forcing for a doubling of preindustrial CO_2 levels

The net radiative flux at the tropopause is determined by the radiative forcing due to the increase in the atmospheric CO_2 concentration and the outward energy flux of the system, assumed to be proportional to the temperature increase T in a linear approximation. The (possibly time-dependent) radiative damping parameter $\lambda(t)$ is related to the effective climate sensitivity $T_e(t)$ by $\lambda(t) = Q_{2CO_2} / T_e(t)$ (Murphy, 1995). By making the strong assumption that effective ocean heat capacity and effective sensitivity are constant in time (for a discussion of this assumption see Watterson, 2000 and Raper et al., 2001), we can readily identify the parameters of equation (5) with the three physical quantities c_{oc}, Q_{2CO_2} and $T_{2CO_2} = \lim_{t\to\infty} T_e(t)$:

$$\mu = \frac{Q_{2CO_2}}{c_{oc} \cdot \ln 2}\,, \qquad \alpha = \frac{Q_{2CO_2}}{c_{oc} \cdot T_{2CO_2}} \tag{6}$$

The dependence of the initial GMT anomaly in the year 1995 on the climate sensitivity can be assessed with a spin-up procedure based on the integral form of equation (5):

$$T(t) = e^{-\alpha\,(t-t_o)} \int_{t_o}^{t} \mu \ln c(t') \;\; e^{\alpha t'}\, dt' \,. \tag{7}$$

Assuming an exponential increase of atmospheric CO_2, and a value of $T(T_{2CO_2} = 3.5\,°C, 1995) = 0.7\,°C$ for the special case considered in Petschel-Held et al. (1999), we can approximate $T(T_{2CO_2}, 1995)$ by a logarithmic function in the relevant interval $T_{2CO_2} \in [1.5\,°C,\, 4.5\,°C]$:

$$T(T_{2CO_2}, 1995) = (0.31 \ln T_{2CO_2} + 0.29)\,°C$$

Fig. 5 compares the response of GMT anomaly to the IPCC IS92a scenario as modelled by equations (3)-(5) with corresponding 'All greenhouse gases (GHGs) and aerosols' projections from SAR (Kattenberg et al., 1996). At first, it seems surprising that a temperature projection based solely on the forcing of atmospheric CO_2 resembles that closely the projections of SAR taking all GHGs and aerosols into account. The explanation is inherent to the IPCC IS92a scenario that assumes a forcing contribution of non-CO_2 GHGs, which is approximately balanced by the negative radiative forcing of the aerosol mask (Kattenberg et al., 1996). In contrast, other scenarios, in particular the new SRES scenarios, project the aerosol emissions to decline considerably faster towards the end of the 21^{st} century (Nakićenović and Swart, 2000). Consequently, a CO_2-only model as used in this analysis will tend to

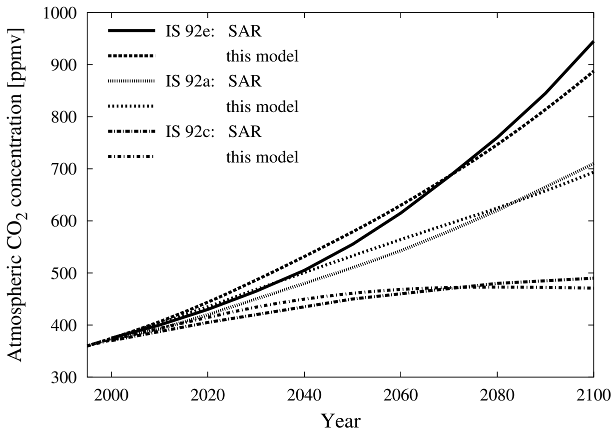

Figure 4. Response of the atmospheric CO_2 concentration to IS92 emissions as projected in SAR (Schimel et al., 1996) and modelled by carbon cycle equation (4).

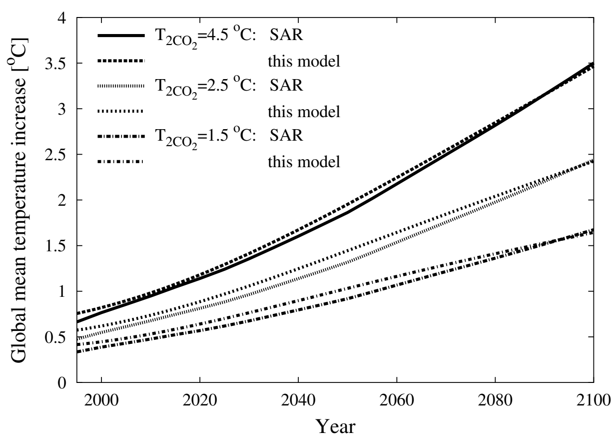

Figure 5. Response of global mean temperature (GMT) to IS92a emissions for three climate sensitivities ($T_{2CO_2} \in \{1.5, 2.5, 4.5\}$ °C) as projected in SAR (Kattenberg et al., 1996) and modelled by equations (3)-(5).

underestimate the climate response by up to 30% depending on the non-CO_2 GHG and aerosol scenario.

The SRES emissions scenarios do not account for climate policies, while many of the CO_2 emissions profiles in the corridors can only materialize, if such policies are applied. If the contribution of non-CO_2 GHGs and aerosols to climate change are put into the equation, the resulting changes to the CO_2 emissions corridors will depend on assumptions about the abatement measures for the other GHGs and aerosols.

If the non-CO_2 GHGs were strongly reduced including in particular the emissions from livestock and agriculture, the rapidly decreasing cooling effect of the aerosols might still be large enough to counterbalance most of the non-CO_2 radiative forcing contribution. In this case, the size of the CO_2 emissions corridors presented will not be reduced significantly. If on the other hand no stringent mitigation policy was imposed on the non-CO_2 GHGs, the size of the CO_2 corridors might be reduced by up to 30% to 40%. Tóth et al. (2003) conduct an uncertainty analysis that shows the large sensitivity of emissions corridors to different assumption about future anthropogenic aerosol emissions.

In this analysis, we restrict ourselves to the impact of CO_2 on the global climate. In doing so, we implicitly make the assumption that the net forcing due to aerosols and non-CO_2 GHGs is neglectable compared to the CO_2 forcing on the global scale. The omission of non-CO_2 GHGs reduces the scope of the sensitivity analysis in one dimension, allowing us to extend its scope in other dimensions. For a similar reason, we neglect the uncertainties in the parametrization of the carbon cycle, the ocean heat uptake and the radiative forcing (see, e.g., Visser et al., 2000 for a discussion of these uncertainties). An analysis of equations (3)-(5) reveals that climate sensitivity T_{2CO_2} is the most influential parameter for the magnitude of the climate response in the given model setting (cf. Dowlatabadi and Kandlikar, 1995).

2.3. Climate impact guardrails

The concept of guardrails draws on the profound intuition that the carrying capacity of planet Earth is limited. This intuition is reflected for instance in the United Nations Framework Convention on Climate Change (UNFCCC), which asks for a stabilization of atmospheric greenhouse gas concentrations at levels that "prevent dangerous anthropogenic interference with the climate system" (Art. 2, UNFCCC; United Nations, 1992). It was also taken up by the German Advisory Council on Global Change (WBGU), when formulating the basic idea of the TWA in a special report for the First Conference of the Parties to the UNFCCC in Berlin (WBGU, 1995). In this report the council put forward its own assessment of viable climate impact guardrails, the so-called WBGU window, which is specified in terms of the increase in global mean temperature since preindustrial times and the rate of temperature change.

We follow the UNFCCC and the WBGU in specifying climate impact guardrails on the highly aggregated level of globally averaged climate change indicators. These indicators summarize an important set of altered climate conditions which can lead to such diverse impacts like floods and droughts, and the extinction of unique ecosystems (cf. Smith et al., 2001). Globally averaged climate change indicators can never provide a comprehensive set of parameters to capture all impacts adequately, of course. However, as the guardrails are meant to exclude intolerable outcomes, we can employ highly aggregated guardrails to get a first-order estimate of the remaining emissions leeway. Any refinement of the climate impact guardrails by additionally considering regional climate change indicators or concrete impact categories will narrow the emissions corridor.

The three prime globally averaged indicators for climate change are atmospheric CO_2 concentration, global mean temperature increase and the rate of temperature change. In the present analysis, we restrict ourselves to GMT increase as the single indicator for the specification of climate impact guardrails. This is justified in the given modelling framework, since a sensitivity analysis of the climate model (3) - (5) shows that GMT increase is the most limiting factor on future CO_2 emissions behavior. The picture changes, if other greenhouse gases and in particular the aerosol dynamics are taken into account (cf. Tóth et al., 2003, Part II).

A climate impact guardrail specified as a limit T_{max} on the amount of GMT increase tries to exclude climate futures which make society vulnerable to an intolerable degree. The explicit choice of T_{max} since preindustrial times can be motivated by various reasons.

- The last frontiers to intolerability are surely constituted by thresholds in the climate system, whose transgression can trigger large scale, abrupt climate discontinuities with potential catastrophic impacts on the socio-economic system (Zickfeld and Bruckner, 2004).
- Another important category concerns limits imposed by the uncertainty about future climate conditions which are far beyond the collective experience of humankind. These limits try to exclude surprises in a climate regime, where no solid projections of altered living conditions and no serious cost-estimates of potential impacts are available.
- However, there is also considerable uncertainty about the damages inflicted by a gradual temperature increase without major abrupt changes in the climate system. Thus, guardrails can be meant to prevent a gradual climate change from reaching a magnitude that is deemed potentially intolerable.

The guardrails can be concerned with such diverse categories as aggregate global or regional economic damages, increased risks from extreme climate events and large threats to unique systems like biodiversity 'hot spots'. Smith et al. (2001), in particular their Fig. 19-7, provide guidance on how these categories might be linked to GMT increase.

In this analysis we consider three guardrails on GMT increase since preindustrial times, namely

$$\mathrm{T}_{\max} = 2\,^{\circ}\mathrm{C}\ , \quad \mathrm{T}_{\max} = 3\,^{\circ}\mathrm{C}\ , \quad \mathrm{T}_{\max} = 4\,^{\circ}\mathrm{C} \tag{8}$$

symbolizing a low, medium and high estimate for the onset of the intolerable climate change domain. The estimate of 2 °C corresponds to the value chosen for the WBGU window (cf. WBGU, 1995). Beyond 2 °C (and to a limited extent also below 2 °C) extreme weather events are very likely to cause severe droughts and floods with higher frequency, a portion of unique systems might suffer extinction, and intolerable net negative impacts on market sectors in many developing countries are likely to occur. The high estimate of 4 °C marks an area of climate change, where the uncertainty in climate predictions becomes overwhelming, and large climate discontinuities are increasingly plausible (Smith et al., 2001).

The implication of the choice of $\mathrm{T}_{\max}$ and $\mathrm{T}_{2\mathrm{CO}_2}$ on the maximum admissible amount of cumulative anthropogenic emissions can be easily assessed by analysing the equilibrium climate state for $t \to \infty$ (cf. Petschel-Held et al., 1999). A stabilization of the anthropogenic impact on climate occurs after anthropogenic emissions have vanished. With $\dot{F} = E = 0, \quad \dot{C} = 0, \quad \dot{T} = 0$, the equilibrium climate change is computed to:

$$\begin{aligned} C_\infty &= \frac{\mathrm{B}}{\sigma} \cdot F_\infty \\ T_\infty &= \frac{\mathrm{T}_{2\mathrm{CO}_2}}{\ln 2} \cdot \ln\left(1 + \frac{\mathrm{B}}{\sigma\, C_{pi}} F_\infty\right) \end{aligned}$$

Recalling $\mathrm{T}_{\max} \geq T_\infty$, we can deduce an upper bound on the maximum admissible amount of cumulative CO_2 emissions. Defining a *climate impact resilience parameter*

$$\kappa = \frac{\mathrm{T}_{\max}}{\mathrm{T}_{2\mathrm{CO}_2}} \quad , \tag{9}$$

we find:

$$F_\infty \leq F_{\max} \equiv \frac{\sigma}{\mathrm{B}}\, C_{pi} \cdot (2^\kappa - 1) \tag{10}$$

The resulting maximum admissible cumulative CO_2 emissions as of 2000, $\Delta F_{\max} = F_{\max} - F(1999)$, are shown in Table III for the ten combinations of $\mathrm{T}_{2\mathrm{CO}_2}$ and $\mathrm{T}_{\max}$ considered in this sensitivity analysis.

Table III. ΔF_{max}, i.e. the remaining maximum admissible amount of cumulative CO_2 emissions as of 2000, for the combinations of GMT guardrail T_{max} and climate sensitivity T_{2CO_2} considered in this sensitivity analysis. The case ($T_{max} = 4\,°C$, $T_{2CO_2} = 2.5\,°C$, *italic*) allows for atmospheric CO_2 levels above 1000 ppmv, and therefore has to be considered with care given the limitations of the carbon cycle model.

T_{max}	T_{2CO_2}	$\kappa = \frac{T_{max}}{T_{2CO_2}}$	ΔF_{max}
4 °C	*2.5 °C*	*1.60*	*7634 GtC*
2 °C	1.5 °C	1.33	5572 GtC
3 °C	2.5 °C	1.20	4709 GtC
4 °C	3.5 °C	1.14	4336 GtC
4 °C	4.5 °C	0.89	2940 GtC
3 °C	3.5 °C	0.86	2786 GtC
2 °C	2.5 °C	0.80	2491 GtC
3 °C	4.5 °C	0.67	1893 GtC
2 °C	3.5 °C	0.57	1468 GtC
2 °C	4.5 °C	0.44	958 GtC

Note that F_{max} depends only on the ratio $\kappa = T_{max} / T_{2CO_2}$, and is extremely sensitive to the value of κ. F_{max} constitutes an absolute upper limit on the maximum admissible amount of cumulative CO_2 emissions. It will be considerably reduced by socio-economic factors restricting the transient emissions behavior in plausible future scenarios (see section 3.3).

The figures in Table III can be compared with estimates of the remaining resource base of fossil carbon, i.e. the amount of proven reserves exploitable at current economic conditions plus the projected amount of resources to be discovered that can be converted into reserves eventually. Additional occurences of fossil carbon, whose long-term economic potential is highly speculative to date, are not included in the resource base. Nakićenović (1996) estimate the resource base to be around 3500 GtC. More recent estimates are considerably higher and range between 5000 GtC (Moomaw and Moreira, 2001) and 6500 GtC (Rogner, 2000). It becomes evident that the fossil carbon budget that can be released to the atmosphere is limited far more by climate change than by the finite resource base.

2.4. Aggregate climate damage guardrails

The guardrails on GMT increase as specified in equation (8) have to be observed at each point in time. This is a necessary condition, if the guardrails are meant to exclude the occurrence of large-scale, irreversible changes in the climate system or potential surprises. However, if the guardrails are intended to limit a gradual climate change, it may be interesting to consider intertemporally aggregated climate damage guardrails in addition to 'knock-out' criteria excluding large-scale catastrophic impacts. Whereas time-aggregated *mitigation* guardrails, e.g., regional net present welfare losses due to emission reduction measures, have been already investigated in the framework of the TWA (cf. Leimbach and Bruckner, 2001), all TWA applications published so far have employed *climate impact* guardrails that were resolved in time.

Time-aggregated climate damage guardrails may be used, for example, to exclude damages of ecosystems that mainly depend on cumulative climatic stress. They also may be applied to restrict the cumulative financial burden of single sectors suffering from global climate change. This may be motivated, for instance, by a limited budget available to compensate the respective damages. In this case, the time-aggregated constraints would generally take into account future damages on a discounted basis.

In the following, we would like to explore the sensitivity of emissions corridors to the time-resolved vs. time-aggregated nature of the guardrails. We are particularly interested in deviations resulting from an increased flexibility that allows for compensating high impacts in some years by low impacts in others. In addition, it will be interesting to study the influence of possible discounting schemes if monetarized damages are considered.

In order to enforce comparability with the case of a global time-resolved climate impact guardrail, we consider time-aggregated constraints on the globally averaged net present climate damage D_{PV} defined as

$$D_{PV} = \int_0^{t_e} e^{-\delta\, t} \cdot d(t) \cdot Q(t)\, dt \le D_{PV,Max} \qquad (11)$$

with $d(t)$ being the globally aggregated (monetarized) damage at time $t \in [0, t_e]$ expressed as a fraction of the gross world product (GWP) $Q(t)$. δ represents the discount rate and $D_{PV,Max}$ the prescribed threshold beyond which cumulative damages are considered to be intolerable.

The overwhelming lack of knowledge concerning possible climate impacts does not allow scientists to reliably specify the globally aggregated climate damages in quantitative terms. We have decided to adopt the illustrative global damage functions frequently used in cost-benefit analysis, but wish to point out that they should be regarded as placeholders for cases in which the knowledge about sectoral or regional impact dynamics suffices to specify more accurate functional forms for suitable subsets of climate impacts (Smith et al., 2001). Therefore, the use of a global damage function in the subsequent analysis should be considered a gedankenexperiment.

In cost-benefit analyses, the globally aggregated climate damage $d(t)$ at time t, expressed as a fraction of the output, is frequently assumed to be proportional to the increase in GMT taken to the power of an uncertain parameter b (cf.Nordhaus, 1994a, Roughgarden and Schneider, 1999):

$$d(t) = \xi \cdot T(t)^{\,\mathrm{b}}$$

In many applications, the dependence of GWP losses on GMT increase is taken to be quadratic (Nordhaus and Boyer, 2000), but there also exist more optimistic estimates (b < 1.5, cf. Roughgarden and Schneider, 1999). In contrast, other studies emphasizing potential abrupt changes in the climate system like the breakdown of the Atlantic thermohaline circulation allow for a higher value of the damage function exponent b ≈ 3 (Mastrandrea and Schneider, 2001). In this analysis, we investigate the sensitivity of emissions corridors to the three different estimates b $= \{1, 2, 3\}$. The proportionality constant ξ between damages and GMT increase to the power of b is highly uncertain (Nordhaus, 1994b; Roughgarden and Schneider, 1999).

In order to compare emissions corridors for time-aggregated guardrails with those derived for time-resolved ones, we introduce an illustrative temperature $\tilde{\mathrm{T}}_{\max}$ implicitly defined by

$$\int_0^{t_e} e^{-\delta\, t} \cdot \xi \cdot \tilde{\mathrm{T}}_{\max}^{\,\mathrm{b}} \cdot Q(t)\, dt \equiv D_{PV,\max}\,.$$

Consequently, $\tilde{\mathrm{T}}_{\max}$ can be interpreted as the GMT that - if it occurs permanently - implies damages equal to the prescribed damage limit $D_{PV,\max}$. Substituting $D_{PV,\max}$ in equation (11) by the proxy damage variable $\tilde{\mathrm{T}}_{\max}$ results in a specification of the time-aggregated climate damage guardrail which does not contain the highly uncertain damage amplitude ξ anymore.

$$\int_0^{t_e} e^{-\delta\, t} \cdot T(t)^{\,\mathrm{b}} \cdot Q(t)\, dt \leq \tilde{\mathrm{T}}_{\max}^{\,\mathrm{b}} \int_0^{t_e} e^{-\delta\, t} \cdot Q(t)\, dt,$$

The emissions corridors calculated on the basis of prescribed values for $\tilde{\mathrm{T}}_{\max}$ therefore will not depend on this parameter.

Assuming a stylized evolution of the economy, namely a steady state optimal growth with stable population and a constant growth rate $\tilde{g}$ of per capita consumption, a pure rate of time preference (PRTP) ρ and a logarithmic dependence of the utility on private consumption, the discount rate δ equals $\delta = \tilde{g} + \rho$ (Nordhaus, 1997). Assuming further a constant savings rate, the output $Q(t)$ grows with $\tilde{g}$ as well. Thus, the assumption of a steady state optimal growth economy with logarithmic utility simplifies the constraint (11) considerably.

$$\int_0^{t_e} T(t)^{\,\mathrm{b}} \cdot e^{-\rho t}\, dt \leq \tilde{\mathrm{T}}_{\mathrm{max}}^{\,\mathrm{b}} \int_0^{t_e} e^{-\rho t}\, dt \qquad (12)$$

As the growth term in the real discount rate δ cancels, the emission corridors depend only on $\tilde{\mathrm{T}}_{\mathrm{max}}$, the damage exponent b, and the PRTP ρ.

In the sensitivity analysis, we will consider four different assumptions about the PRTP.

$$\rho = 0\,\%/\mathrm{a}\,, \quad \rho = 1\,\%/\mathrm{a}\,, \quad \rho = 2\,\%/\mathrm{a}\,, \quad \rho = 3\,\%/\mathrm{a}\,. \qquad (13)$$

In the spirit of the tolerable windows approach, the choice of the PRTP is left to the climate change policy maker seeking scientific advice[1]. This highlights the fact that the tolerable windows approach clearly is a normative decision making framework, while other frameworks like cost-benefit analysis based on optimal growth models are also applicable, at least partly, on descriptive grounds. The distinction becomes particularly important, when the PRTP is interpreted as the preference of a representative present-day market actor. Her PRTP can be deduced from the real interest rate observed on the market under given assumptions about the elasticity of the marginal utility of per capita consumption (Tóth, 1995; Arrow et al., 1996b; Nordhaus, 1997). It is frequently estimated to be about 3 %/a (cf. Nordhaus, 1994a), which is the upper bound on the range of values considered in this sensitivity analysis. In contrast to cost-benefit analysis, a decision maker employing the tolerable windows approach could not invoke such a descriptive line of reasoning for motivating the choice of PRTP. Instead, she would have to explicitely justify on normative grounds why she adopted the preference of present-day market actors to devalue the prospects of future generations (see Lind, 1995 for the difficulties of possible justification schemes).

[1] The same would apply to the elasticity of the marginal social utility of consumption, a measure of the inequality aversion which is set equal to one in the derivation of the climate damage guardrails considered here (Nordhaus, 1997, page 318).

Arrow et al. (1996b) provide an overview about various choices of the PRTP that were made in the context of climate policy analysis. On ethical grounds it is difficult to support a rate of pure time preference much above zero (Cline, 1992; Azar and Sterner, 1996). For $\rho = 0$ the climate damages expressed as a fraction of the output are treated equally across time. Obviously, this is still a weaker requirement than constraining GMT increase to be not larger than $\tilde{\mathrm{T}}_{\mathrm{max}}$ at any time (see equation 8), since a temporary violation of the climate impact guardrail can be compensated by other periods with $T < \tilde{\mathrm{T}}_{\mathrm{max}}$. The more non-linear the damage function is, the larger is the penalty for exceeding $\tilde{\mathrm{T}}_{\mathrm{max}}$.

Allowing climate policy makers to restrict the climatic burden experienced by different regions, sectors, and generations in a clear outcome related manner is one of the cornerstones underlying the tolerable windows approach (Bruckner et al., 1999; Helm et al., 1999; Bruckner et al., 2003a). This enables policy makers to express concern about the opportunity to compensate any losses suffered by any regions, sectors or generations by monetary transfers. In our opinion, it will be impossible to establish a complete, consistent and generally accepted valuation of climate impacts that could be represented by a globally aggregated climate damage function implying unrestricted substitution between different impact categories and regions (cf. Arrow et al., 1996a). We therefore do not recommend to use time-aggregated climate damage guardrails for policy advice in the framework of the tolerable windows approach, as long as a globally aggregated climate damage function is used. However, such guardrails can be a reasonable choice for limiting specific regional or sectoral damages. This applies, for instance, to impact categories that allow for an almost perfect monetary compensation, such as infrastructure damages in the energy sector.

2.5. Mitigation guardrails

Modelling the future path of anthropogenic GHG emissions is a difficult task riddled with uncertainties. This is reflected, e.g., in the IPCC Special Report on Emissions Scenarios (SRES) which stresses the point that global emissions futures emerging from a vast number of interactions in the socio-economic sphere are inherently unpredictable (Nakićenović and Swart, 2000). Anthropogenic CO_2 emissions can be factorized along the lines of the Kaya identity (Kaya, 1990).

$$\begin{aligned} CO_2 \text{ emissions} \quad = \quad & \text{carbon intensity } (CO_2 \text{ per unit energy}) \quad \times \\ & \text{energy intensity (energy per unit GWP)} \quad \times \\ & \text{GWP per capita} \times \text{population} \end{aligned}$$

We avoid to consider the socio-economic drivers of these macroeconomic variables explicitely. Instead, we specify the guardrails for the overall mitigation capacity of the socio-economic system on the aggregate level of global CO_2 emissions. In doing so, we proceed very much in the same way as we did for the climate impact guardrail T_{max}, which is not specified in terms of actual climate change impacts, but on the aggregate level of global mean temperature.

The freedom to do so emanates from the concept of emissions corridors. The optimization procedure approximating the corridor boundary automatically assumes that the unspecified socio-economic factors combine in a way so to generate emissions paths, which attain the highest (lowest) possible emissions under the given constraints. If we restrict the emissions behavior only by the least common denominator for admissible emissions futures, the resulting corridor will provide a 'best case' estimate in the sense that any further constraint on the socio-economic drivers could only narrow the corridor.

We have chosen two guardrails to exclude emissions paths inflicting intolerable mitigation burdens. The first guardrail specifies a maximum admissible reduction rate r of CO_2 emissions in the long run.

$$-\mathrm{r} \leq g(t) \quad \forall\, t \quad \text{with}\; g(t) = \dot{E}(t)/E(t) \tag{14}$$

The reduction rate can relate to various long-term developments in the drivers of anthropogenic CO_2 emissions. The majority of Post-SRES mitgation scenarios estimates the increase in carbon efficiency due to a phase-out of fossil fuels to be the most important factor for emissions reductions in the long run (Morita and Robinson, 2001, Fig. 2.18). In this sensitivity analysis, we consider maximum admissible long-term reduction rates of anthropogenic CO_2 emissions that range between 1%/a and 4%/a. In the latter 'fast reduction' case it is assumed that the replacement of fossil fuels happens as fast as the fossil capital stock depreciates. In the former 'slow' reduction case it is assumed that the expansion of backstop energy technologies like renewable energy is constrained by scarce investment and land surface resources, and increasing world energy demand reinforces the prolonged use of fossil fuels.

The second guardrail addresses the inertia in the socio-economic system and in particular the energy system. It is specified in terms of a minimum transition time t_{trans} to switch from currently growing emissions to decreasing emissions. The transition time is determined in particular by technological developments that are needed for lowering the costs of carbon-free backstop technologies. As these developments require a considerable amount of R&D investments and learning by doing beforehand, the inertia in the CO_2 emissions mitigation capacity is largely dominated by feasible learning rates and the potential for induced technological change in the backstop technology sector (cf. Edenhofer et al., 2004). Grubb (1997), for instance, has demonstrated empirically that without specific policies, new energy sources have taken about 50 years to penetrate from 1% to only 50% of their ultimate potential. In this sensitivity analysis, we consider transition times of 20 and 40 years. For illustrative purposes, we also investigate the idealized case of no inertia ($\mathrm{t_{trans}} = 0\,\mathrm{a}$).

Finally, we impose the plausibility constraint that growing global emissions can be followed by a reduction period, but not vice versa. We formulate this condition even stronger by asking that the growth rate itself does not grow at any point in time within the time horizon of the optimization. The strong formulation is mainly motivated by methodical considerations, since it enforces single-peaked emissions paths without jeopardizing the stability of the optimization algorithm. Since it requires the growth rate g to be constant or decreasing in time with a maximum growth rate g_o in the beginning (year 2001), some emissions scenarios, which, e.g., assume a switchback to coal after the exploitation of oil reserves, do not comply with it (for an example see marker scenario A2 in Nakićenović and Swart, 2000). However, the majority of emissions scenarios does so, and in the face of climate change the assumption of a constant or decreasing growth rate will be even more plausible.

We combine the condition of decreasing emissions growth and the guardrail on the transition time $\mathrm{t_{trans}}$ in the following inequality:

$$-\frac{\mathrm{g}_o + r}{\mathrm{t_{trans}}} \leq \dot{g}(t) \leq 0 \quad \forall\, t \tag{15}$$

Note that for very small transition times the change in the growth rate is almost unlimited from below, allowing for an abrupt switch in the emissions path.

In order to avoid highly uncertain 'business as usual' assumptions about future emissions paths, we interprete every emissions path not as the course of physical emissions, but as the distribution of emissions rights over time. Considering an 'emissions rights path' instead of a 'physical emissions path' allows us to neglect socio-economic assumptions about plausible emissions growth rates, since emissions rights can readily exceed the actual emissions. Thus, the initial CO_2 emissions growth rate g_o in equation (15) can be chosen to be equal or any value larger than the average emissions growth rate $\bar{\mathrm{g}}_o$ in the period 1995-2000. Accordingly, it is adjusted freely within the limit $\mathrm{g}_o \geq \bar{\mathrm{g}}_o$ by the optimization algorithm. In this way, we can restrict the total amount of emissions rights as well as their distribution over time solely by the

Table IV. The 138 parameter constellations considered for the sensitivity analysis.

Parameters	Cases considered
$T_{2CO_2} \times T_{max}$	$\{1.5\,°C, 2.5\,°C, 3.5\,°C, 4.5\,°C\} \times 2\,°C$ $\{2.5\,°C, 3.5\,°C, 4.5\,°C\} \times \{3\,°C, 4\,°C\}$
$\times$	$\times$
$r \times t_{trans}$	$\{0.01\,a^{-1},\ 0.02\,a^{-1},\ 0.04\,a^{-1}\} \times \{0\,a,\ 20\,a,\ 40\,a\}$
$T_{2CO_2} \times (T_{max}, b)$	$\{1.5\,°C, 2.5\,°C, 3.5\,°C, 4.5\,°C\} \times \{(2\,°C, 1), (2\,°C, 2), (2\,°C, 3)\}$
$\times$	$\times$
δ	$0\,a^{-1},\ 0.01\,a^{-1},\ 0.02\,a^{-1},\ 0.03\,a^{-1}$
$\times$	$\times$
$r \times t_{trans}$	$0.02\,a^{-1} \times 20\,a$

objective to avoid an intolerable climate change and unacceptable mitigation burdens.

2.6. Scope of the sensitivity analysis

The elements of the sensitivity analysis presented in this paper are summarized in Table IV. The uncertainty about the magnitude of the climate response is assessed by varying $T_{2CO_2} \in \{1.5\,°C, 2.5\,°C, 3.5\,°C, 4.5\,°C\}$. The different expectations about the limited resilience of human-environment systems to climate change are scanned by varying either a time-resolved guardrail on the maximum admissible amount of global mean temperature change ($T_{max} \in \{2\,°C, 3\,°C, 4\,°C\}$) or a time-aggregated climate damage limit proportional to $\tilde{T}^b_{max}$ with $\tilde{T}_{max} = 2\,°C$ and $b \in \{1, 2, 3\}$. The aggregation of climate damages is performed for four different rates of social time preference $\rho \in \{0\,a^{-1},\ 0.01\,a^{-1},\ 0.02\,a^{-1},\ 0.03\,a^{-1}\}$. Three assumptions about the maximum admissible emissions reductions rate $r \in \{0.01\,a^{-1}, 0.02\,a^{-1},\ 0.04\,a^{-1}\}$ are considered. The limitation on the transition pace towards a decoupling of economic growth and CO_2 emissions is varied in the range $t_{trans} \in \{0\,a, 20\,a, 40\,a\}$.

The upper boundaries of the emissions corridors are calculated for the period 2001-2100 in time steps of 5 years. The lower boundary is determined by a single minimum emissions path that decays exponentially with reduction rate r in the long run. The optimization tasks are subject to the dynamic constraints (3)-(5), the time-resolved global state constraints (8), or alternatively, the time-aggregated global state constraint (12), and the local constraints (14), (15). The time horizon t_{end} of all optimizations is set to the year 2300 in order to ensure that an emissions path peaking somewhere between 2001 and 2100 will not lead to a guardrail violation in the distant future. For the numerical discretization of the climate model (3)-(5), we apply a simple predictor-corrector scheme with a time step of one year. The package GAMS (General Algebraic Modeling System; Brooke et al., 1992) in combination with the solver CONOPT2 (Drud, 1992) is used for tackling the multiple nonlinear optimization problems.

3. Results

The results comprise 138 emissions corridors for all parameter constellations considered in the course of the sensitivity analysis (see Table IV). In order to present the results in a concise, yet comprehensive way, we employ the following strategy. In section 3.1 we investigate the corridor sensitivity to changes in T_{2CO_2}, r and t_{trans} and the time resolved climate impact guardrail T_{max} by varying one parameter while keeping the others fixed. In section 3.2 we explore the gedankenexperiment outlined in section 2.4, and analyse the corridor sensitivity to the time-aggregated climate damage guardrail $(\tilde{T}_{max}, b)$ for different values of climate sensitivity T_{2CO_2} and rates of time preference ρ. In section 3.3, we use the maximum admissible cumulative emissions in the year 2100 as an indicator to grasp the corridor sensitivity across all 90 parameter constellations (T_{max}, T_{2CO_2}, r, t_{trans}) for time-resolved climate impact guardrails.

3.1. Emissions corridors for time-resolved climate impact guardrails

Fig. 6 shows the enormous sensitivity of the emissions corridors to the choice of time-resolved climate impact guardrail. The size of the emissions corridor, i.e. the area between upper and lower boundary, shrinks considerably when moving from $T_{max} = 4\,°C$ to $T_{max} = 2\,°C$, leading to fundamental differences in the assessment of adequate emissions reductions. No immediate mitigation seems necessary for a guardrail $T_{max} = 4\,°C$, symbolizing the expectation of a high resilience of human-environment systems to climate change. In contrast, drastic mitigation measures are needed to observe the guardrail $T_{max} = 2\,°C$, which was explicitely proposed by the WBGU (1995). Global CO_2 emissions are not allowed to exceed 10 GtC at any time and must decrease after 2015 at the latest. A similarly large sensitivity of emissions corridors to the absolute temperature limit T_{max} was seen in the analysis of Tóth et al. (2003) that employed a sophisticated integrated economy-climate model. Note that the lower boundary of the corridors does not change for different choices of climate impact guardrails, since it depends solely on the mitigation guardrails, i.e. the maximum admissible reduction rate r and minimum transition time t_{trans}.

As can be seen in Fig. 7, the sensitivity of the global emissions corridor to a variation of T_{2CO_2} is of the same order of magnitude as it is to a variation of T_{max}. Moreover, a stepwise decrease of T_{2CO_2} seems to increase the corridor size even stronger than a stepwise increase of T_{max}. An explanation is provided by equation (4) and (5). Consider a change in $T_{max} \to T'_{max}$ and $T_{2CO_2} \to T'_{2CO_2}$. We can ask how an emissions profile touching the upper boundary of the emissions corridor for (T_{max}, T_{2CO_2}) must be scaled by a constant factor s, so that it touches again the upper boundary of the corridor for (T'_{max}, T'_{2CO_2}), i.e.

$$\text{what } s \text{ scales } E(t) \text{ with} \qquad T_{max} = \max_t T(C[E(t)], T_{2CO_2})$$

$$\text{to } s \cdot E(t) \text{ with} \qquad T'_{max} = \max_t T(C[\,s \cdot E(t)], T'_{2CO_2}) \;.$$

It is shown in the appendix that the factor s can be directly linked to the climate impact resilience parameter κ (see equation 9) by neglecting the short-term behavior of the carbon-cycle and the different delays of the climate response for different T_{2CO_2}. In this approximation, with $c(t_{max})$ the atmospheric carbon dioxide concentration relative to its preindustrial value upon reaching T_{max} at time t_{max}, it is

$$s \approx \frac{c(t_{max})^{\kappa'/\kappa} - 1}{c(t_{max}) - 1} \qquad \text{for } \kappa' \geq \kappa \;. \qquad (16)$$

The increase in corridor extension is governed exponentially by the relative change in the climate response parameter κ, which in turn is proportional to T'_{max}/T_{max} and inverse proportional to T'_{2CO_2}/T_{2CO_2}. Therefore the overall emissions maneuvering space increases significantly faster as we move from medium to low T_{2CO_2} (or low to medium T_{max}) than from high to medium T_{2CO_2} (or medium to high T_{max}). A reduction of the uncertainty range of T_{2CO_2} on its lower bound is very important for narrowing the “best case” emissions leeway.

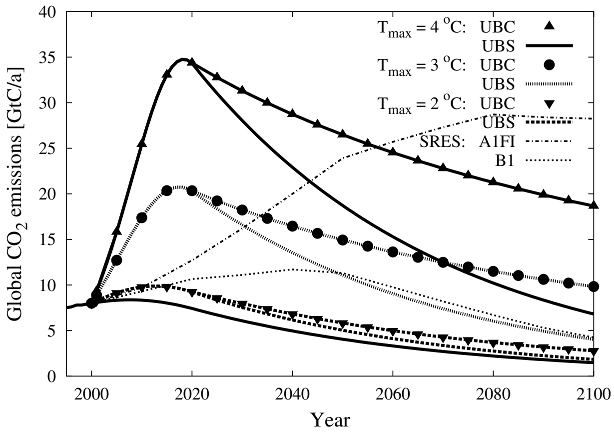

Figure 6. Emissions corridors and their largest sufficient subsets for $T_{max} = 2\,^{\circ}C$, $3\,^{\circ}C$ and $4\,^{\circ}C$ and fixed (T_{2CO_2}, r, t_{trans}) = ($3.5\,^{\circ}C$, $0.02\,a^{-1}$, 20 a). The upper corridor boundary (**UBC**) and the upper boundary of the largest sufficient subset (**UBS**) vary with T_{max}. The lower boundary is common to all corridors and subsets. SRES scenarios A1FI and B1 represent a high and low emissions projection, respectively, for the 21^{st} century (Nakićenović and Swart, 2000).

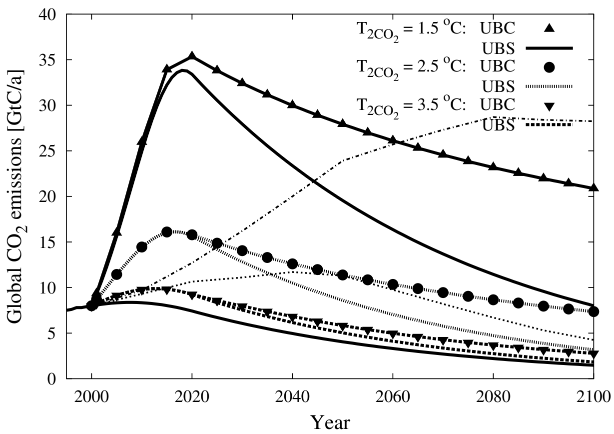

Figure 7. Emissions corridors and their largest sufficient subsets for $T_{2CO_2} = 1.5\,^{\circ}C$, $2.5\,^{\circ}C$ and $3.5\,^{\circ}C$ and fixed (T_{max}, r, t_{trans}) = ($2\,^{\circ}C$, $0.02\,a^{-1}$, 20 a). The upper corridor boundary (**UBC**) and the upper boundary of the largest sufficient subset (**UBS**) vary with T_{2CO_2}.The lower boundary is common to all corridors and subsets. Also shown are the SRES scenarios A1FI and B1 (see figure key of Fig. 6).

Fig. 8 depicts the emissions corridors for different maximum admissible reduction rates r. Note that the exponential decay of the lower

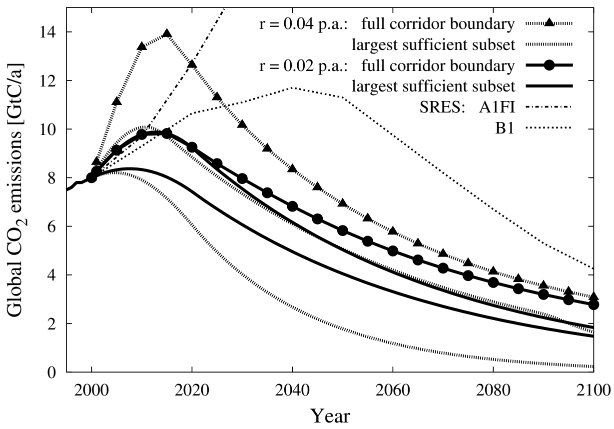

Figure 8. Emissions corridors and their largest sufficient subsets for $r = 0.02\,a^{-1}$ and $0.04\,a^{-1}$ and fixed $(T_{2CO_2}, T_{max}, t_{trans}) = (2\,°C,\ 3.5\,°C,\ 20\,a)$. Both upper and lower boundaries vary with the parameter r. Corridors and sufficient subsets exhibit the same lower boundary. The y-axis is scaled differently than in Fig. 6 and 7.

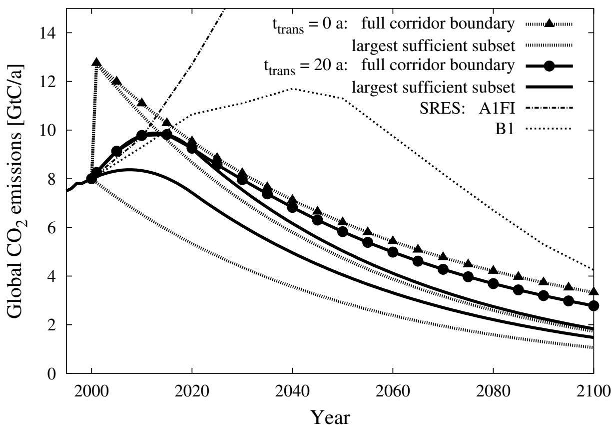

Figure 9. Emissions corridors and their largest sufficient subset for $t_{trans} = 0$ and 20 years and fixed $(T_{max}, T_{2CO_2}, r) = (2\,°C,\ 3.5\,°C,\ 0.02\,a)$. Both upper and lower boundaries vary with the parameter t_{trans}. Corridors and sufficient subsets exhibit the same lower boundary.

corridor boundary changes along with r. This change can be crucial for unfavourable combinations of T_{max} and T_{2CO_2}. If the admissible reduction rate r were to be lowered to $0.01\,a^{-1}$, the lower and upper boundary would overlap in the second half of the 21st century. This means that no emissions paths can observe all guardrails simultaneously, and the corridor ceases to exist.

The change in the upper boundary reflects the change in the emissions reductions ability. The growing ‘hill’ at the beginning of the 21[st] century for growing r is due to emissions paths which use the high reduction capacity in the long run to attain high emissions values in the short term. Another indicator for the increase in emissions flexibility for increasing r is the growing divergence between the size of the corridor and its largest sufficient subset. For $r = 0.04\,a^{-1}$, the upper boundary of the corridor is constituted by extreme up/down emissions paths, which overshoot the upper boundary of the sufficient subset, i.e. the path maximizing cumulative emissions in 2100 (see section 2.1), for a short time period.

Fig. 9 shows the emissions corridors for different minimum transition times t_{trans}. The guardrail has a strong impact on the lower boundary by determining the residual rise of emissions until the trend can be reversed. It also influences the upper boundary in connection with the climate impact guardrail by constraining the maximum admissible initial growth rate of emissions. In the second half of the 21[st] century, however, the influence of economic inertia on the corridors diminishes considerably.

The SRES scenario B1 depicting a sustainable, globalized future is among the lowest emissions projections of Nakićenović and Swart (2000), but nevertheless leaves the corridor for any choice of mitigation guardrails r and t_{trans} in the case $(T_{max}, T_{2CO_2}) = (2\,°C,\ 3.5\,°C)$. This indicates the need for a climate policy, but does not tell very much about the necessity of short term commitments as stipulated, for instance, by the Kyoto protocol. It can be seen from Fig. 8 and 9 that a high emissions flexibility, i.e. a short transition time t_{trans} and a high reduction rate r, can allow for ‘wait then run’ emissions paths frequently advocated in the context of cost-effectiveness analyses (cf. Wigley et al., 1996) without jeopardizing the climate impact guardrail. However, if the mitigation capacity is in the vicinity of $r = 0.02\,a^{-1}$ and $t_{trans} = 20\,a$, stringent short term commitments become mandatory. The Kyoto protocol, for instance, does not seem to be sufficient to stabilise global CO_2 emissions below 10 GtC before 2015, as it would be required for $T_{max} = 2\,°C$ and $T_{2CO_2} = 3.5\,°C$. The discussion shows that different assumptions about the *economic parameters* r, t_{trans} can fundamentally change the assessment of adequate climate policies, as has been seen before for the *resilience parameters* T_{max}, T_{2CO_2}.

Comparing Fig. 6 and 7 with Fig. 8 and 9, it is obvious that the resilience parameters T_{max} and T_{2CO_2} influence the emissions corridor in a very different way than the economically motivated parameters r and t_{trans}. The former have a major impact on the overall size of the corridor by shifting the level of the upper boundary between low and high emissions values. The latter influence in particular the shape of lower and upper boundary. This shows itself in their large impact on the corridor size in the early 21st century (parameter t_{trans}), as well as in a considerable shift of the lower boundary in the late 21st century (parameter r). Using the metaphor of a ship's passage, we can characterize the different roles of resilience and economic parameters as follows. The former affect the maneuvering space by determining the coastlines of the strait, while the latter affect the maneuvering space by determining the maneuvering capacity of the ship.

Only for a high climate impact resilience κ, the mitigation guardrails will play a minor role (cf. section 3.3). If, in contrast, the climate parameters T_{max} and T_{2CO_2} narrow the coastlines of the strait considerably, the maneuvering capacity will determine whether the passage is feasible at all, and how much effort it will take. The mitigation guardrails relate to economic factors by indicating a regime of increasingly unbearable abatement costs (see section 2.5). Thus, if the passage requires to maneuver 'at the limits', the economic costs will be considerably higher than for 'every day' maneuvers. However, it is important to note that the maneuvering capacity itself might be to some extent manageable by mankind. Technological innovation, for instance, has the potential to reduce the minimum transition time t_{trans} and increase the maximum long-term reduction rate r. In this way, passages can become feasible that seemed to be impassable given the current state of the socio-economic system (Edenhofer et al., 2004). Such effects might also change the assessment of short-term commitments, if it is assumed that such commitments can influence not only the actual emissions paths, but also the overall maneuvering capacity (Grubb, 1997).

3.2. Emissions corridors for time-aggregated climate damage guardrails

Time-aggregated climate damage guardrails specified in terms of the proxy variable $\tilde{T}_{max}$ are less restrictive than the corresponding time-resolved climate impact guardrails with $T_{max} = \tilde{T}_{max}$, since a temporary exceedance of $\tilde{T}_{max}$ can be compensated by $T < \tilde{T}_{max}$ during other periods in time. As was pointed out in section 2.4, such a type of guardrail can only be sensible if it aims at limiting a gradual climate change that inflicts damages which can be compensated in time. Fig. 10 shows the sensitivity of the corridors to the adoption of a time-aggregated guardrail $\tilde{T}_{max} = 2\,°C, b = 2$ vs. a time-resolved guardrail $T_{max} = 2\,°C$ for two different values of climate sensitivity. Here we have assumed that the decision maker exhibits no time preference ($\rho = 0\,a^{-1}$ in equation 12), so that the time-aggregated guardrails require the relative damages $d(t) \sim T(t)^2$ to be below $\tilde{\mathrm{T}}_{\max}^2$ on the average. Compared to the case of time-resolved guardrails, the size of the corridor approximately doubles for low to medium climate sensitivity ($\mathrm{T}_{2\mathrm{CO}_2} = 2.5\,°\mathrm{C}$) and nearly triples for medium to high climate sensitivity ($\mathrm{T}_{2\mathrm{CO}_2} = 3.5\,°\mathrm{C}$).

The picture changes even more drastically, if we consider a decision maker with a PRTP $\rho > 0\,\mathrm{a}^{-1}$. As pointed out in section 2.4, the adoption of a positive PRTP devaluing the prospects of future generations compared to the prospects of the present-day generation needs to be justified on normative grounds in the framework of the TWA. A comparison of Fig. 10 and Fig. 11 illustrates the large difference in emissions corridors for the two PRTPs $\rho = 0\,\mathrm{a}^{-1}$ and $\rho = 0.02\,\mathrm{a}^{-1}$. The positive PRTP shifts the upper corridor boundary upwards over the whole period 2000-2100, but the effect grows enormously towards the end of the 21st century. As an example, consider the case $\mathrm{T}_{2\mathrm{CO}_2} = 2.5\,°\mathrm{C}$. While in the year 2015 the maximum admissible emissions for a time-aggregated guardrail with $\rho = 0.02\,\mathrm{a}^{-1}$ are 1.6 times higher than for $\rho = 0\,\mathrm{a}^{-1}$, and 2.4 times higher than for the corresponding time-resolved guardrail $\mathrm{T}_{\max} = \tilde{\mathrm{T}}_{\max}$, these ratios grow to 4.3 and 7.2, respectively, in the year 2100. Due to the discounting of violations $T > \tilde{\mathrm{T}}_{\max}$ in the distant future, the upper corridor boundary bends upwards in the long term.

The widening of emissions corridors when moving from a time-resolved guardrail $\mathrm{T}_{\max}$ to the corresponding time-aggregated guardrail with $\tilde{\mathrm{T}}_{\max} = \mathrm{T}_{\max}$ depends not only on the assumption about the PRTP, but also on the damage function exponent b. The more nonlinear the dependence of damages on GMT increase, the larger is the penalty for exceeding $\tilde{\mathrm{T}}_{\max}$ at a given point in time. Thus, we expect that the widening of corridors is less pronounced, the higher the damage function exponent is assumed to be. Fig. 12 shows that this effect is neglectable for the case $\rho = 0\,\mathrm{a}^{-1}$. However, the sensitivity of emissions corridors to the exponent b grows considerably, if positive PRTPs $\rho > 0\,\mathrm{a}^{-1}$ are considered. As illustrated in Fig. 12 for the case $\rho = 0.02\,\mathrm{a}^{-1}$, using a high damage function exponent b = 3 partly counteracts the effect of the positive PRTP, although the influence of the PRTP on the corridor clearly dominates. In the other direction, b = 1 allows for a considerably steeper upward trend in the corridor boundary.

Fig. 13 allows to compare the emissions corridors for the time-aggregated guardrail $\tilde{\mathrm{T}}_{\max} = 2\,°\mathrm{C}$, b = 2 for different values of the PRTP. It can be seen that the size of the corridor as well as the upward trend of the upper boundary in the long term is amplified nonlinearly when increasing the PRTP stepwise from $\rho = 0\,\mathrm{a}^{-1}$ to $\rho = 0.03\,\mathrm{a}^{-1}$. For the latter case, the upper corridor boundary can even increase exponentially under a global time-aggregated damage guardrail. An inspection of the the upper boundary of the largest sufficient subsets, i.e. the emis-

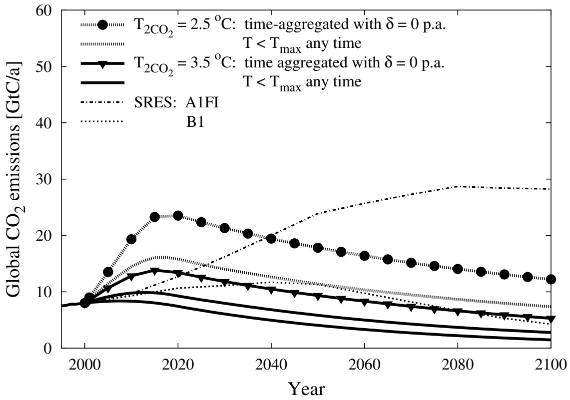

Figure 10. Emissions corridors for the time-aggregated climate damage guardrail $\tilde{\mathrm{T}}_{\max} = 2\,^{\circ}\mathrm{C}, \mathrm{b} = 2$, and the assumption of no time preference ($\delta = 0\,\mathrm{a}^{-1}$) for two different values of climate sensitivity $\mathrm{T}_{2\mathrm{CO}_2} = 2.5\,^{\circ}\mathrm{C}$, $3.5\,^{\circ}\mathrm{C}$ and fixed $(\mathrm{r}, \mathrm{t}_{\mathrm{trans}}) = (0.02\,\mathrm{a}^{-1}, 20\,\mathrm{a})$. Shown are also the corresponding corridors for the time-resolved climate impact guardrail $\mathrm{T}_{\max} = 2\,^{\circ}\mathrm{C}$ (cmp. fig. 7). The lower boundary is common to all corridors.

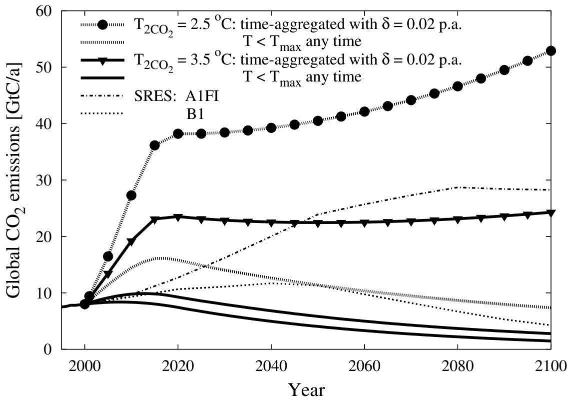

Figure 11. Emissions corridors for the time-aggregated climate damage guardrail $\tilde{\mathrm{T}}_{\max} = 2\,^{\circ}\mathrm{C}, \mathrm{b} = 2$, and a pure rate of time preference $\delta = 0.02\,\mathrm{a}^{-1}$ for two different values of climate sensitivity $\mathrm{T}_{2\mathrm{CO}_2} = 2.5\,^{\circ}\mathrm{C}$, $3.5\,^{\circ}\mathrm{C}$ and fixed $(\mathrm{r}, \mathrm{t}_{\mathrm{trans}}) = (0.02\,\mathrm{a}^{-1}$, $20\,\mathrm{a})$. Shown are also the corresponding corridors for the time-resolved climate impact guardrail $\mathrm{T}_{\max} = 2\,^{\circ}\mathrm{C}$ (cmp. Fig. 7, 10). The lower boundary is common to all corridors.

sions profile maximizing cumulative emissions in the year 2100, shows that a positive PRTP favours high emissions values in the distant future. The sufficient subsets are “shifted” towards later times as the PRTP increases. For $\rho = 0\,\mathrm{a}^{-1}$, the subset boundary follows closely the upper corridor boundary in the early 21$^{\mathrm{st}}$ century, as was seen before

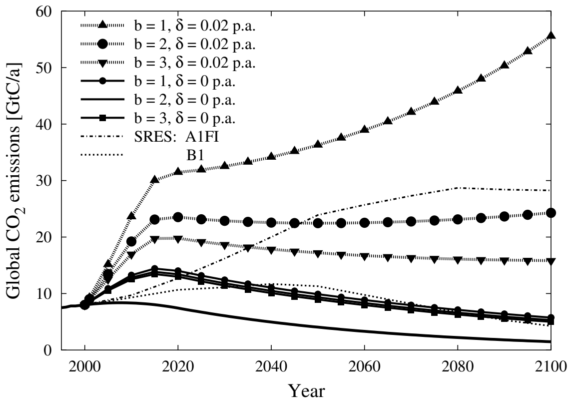

Figure 12. Emissions corridors for time-aggregated climate damage guardrails $\tilde{T}_{max} = 2\,°C$ with three different assumptions about the damage function exponent b = 1, 2, 3 and two different pure rates of time preferences $\delta = 0\,a^{-1}$, $0.02\,a^{-1}$ for fixed (T_{2CO_2}, r, t_{trans}) = (3.5 °C, $0.02\,a^{-1}$, 20 a). The lower boundary is common to all corridors.

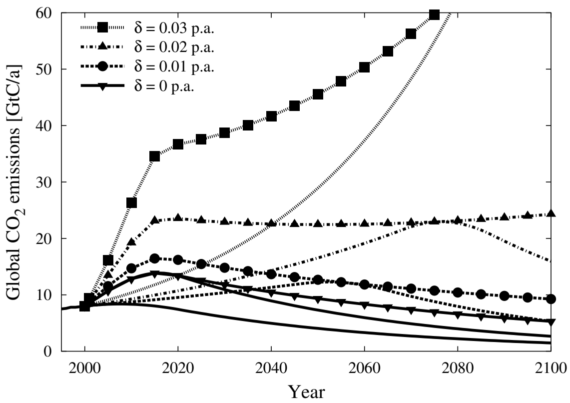

Figure 13. Emissions corridors for the time-aggregated climate damage guardrail $\tilde{T}_{max} = 2\,°C, b = 2$, for different pure rates of time preferences $\delta = 0\,a^{-1}$, $0.01\,a^{-1}$, $0.02\,a^{-1}$, $0.03\,a^{-1}$ and fixed (T_{2CO_2}, r, t_{trans}) = (3.5 °C, 0.02 a^{-1}, 20 a). Shown are the upper boundary of the corridors (line interspersed with point symbols) as well as the upper boundary of the largest sufficient subsets (line only). The lower boundary is common to all corridors.

for the case of time-resolved climate impact guardrails (cf. section 3.1). For $\rho = 0.03\,a^{-1}$ however, the subset boundary reaches the upper corridor boundary only in the late 21st century, and follows closely an emissions profile that maximizes emissions in the period 2080-2090. All this indicates that a positive PRTP can alter both the size and shape of emissions corridors dramatically, as long as only a time-aggregated global damage guardrail is considered.

The results of this gedankenexperiment show a sensitivity to the choice of PRTP that is in qualitative agreement with well known results from cost-benefit analyses. For a commonly used PRTP $\rho = 0.03\,\mathrm{a}^{-1}$, most cost-benefit analyses recommend to delay serious action against climate change (Nordhaus, 1994a; Nordhaus and Boyer, 2000). While this outcome of cost-benefit analyses is very sensitive to the choice of the PRTP (Nordhaus, 1994a; Mastrandrea and Schneider, 2001), it is also influenced strongly by other important assumptions such as the choice of the damage function exponent b (Roughgarden and Schneider, 1999). In contrast, the sensitivity analysis presented here identifies the PRTP as the dominant factor influencing the stringency of a time-aggregated climate damage guardrail. This is partly due to the fact that we have assumed a steady-state optimal growth which is not disrupted by any climate impacts whatsoever large, when constructing the specific form (12) of climate damage guardrails used in this analysis. Thus, the climate impacts on the cause-effect chain in which each generation is embedded are not captured endogenously, and guardrail (12) is likely to take on a different form, when climate impacts reach an order of magnitude that has the potential to slow or even disrupt growth of GWP.

This reinforces our discussion in section 2.4 that the analysis of globally aggregated climate damage guardrails presented here is rahter a gedankenexperiment than a policy-relevant exercise. In the framework of the TWA, the choice of a time-aggregated damage guardrail including the choice of a PRTP is a normative one. Adopting a pure rate of time preference exhibited by present-day market actors therefore cannot be justified on purely descriptive grounds. Moreover, a sensible application of time-aggregated guardrails should be restricted to categories where damages can be compensated in time. By the same token, regional or sectoral aggregates of damage guardrails are only reasonable choices, if damages can be compensated across regions and sectors. Due to these limitations, we do not think that policy-relevant climate damage guardrails based on global climate damage estimates can be established. However, such guardrails can be reasonable choices for limiting specific regional or sectoral damages

3.3. Overall sensitivity of emissions corridors

Having discussed the sensitivity of emissions corridors to time-aggregated climate damage guardrails with various assumptions about the pure rate of social time preference, we return to the case of time-resolved climate impact guardrails. To assess the sensitivity of emissions corridors for this case across the full range of parameter constellations for this case, we need to condense the information contained in a corridor into a single index. For this purpose we have chosen the *maximum admissible cumulative emissions in the period 2000-2100 (MACE)*. MACE can be calculated by maximizing the cumulative emissions until the year 2100 subject to the constraints (8),(14) and (15). Note that the resulting emissions path is the upper boundary of the largest sufficient subset of the emissions corridor. Admittedly, MACE cannot capture a variety of information such as the shape of the corridor boundaries. However, it provides an intuition for the size of the CO_2 emissions leeway in the 21^{st} century. We wish to point out that the exclusive rather than inclusive character of the guardrails implies that any cumulative emissions exceeding MACE corresponds to an intolerable emissions future with respect to the prescribed guardrails, while cumulative emissions below MACE are by no means necessarily tolerable.

We use the latest IPCC scenarios for global CO_2 emissions futures in the 21^{st} century (SRES scenarios; Nakićenović and Swart, 2000) to put the calculated MACE values for the 90 parameter constellations into perspective. A classification of SRES scenarios in terms of cumulative emissions until 2100 that was put forward in Figure SPM-4a, pg.8, in Nakićenović and Swart (2000) is employed to characterize the MACE values in terms of how far they are exceeded by the highest SRES emissions future. Intuitively, this exceedance can be interpreted as a measure for the stringency of cumulative emissions reductions that have to be achieved for observing the climate impact guardrail T_{max}. Table V relates the classification of global MACE to the original classification of future global emissions scenarios in Nakićenović and Swart (2000). The color coding is employed to aid the presentation of MACE values across all cases under consideration.

The sensitivity of global MACE values to the 90 constellations of $(T_{max}, T_{2CO_2}, r, t_{trans})$ is shown in Fig. 14. White cells depict the cases where no corridor exists, i.e. all possible futures are intolerable under the given constraints. It should be obvious that the color coding can only be used for comparisons on relative terms. It has no implications whatsoever for an absolute 'averaged' magnitude of emissions reductions, since the frequency of occurence of the various classes depend solely on our subjective choice of the parameter constellations.

In each column the cases are ordered from low to high climate impact resilience in terms of $\kappa = T_{max}/T_{2CO_2}$. As illustrated by the predominantly horizontal partitioning of MACE values into classes, this quantity dominates the size of the emissions leeway, and thus the magnitude of MACE. Deviations from this ordering scheme due the increasing de-

Table V. Correspondence between the original classification of SRES cumulative emissions (Nakićenović and Swart, 2000) for the period 2000-2100 and the classification of maximum admissible cumulative emissions in 2000-2100 (MACE) deduced from it. Note that the change in numbers as compared to Fig. SPM-4a, pg. 8 in Nakićenović and Swart (2000) is due to the consideration of the period 2000-2100 instead of 1990-2100.

Scenario / MACE range	SRES classification	classification of MACE	
cumulative emissions for the period 2000 - 2100		Amount of emissions reductions likely to be	Color
> 2450 GtC	above SRES range	neglectable	dark blue
1720 - 2450 GtC	high	weak	light blue
1370 - 1720 GtC	medium high	medium weak	green
1020 - 1370 GtC	medium low	medium strict	yellow
650 - 1020 GtC	low	strict	light red
< 650 GtC	below SRES range	severe	magenta

lay of climate response for increasing T_{2CO_2} can be seen for the pairs ($\kappa = 1.20,\ \kappa = 1.14$) and ($\kappa = 0.89,\ \kappa = 0.86$). In the former case, the lower value of κ is counteracted by the delay in GMT response, which leads to a smaller maximum GMT increase (see Appendix). In the latter case, the difference in the κ values is amplified by the same effect. Note that the case $\kappa = 1.6$ leads to atmospheric CO_2 levels of 1000 - 1100 ppmv, which is far beyond the linearization limit of equation (4), and therefore has to be considered with care.

In each row the cases are ordered along the lines of the economically motivated parameters r and t_{trans}. The MACE values increase slightly with increasing emissions flexibility. While the increase in MACE with decreasing t_{trans} seems to be rather linear, a doubling of the maximum admissible reduction rate from $r = 0.01\,a^{-1}$ to $r = 0.02\,a^{-1}$ increases MACE much more strongly than a doubling from $r = 0.02\,a^{-1}$ to $r = 0.04\,a^{-1}$. For a corridor to exist, its upper boundary needs to be located entirely above its lower boundary. Therefore the mitigation guardrails are as important as κ for determining the very existence of a corridor. As Fig. 14 shows, the cases without admissible solutions are located in the corner with the lowest emissions flexibility and lowest climate impact resilience κ.

Maximum Cumulative Emissions in 2100 (GtC)	r=0.04 t=0 a	r=0.04 t=20 a	r=0.04 t=40 a	r=0.02 t=0 a	r=0.02 t=20 a	r=0.02 t=40 a	r=0.01 t=0 a	r=0.01 t=20 a	r=0.01 t=40 a
T_{max} = 4 °C T_{2CO}=2.5 °C κ =1.60	***3070***	***3024***	***2984***	***3052***	***2973***	***2881***	***2823***	***2705***	***2577***
T_{max} = 2 °C T_{2CO}=1.5 °C κ = 1.33	**1944**	**1906**	**1874**	**1944**	**1902**	**1863**	**1908**	**1846**	**1780**
T_{max} = 3 °C T_{2CO}=2.5 °C κ = 1.20	**1826**	**1801**	**1782**	**1824**	**1789**	**1750**	**1714**	**1661**	**1603**
T_{max} = 4 °C T_{2CO}=3.5 °C κ = 1.14	**1928**	**1911**	**1894**	**1891**	**1850**	**1802**	**1701**	**1646**	**1587**
T_{max} = 4 °C T_{2CO}=4.5 °C κ = 0.89	**1420**	**1410**	**1397**	**1370**	**1339**	**1309**	**1206**	**1168**	**1135**
T_{max} = 3 °C T_{2CO}=3.5 °C κ = 0.86	**1163**	**1152**	**1145**	**1154**	**1133**	**1113**	**1059**	**1031**	**1007**
T_{max} = 2 °C T_{2CO}=2.5 °C κ = 0.80	**910**	**900**	**895**	**910**	**898**	**890**	**879**	**861**	**848**
T_{max} = 3 °C T_{2CO}=4.5 °C κ = 0.67	**848**	**843**	**840**	**834**	**821**	**810**	**751**	**737**	**--**
T_{max} = 2 °C T_{2CO}=3.5 °C κ = 0.57	**562**	**559**	**558**	**561**	**557**	**--**	**535**	**--**	**--**
T_{max} = 2 °C T_{2CO}=4.5 °C κ = 0.44	**383**	**382**	**--**	**382**	**--**	**--**	**--**	**--**	**--**

Figure 14. Maximum admissible cumulative emissions in the period 2000-2100 (MACE) for all combinations of T_{max}, T_{2CO_2}, r, t_{trans}. See Table V for the color rating. White cells denote the non-existence of a corridor. The case (T_{max} = 4 °C, T_{2CO_2} = 2.5 °C, *italic*) allows for atmospheric CO_2 levels above 1000 ppmv, and therefore has to be considered with care given the limitations of the carbon cycle model.

The most striking feature of Fig. 14 is the enormous sensitivity of MACE values to κ. As we change κ from 1.6 to 0.44, we move from MACE values questioning the necessity of any emissions reductions (dark blue) to values indicating a strong need for a severe cut on cumulative emissions (magenta). For $\kappa = 0.44 - 0.67$ we even find regimes where no emissions profile whatsoever would yield an admissible outcome as defined by the guardrails. The clear-cut dependence of MACE on κ suggests an, admittedly crude, classification of emission reduction regimes along the lines of table V. For $\kappa > 1.5$ such a regime is likely to be superfluous, while the cumulative amount of necessary emissions cuts increases from *weak to medium* ($1.5 \geq \kappa > 1.0$) to *medium to strong* ($1.0 \geq \kappa > 0.5$) and finally *severe* ($0.5 \geq \kappa$) as κ decreases. To put these numbers into perspective, Füssel and van Minnen (2001) calculate values of $\kappa = (0.2 - 0.3,\ 0.5 - 0.6,\ 0.8 - 0.9,\ 1 - 1.2)$ to prevent an average $(10\%, 20\%, 30\%, 40\%)$ change of biome types in the world's protected areas. Tóth et al. (2003) use this indicator for the specification of climate impact guardrails. They show that the emissions corridors resulting from their model setting are very sensitive to the choice of maximum admissible fractional biome change. This supports our assessment about the important role of the climate impact resilience parameter κ.

However, we must be careful to equate the amount of cumulative emissions cuts with the timing and the costs of a climate policy regime. As pointed out in section 3.1, the concrete configuration of a policy regime as well as the associated economic costs will depend strongly on the assumption about the mitigation guardrails. If, for example, emissions flexibility is assumed to be high, large emissions reductions can be realized in the long run without imposing restrictive short term emissions quotas. If, however, emissions flexibility is perceived to be low then a stringent climate policy in the early 21^{st} century seems to be mandatory for low to medium climate impact resilience $\kappa < 0.8$. Thus, the assumptions on both the climate impact resilience condensed in the parameters T_{max} and T_{2CO_2} and the emissions flexibility captured in the parameters r and t_{trans} are crucial for evaluating the adequacy of a particular climate policy.

Our results can be compared qualitatively to other sensitivity studies that employ alternative decision-making frameworks. A multitude of cost-effectiveness analyses assess different stabilization levels for atmospheric CO_2 concentrations (cf., e.g., Richels and Edmonds, 1995, Wigley et al., 1996, Manne and Richels, 1997). CO_2 stabilization levels can be linked roughly to assumptions about the climate impact resilience parameter $\kappa = T_{max}/T_{2CO_2}$. In the given model setting, excluding other than CO_2 greenhouse gases, stabilization levels of (450, 550, 750, 1000 ppmv) imply values of $\kappa = (0.5 - 0.6, 0.7 - 0.9, 1.1 - 1.4, > 1.5)$. Most cost-effectiveness analyses show that mitigation costs increase significantly, when the stabilization target is set below 500 ppmv (Manne and Richels, 1997). This agrees roughly with the area in Fig. 14, where corridors cease to exist for limited mitigation capacity r and t_{trans}. Most cost-effectivenes analyses recommend to delay early mitigation actions, thus advocating emissions profiles that follow the upper boundary of the corridors in the early 21^{st} century (Wigley et al., 1996). This is to be expected, since a cost-effective analysis amounts to choosing the 'least-cost' - with respect to mitigation costs - 'admissible' - with respect to the climate impact guardrail - emissions profile from the corridors. However, the discussion in section 3.1 shows that the delay of early emissions reductions hinges crucially on assumptions about the inertia of the economic system and its long-term reduction ability. Ha-Duong et al. (1997) draw a similar conclusion for the influence of economic inertia on cost-effective emissions paths.

Multi-agent modelling approaches have been used to frame the largely diverging assumptions about key parameters of the climate change debate in terms of different cultural perspectives (Van Asselt and Rotmans, 1996). Janssen and de Vries (1998), for example, take on a similar broad perspective as we do here by linking parameters relating to climate impact resilience (climate sensitivity, climate damage costs) and mitigation capacity (mitigation costs, technological progress) to three agents with different approaches to climate change. They show that misguided assumptions about the nature of the climate change issue ('dystopias') can lead to extremely inadequate climate policies. This finding is supported by the large sensitivity of emissions corridors to the set of parameters consideed here.

Given the strong dependence of adequate climate policies on key parameters, several authors have advocated robust rather than cost-efficient strategies for climate protection (cf. Lempert and Schlesinger, 2000). The large differences between emissions corridors for different parameter settings indicate that 'One Shot' climate policies are unlikely to be robust in the sense that they cannot guarantee to avoid the intolerable domain as long as size and shape of the 'true' emissions leeway are unknown. This supports the adoption of adaptive climate protection strategies that can react to a stepwise resolution of the large uncertainty surrounding the climate change issue (Lempert et al., 1996). In exploratory modeling (Bankes, 1993), the robustness of such strategies has been frequently assessed in terms of their regret relative to the optimal strategy under certainty across the uncertainty space (see, e.g., Lempert et al., 2000, Robalino and Lempert, 2000). It is interesting to note that emissions corridors provide an alternative criterion for robustness: robust adaptive strategies are those that do not leave the emissions corridors for all possible parameter constellations. Thus, the sensitivity of emissions corridors to key assumptions in the climate change debate can be used as background information for the construction of robust climate policies on the basis of more resolved integrated assessment models.

4. Conclusions

The analysis presented in this paper provides a rather broad panoramic view across pertinent issues of the climate change debate. We have considered uncertain key parameters for the assessment of climate protection policies, which are related to different expectations about the severity of climate impacts, the magnitude of the climate response, the feasibility of mitigation efforts, and the pace of decoupling emissions from economic growth. Naturally the broad perspective comes at the expense of the resolution of the sight. We have combined a simple climate model with first-order assumptions about the future emissions behavior to scan the sensitivity of the emissions leeway in the 21^{st} century to the aforementioned parameters.

In doing so, the framework of the tolerable windows approach allows us not only to formalize the notion of a leeway, but also aids us in taking on such a broad and coarse perspective. As the guardrails are meant to exclude the intolerable domain of climate change as well as inacceptable mitigation policies, we can identify the last frontiers to intolerability by employing least-common-denominator-type assumptions. This leaves the exploration of the tolerable domain and the selection of preferable policy paths to other more detailed studies with more sophisticated Integrated Assessment models (Manne et al., 1995; Morgan and Dowlatabadi, 1996; Tol, 1997; Alcamo et al., 1998; Nordhaus and Boyer, 2000; Tóth et al., 2003; Edenhofer et al., 2004).

In this respect, the analysis presented here could be extended fruitfully by including some important parameters and relationships neglected so far. In calculating the climate response we did not consider non-CO_2 greenhouse gases and aerosols, nonlinear feedbacks in carbon cycle and temperature response and the uncertainty in radiative forcing estimates (Visser et al., 2000). Addressing these issues requires the application of a comprehensive integrated assessment climate model like, for instance, the ICLIPS climate model (Bruckner et al., 2003b) that was used for a more focused sensitivity analysis of emissions corridors in Tóth et al. (2003). With regard to the emissions behavior, the economically motivated constraints were not allowed to change over time. In addition, the assumption of a single global emitter is highly idealized. In Kriegler and Bruckner (2002, 2003) we have relaxed this assumption, and considered the industrial and developing countries as two distinct emitters. Obviously, a sensitivity analysis can only be considered a first step towards a comprehensive uncertainty analysis. Taking into account probabilities in the derivation of emissions corridors under risk constitutes a challenging line of ongoing research on the further development of the TWA (cf. Bruckner et al., 1999, Zickfeld and Bruckner, 2004).

The underlying simple model has allowed us to extend the methodological basis for the calculation of emissions corridors by retrieving some information about their inner structure. We have provided a simple method to calculate the largest sufficient subset of emissions corridors for a special type of dynamic systems. We also have developed a concept to consider time-aggregated climate damage guardrails in the framework of the tolerable windows approach. Such guardrails can be a sensible choice if they are imposed on gradual climate change impacts in specific regions and sectors that can be compensated in time. Time-aggregated guardrails enlarge the emissions maneuvering space considerably, since they allow a temporary violation of a prescribed temperature limit. If a pure rate of social time preference is applied to the intertemporal aggregation, the emissions corridor can be substantially widened in the long run. However, it must be noted that in the framework of the TWA a time preference $\rho > 0$ corresponds to the purely normative judgement of the decision maker that it is reasonable to devalue the prospects of future generations (cf. Lind, 1995, Arrow et al., 1996b).

A main result of our analysis is the identification of the different roles that the uncertain resilience and economic parameters play in determining the emissions maneuvring space for the 21^{st} century. Roughly speaking, the resilience parameters, i.e the climate impact guardrail on GMT increase and climate sensitivity, have a dominant influence on the overall extension of the emissions corridors, while the economic factors, i.e. the maximum reduction rate in the long term and the minimum transition time of the economic system, affect predominantly the shape of the corridors and the timing of emissions reductions (cf. Tóth et al., 2003). Since the economic factors also determine the lower corridor boundary, they are as crucial as the climatic parameters for the very existence of an emissions corridor.

In an approximation, the corridor size can be linked to a climate impact resilience parameter $\kappa = \mathrm{T}_{\mathrm{max}}/\mathrm{T}_{2\mathrm{CO}_2}$, which provides a simple, but meaningful way to blend assumptions about the magnitude of and the vulnerability to climate change. Therefore it may be used to classify the cumulative amount of required emissions reductions. The analysis presented here suggests that for $\kappa > 1.5$ emissions reductions are likely to be superfluous, while they are required to be *weak to medium* for $1 \leq \kappa < 1.5$, *medium to strong* for $0.5 \leq \kappa < 1$ and finally *severe* for $0.5 \leq \kappa$. However, the configuration and costliness of the corresponding policy regime for achieving the required emissions reductions is determined by economic factors like minimum transition time and maximum long term reduction rate. For high emissions flexibility, a large increase in emissions in the early 21st century can be counterbalanced by a fast reduction in the long run. If the emissions flexibility is low, more balanced emissions strategies including early action in the case of a low to medium climate impact resilience have to be chosen. Thus, emissions flexibility has to be assessed in detail when addressing the viability of 'wait then run' vs. 'early action' strategies (cf. Wigley et al., 1996, Ha-Duong et al., 1997).

The large sensitivity of emissions corridors to key assumptions in the climate change debate emphasizes the need to assess the robustness of particular climate policies (cf. Lempert and Schlesinger, 2000). Guardrails can serve as a criterion for robustness in the sense that a policy would be considered robust, if it observed the guardrails in 'most' of the possible states of the world. In this regard, a set of emissions corridors across the uncertainty space of the climate change debate can provide important background information for testing specific climate policy proposals. Thus, the concept of emissions corridors can help to structure the debate around adequate climate policies, to separate the role of value assumptions (in the form of guardrails) from model mechanics, and to identify suitable robust policies in an iterative manner.

Appendix

Consider changing climate impact guardrail and climate sensitivity $(\mathrm{T}_{\max}, \mathrm{T}_{2\mathrm{CO}_2}) \rightarrow (\mathrm{T}'_{\max}, \mathrm{T}'_{2\mathrm{CO}_2})$. We ask how an emissions profile touching the upper boundary of the emissions corridor for $(\mathrm{T}_{\max}, \mathrm{T}_{2\mathrm{CO}_2})$ must be scaled by a constant factor s, so that it touches again the upper boundary of the corridor for $(\mathrm{T}'_{\max}, \mathrm{T}'_{2\mathrm{CO}_2})$, i.e. what s translates

$$\mathrm{T}_{\max} = \max_t \, T\,(\,C[E(t)], \mathrm{T}_{2\mathrm{CO}_2}\,)$$

to

$$\mathrm{T}'_{\max} = \max_t \, T\,(\,C[\,s\,E(t)], \mathrm{T}'_{2\mathrm{CO}_2}\,) \quad ?$$

If we neglect the exponential decay of the initial atmospheric CO_2 anomaly C_o in 2000, i.e. if we consider the CO_2 concentration for $t \gg t_o$, and if we look at CO_2 anomalies $\gg 30$ ppmv, the integral form of equation (4) (cmp. equation 7) allows us to establish the following approximation:

$$\begin{aligned} C[s\,E(t)] &\approx s\,C[E(t)] - (s-1)\,\frac{\mathrm{B}}{\sigma}\,F_o, \quad t \gg t_o \\ &\approx s\,C[E(t)], \quad s \geq 1,\;\; C[E(t)] \gg \frac{\mathrm{B}}{\sigma}\,F_o \end{aligned}$$

At the time $t_{\max}$ of reaching the maximum GMT anomaly $\mathrm{T}_{\max}$, equation 5 takes on the form:

$$\frac{\mathrm{T}_{\max}}{\mathrm{T}_{2\mathrm{CO}_2}} = \frac{\ln c(t_{\max})}{\ln 2}$$

This relation can be used to express the emissions scaling factor s for moving from $(\mathrm{T}_{\max}, \mathrm{T}_{2\mathrm{CO}_2}) \rightarrow (\mathrm{T}'_{\max}, \mathrm{T}'_{2\mathrm{CO}_2})$ in terms of the ratio of climate impact resilience parameters:

$$\begin{aligned} \frac{\kappa'}{\kappa} &\equiv \frac{\mathrm{T}'_{\max}}{\mathrm{T}_{\max}} \cdot \frac{\mathrm{T}_{2\mathrm{CO}_2}}{\mathrm{T}'_{2\mathrm{CO}_2}} \\ &= \frac{\ln\, c(t'_{\max})}{\ln\, c(t_{\max})} \\ &\approx \ln\,(1 + s \cdot \frac{C(t'_{\max})}{C_{pi}}) \,/\, \ln\,(1 + \frac{C(t_{\max})}{C_{pi}}) \\ \Rightarrow\; s &\approx \frac{c(t_{\max})^{\,\kappa'/\kappa} - 1}{c(t'_{\max}) - 1}, \qquad \kappa' \geq \kappa \end{aligned}$$

If we neglect the different delays of the climate response for different $\mathrm{T}_{2\mathrm{CO}_2}$, i.e. $t'_{\max} \approx t_{\max}$, the scaling factor s for moving from $(\mathrm{T}_{\max}, \mathrm{T}_{2\mathrm{CO}_2}) \rightarrow (\mathrm{T}'_{\max}, \mathrm{T}'_{2\mathrm{CO}_2})$ will depend solely on κ'/κ. This would imply that the size of a corridor remains unchanged when moving from the case $(\kappa, \mathrm{T}_{\max}, \mathrm{T}_{2\mathrm{CO}_2})$ to $(\kappa, \mathrm{b} \cdot \mathrm{T}_{\max}, \mathrm{b} \cdot \mathrm{T}_{2\mathrm{CO}_2})$ with b>1.

However, due to the dependence of the temperature response parameter α on $\mathrm{T}_{2\mathrm{CO}_2}$ (see equation 6), a larger $\mathrm{T}_{2\mathrm{CO}_2}$ further delays the climate response, i.e. the maximum GMT increase will be reached at a later point in time. Thus, $t'_{\max} > t_{\max}$ if $\mathrm{T}'_{2\mathrm{CO}_2} > \mathrm{T}_{2\mathrm{CO}_2}$ and $\kappa' = \kappa$. Since the carbon dioxide concentration in the atmosphere decreases in time after having reached its maximum value $c^*(t^*)$ at $t^* < t_{\max}$, it also holds true that $c(t'_{\max}) < c(t_{\max})$ if $\mathrm{T}'_{2\mathrm{CO}_2} > \mathrm{T}_{2\mathrm{CO}_2}$ and $\kappa' = \kappa$. Thus, taking this second-order effect into account, the size of the corridor increases slightly when moving from $(\kappa, \mathrm{T}_{\max}, \mathrm{T}_{2\mathrm{CO}_2})$ to $(\kappa, \mathrm{b} \cdot \mathrm{T}_{\max}, \mathrm{b} \cdot \mathrm{T}_{2\mathrm{CO}_2})$ with b>1.

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