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Global and Annex I emissions corridors for the 21st century

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Abstract: We analyze global and Annex I emissions corridors for the 21st century. Emissions corridors represent the range of admissible emissions futures which observe some predefined constraints. They are calculated on the conceptual and methodological basis of the tolerable windows approach. We assess the sensitivity of the corridors to limits on the non-intolerable magnitude of climate change, the acceptable rate of emissions reductions and the feasible transition pace towards a decarbonizing economy. In addition we consider the influence of climate sensitivity on the corridors. While we calculate the global emissions corridors for the idealized assumption of a single global emitter, the Annex I emissions corridors are computed for the case of two emitters that have to obtain equal per capita emissions rights as of the year 2050. Results show a large dependence of the corridors on the climate change limit and the climate sensitivity. When the limits are varied within their plausible range, we move from a climate policy regime with vanishing emissions corridors to a regime, where no action seems necessary. The economic parameters have a much larger impact on the the Annex I corridors than on the global emissions corridors. Due to the long term requirement of equal per capita emissions rights, the size of Annex I emissions corridors is strongly influenced by the emissions reductions capabilities of the Annex I countries in the long as well as in the short run.

Keywords: Tolerable windows approach; Guardrail approach; Emissions corridors; Sensitivity analysis

1 INTRODUCTION

The aim of this paper is to compare the sensitivity of emissions corridors for the idealized case of a single global emitter to the sensitivity of Annex I emissions corridors calculated under the assumption of two emitters that have to obtain equal per capita emissions rights as of year 2050. 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 guardrail on climate change is formalized in terms of the maximum admissible increase in global mean temperature T_{\max} since preindustrial times. The guardrails on the emissions mitigation capability of the socio-economic system are captured in terms of a maximum admissible reduction rate r and a minimum transition time t_{trans} required

for the implementation of a decarbonizing economy. In addition, we consider different values of the climate sensitivity $T_{2 \times \text{CO}_2}$ that is a key uncertainty in assessing the magnitude of the climate response to an increase in radiative forcing.

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 guardrails for the future development of a dynamic system into the bundle of admissible control paths (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* for action. This is illustrated in particular by the concept of *emissions corridors*, which constitutes the projection of the bundle of admissible emissions paths onto the sub-

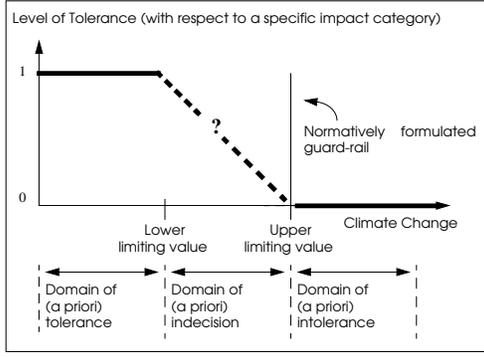


Figure 1: The guardrails as intolerability limits on the continuum of climate change.

space spanned by emissions and time.

A sensible application of the TWA to real world decision making problems requires a proper interpretation of the guardrails. As Fig. 1 indicates, it is generally not possible to draw a guardrail as a sharp boundary between a tolerable and an intolerable domain in real world applications. Instead, 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 interpret the guardrails as specifying intolerability limits. Thus, admissible policies yielding non-intolerable outcomes are by no means equally ‘safe’ strategies, but only successful in observing the last frontiers to intolerability.

2 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]. Here, we recapitulate only some basic concepts which are necessary for the understanding of what follows. A corridor $\text{Cor}(y, t)$, with y being a particular control or state variable of a dynamical system modelled by a set of ordinary differential equations, represents the *admissible range* of values of y generated by all system futures which observe the predefined guardrails. An emissions corridor $\text{Cor}(E, t)$, for instance, 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 is necessarily admissible. We can only say for sure that every path leaving the corridor is necessarily in-

Variables

E	Anthropogenic CO ₂ emissions [GtC a ⁻¹]
F	Cumulative anthrop. CO ₂ emissions [GtC]
C	Atmospheric CO ₂ anomaly [ppmv]
T	Global mean temperature anomaly [°C]

Initial conditions (year 1995, p_i = preindustrial)

$E_o = 7.5$	GtC a ⁻¹
$F_o = 426$	GtC
$C_o + C_{p_i} = 360$	ppmv $\Rightarrow c_o = 1.286$
$T_o + T_{p_i} = (0.31 \ln(T_{2 \times \text{CO}_2}) + 0.29) + 14.6$	°C

Parameters

CO ₂ emissions to concentration conversion factor:	$\beta = 0.47$ ppmv GtC ⁻¹
Carbon cycle response parameter:	$\sigma = 0.0215$ a ⁻¹
Atmospheric retention factor:	$B/(\beta\sigma) = 0.15$
Temp. forcing for a doubling of atmospheric CO ₂ :	$\mu = 0.087$ °C a ⁻¹
Temp. resp. parameter:	$\alpha = 0.06$ °C a ⁻¹ / T _{2×CO₂}
Climate sensitivity:	T _{2×CO₂} ∈ [1.5 °C, 4.5 °C]

Table 1: State variables and parameters of the climate model.

admissible. This property reinforces that the TWA is directed toward excluding inadmissible solutions rather than identifying tolerable solutions.

If an emissions corridor is simply connected, it is determined completely by its outer boundary. This boundary can be computed in a rather simple and efficient manner by subsequently maximizing and minimizing the emissions for fixed values in time [Leimbach and Bruckner, 2001]. The entire boundary of the corridor is put up by such emissions paths. In general, however, the boundary is not an admissible path by itself.

3 CLIMATE MODEL

We use a simple model [Petschel-Held et al., 1999; Kriegler and Bruckner, 2002] to describe the response of the globally aggregated climate to anthropogenic forcing (see Table 1 for definitions of variables and parameters).

$$\dot{F} = E \quad (1)$$

$$\dot{C} = \beta E + BF - \sigma C \quad (2)$$

$$\dot{T} = \mu \ln(c) - \alpha T \quad \text{with } c = \frac{C + C_{p_i}}{C_{p_i}} \quad (3)$$

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 (1)-(3) 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 others, by the objective to avoid an unstable and irregular climate regime. We use such a highly simplified model in order to be able to take on a broad perspective in the sensitivity analysis. In Kriegler and Bruckner [2002], we have compared the model behavior to projections of the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC; Kattenberg et al. [1996]) in detail. In this paper we only summarize a few basic properties and limitations of the model.

For our purposes, the model compares sufficiently well to future climate projections in the Second Assessment Report. Since the model considers only carbon dioxide, it will underestimate the GMT response to global emissions scenarios like most of the SRES scenarios [Nakićenović and Swart, 2000], in which the additional radiative forcing of non-CO₂ greenhouse gases exceeds the negative contribution of aerosols in the long run. One main assumption of the model is that the parameters μ and α depending on oceanic heat capacity and climate sensitivity $T_{2 \times CO_2}$ are constant in time. However, given the complexity of the climate system this is a highly idealized assumption. A sensitivity analysis of the model shows that $T_{2 \times CO_2}$ is the most influential parameter for the magnitude of the climate response in the model setting. However, ocean heat capacity and radiative forcing also play important roles.

4 GUARDRAILS

The concept of guardrails draws on the profound intuition that the carrying capacity of Planet Earth is limited. This intuition was 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 [German Advisory Council on Global Change (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 GMT anomaly and its time derivative.

4.1 Climate impact guardrails

The choice of climate impact guardrails can be motivated by the possibility of large scale, abrupt

climate discontinuities. However, the guardrails can also be meant to prevent a regular climate change from reaching a domain of intolerable climate change impacts. In this analysis, we consider three guardrails on GMT anomaly, namely

$$T_{\max} = 2 \text{ } ^\circ\text{C} , \quad T_{\max} = 3 \text{ } ^\circ\text{C} , \quad T_{\max} = 4 \text{ } ^\circ\text{C} \quad (4)$$

symbolizing a low, medium and high estimate for the onset of the intolerable climate domain. The low estimate of 2 °C corresponds to the value chosen for the WBGU window [German Advisory Council on Global Change (WBGU), 1995]. 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].

4.2 Economic flexibility guardrails

In this analysis we avoid considering the complex socio-economic dynamics explicitly. The freedom to do so emanates from the concept of emissions corridors. The optimization procedure to calculate points on the corridor boundary automatically arranges the unspecified socio-economic factors in a way so to generate emissions paths, which attain the highest (lowest) possible emissions under the given constraints. In order to avoid highly uncertain ‘business as usual’ emissions scenarios, we interpret every emissions path not as the course of physical emissions, but as the distribution of emissions rights over time. Since emissions rights can readily exceed the actual emissions, we can restrict the total amount of emissions rights as well as their distribution over time solely by excluding intolerable climate impacts, unacceptable mitigation measures and unwarranted ‘free rider’ behavior.

We constrain the emissions paths of the idealized global emitter as well as of the industrial (= Annex I) and developing (= Non-Annex I) countries by three conditions. The first condition specifies the maximum acceptable reduction rate r .

$$-r \leq g(t) \quad \forall t \quad \text{with } g(t) = \dot{E}(t)/E(t) \quad (5)$$

The second condition ensures that growing emissions of an emitter can be followed by a reduction period, but not vice versa. We formulate it even stronger by asking that the growth rate itself does not grow at any point in time in order to enforce single-peaked emissions paths without jeopardizing the stability of the optimization algorithm. This constraint is the least general one, since it requires the growth rate g to be monotonically decreasing in time with a maximum growth rate g_o in

the year 2000. However, in the presence of a climate change mitigation policy the assumption of a decreasing growth rate is plausible.

The third condition addresses economic inertia by imposing a smoothness constraint on the transition to a decarbonizing economy. It is cast in terms of the minimum transition time t_{trans} to switch from the maximum growth rate g_o to the maximum reduction rate r . The last two conditions can be combined in the following inequality:

$$-\frac{g_o + r}{t_{\text{trans}}} \leq \dot{g}(t) \leq 0 \quad \forall t \quad (6)$$

We do not assume different values of the reduction rate r and transition time t_{trans} for industrial and developing countries in order to reduce the number of parameter combinations for the sensitivity analysis. Considering historic accountability and present capacity, such an assignment might seem unfair. However, the particular responsibility of the industrial countries is included through an equity principle. We require that industrial and developing countries have to obtain equal per capita emissions rights as of the year 2050.

$$\frac{E_{\text{DC}}(t)}{P_{\text{DC}}} = \frac{E_{\text{IC}}(t)}{P_{\text{IC}}} \quad t \geq 2050 \quad (7)$$

$$\text{with} \quad \begin{aligned} P_{\text{DC}} &= 4.18 \text{ billion people in 1990} \\ P_{\text{IC}} &= 1.11 \text{ billion people in 1990} \end{aligned}$$

5 GLOBAL EMISSIONS CORRIDORS

We analyze the sensitivity of emissions corridors for the idealized case of a single global emitter to 90 parameter constellations of $(T_{\text{max}}, T_{2 \times \text{CO}_2}, r, t_{\text{trans}})$. Different expectations about the limited resilience of human-environment systems to climate change are scanned by varying $T_{\text{max}} \in \{2^\circ\text{C}, 3^\circ\text{C}, 4^\circ\text{C}\}$. The uncertainty about the magnitude of the climate response is assessed by varying $T_{2 \times \text{CO}_2} \in \{1.5^\circ\text{C}, 2.5^\circ\text{C}, 3.5^\circ\text{C}, 4.5^\circ\text{C}\}$. Three assumptions about the maximum admissible emissions reductions rate $r \in \{0.01, 0.02, 0.04\}$ are considered. The limitation on the transition pace towards a decarbonizing economy is varied in the range $t_{\text{trans}} \in \{0 \text{ a}, 20 \text{ a}, 40 \text{ a}\}$.

Fig. 2 shows the enormous influence of the choice of climate impact guardrail on the size of the emissions corridor, i.e. the area between upper and lower boundary. For instance, no immediate mitigation seems necessary for a guardrail $T_{\text{max}} = 4^\circ\text{C}$. Nevertheless there are SRES scenarios for fossil fuel intensive futures with high economic growth (SRES

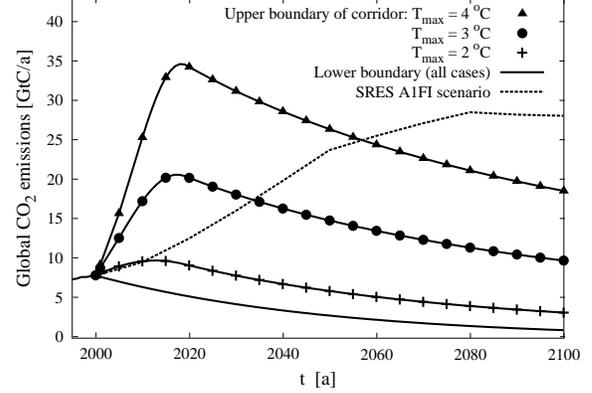


Figure 2: Global emissions corridors for $T_{\text{max}} = 2^\circ\text{C}, 3^\circ\text{C}$ and 4°C and fixed $(T_{2 \times \text{CO}_2}, r, t_{\text{trans}}) = (3.5^\circ\text{C}, 0.02, 20 \text{ a})$. The lower boundary is common to all corridors.

A1FI; Nakićenović and Swart [2000]) that leave the corridor even for the choice of the leanest climate impact guardrail. Drastic mitigation measures are needed in the case of the guardrail $T_{\text{max}} = 2^\circ\text{C}$. Global CO_2 emissions are not allowed to exceed 10 GtC at any time and must decrease after 2030 at the latest.

As analyzed in detail in Kriegler and Bruckner [2002], the size of the corridor is approximately linked to a climate impact response parameter

$$\kappa = \frac{T_{\text{max}}}{T_{2 \times \text{CO}_2}}. \quad (8)$$

This can be clearly seen, when studying the sensitivity of the *maximum admissible cumulative emissions in the period 2000-2100* (MACE) as a simple indicator for the size of the emissions leeway. Fig. 3 shows the value of MACE across all 90 parameter constellations $(T_{\text{max}}, T_{2 \times \text{CO}_2}, r, t_{\text{trans}})$. To highlight the major trends, we have divided the MACE values into six classes ranging from very large emissions leeways ($\text{MACE} > 2450 \text{ GtC}$) over large ($1720 < \text{MACE} \leq 2450 \text{ GtC}$), medium large ($1370 < \text{MACE} \leq 1720 \text{ GtC}$), medium small ($1020 < \text{MACE} \leq 1370 \text{ GtC}$), small ($650 < \text{MACE} \leq 1020 \text{ GtC}$) to very small ($\text{MACE} < 650 \text{ GtC}$) emissions leeways. This classification is drawn from a classification of global emissions scenarios put forward in Figure SPM-4a in Nakićenović and Swart [2000].

In each column the parameter constellations are ordered from small to large climate impact response parameters κ (the smaller κ , the higher the climate impact response). The predominantly horizontal partitioning of MACE values into classes

	r=0.04	r=0.04	r=0.04	r=0.02	r=0.02	r=0.02	r=0.01	r=0.01	r=0.01
$T_{\max} = 4^{\circ}\text{C}$	3070	3024	2984	3052	2973	2881	2823	2705	2577
$T_{2CO_2}=2.5^{\circ}\text{C}$ $\kappa = 1.60$									
$T_{\max} = 2^{\circ}\text{C}$	1944	1906	1874	1944	1905	1865	1908	1846	1780
$T_{2CO_2}=1.5^{\circ}\text{C}$ $\kappa = 1.33$									
$T_{\max} = 3^{\circ}\text{C}$	1826	1801	1782	1824	1789	1750	1714	1661	1603
$T_{2CO_2}=2.5^{\circ}\text{C}$ $\kappa = 1.20$			LARGE				MEDIUM		
$T_{\max} = 4^{\circ}\text{C}$	1928	1911	1894	1891	1850	1802	1701	1646	1587
$T_{2CO_2}=3.5^{\circ}\text{C}$ $\kappa = 1.14$									
$T_{\max} = 4^{\circ}\text{C}$	1420	1410	1397	1370	1344	1314	1206	1176	1143
$T_{2CO_2}=4.5^{\circ}\text{C}$ $\kappa = 0.89$									
$T_{\max} = 3^{\circ}\text{C}$	1163	1154	1147	1154	1137	1118	1050	1037	1014
$T_{2CO_2}=3.5^{\circ}\text{C}$ $\kappa = 0.86$									
$T_{\max} = 2^{\circ}\text{C}$	910	903	898	910	902	894	879	866	853
$T_{2CO_2}=2.5^{\circ}\text{C}$ $\kappa = 0.80$									
$T_{\max} = 3^{\circ}\text{C}$	848	844	841	834	824	815	751	742	732
$T_{2CO_2}=4.5^{\circ}\text{C}$ $\kappa = 0.67$									
$T_{\max} = 2^{\circ}\text{C}$	562	560	559	561	559	557	535	534	534
$T_{2CO_2}=3.5^{\circ}\text{C}$ $\kappa = 0.57$									
$T_{\max} = 2^{\circ}\text{C}$	384	384	384	383	383	383			
$T_{2CO_2}=4.5^{\circ}\text{C}$ $\kappa = 0.44$									

Figure 3: Global maximum admissible cumulative emissions [GtC] in the period 2000-2100 (MACE) for all combinations of T_{\max} , $T_{2\times CO_2}$, r , t_{trans} and the assumption of a single global emitter. Black cells denote the non-existence of a corridor.

indicates that this quantity dominates the magnitude of global MACE. As we change κ from 1.6 to 0.44, we move from MACE values questioning the necessity of a climate policy regime to values indicating a strong need for severe mitigation efforts. For $\kappa = 0.44$ we even find regimes where no climate policy whatsoever would yield a non-intolerable outcome as prescribed by the guardrails. To put these numbers into perspective, Fussler 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. Nordhaus [1994] assumes a value of $\kappa = 0.86$ in his cost-benefit analysis for the scenario of a catastrophic climate change beyond $T_{\max} = 2.5^{\circ}\text{C}$.

6 EMISSIONS CORRIDORS FOR THE ANNEX I COUNTRIES

The emissions corridors for the Annex I countries are calculated under the assumption of two global emitters, i.e. the Annex I and Non-Annex I countries, which have to obtain equal per capita emissions rights as of the year 2050. Fig. 4 shows the sensitivity of the maximum admissible cumulative emissions in the period 2000-2100 (MACE) of the

	r=0.04	r=0.04	r=0.04	r=0.02	r=0.02	r=0.02	r=0.01	r=0.01	r=0.01
$T_{\max} = 4^{\circ}\text{C}$	161	119	86	105	88	74	75	68	62
$T_{2CO_2}=2.5^{\circ}\text{C}$ $\kappa = 1.60$									
$T_{\max} = 2^{\circ}\text{C}$	558	516	534	662	564	488	500	470	439
$T_{2CO_2}=1.5^{\circ}\text{C}$ $\kappa = 1.33$						MEDIUM LARGE			
$T_{\max} = 3^{\circ}\text{C}$	916	694	521	611	526	458	449	420	396
$T_{2CO_2}=2.5^{\circ}\text{C}$ $\kappa = 1.20$							MEDIUM SMALL		
$T_{\max} = 4^{\circ}\text{C}$	976	740	554	627	540	469	443	415	392
$T_{2CO_2}=3.5^{\circ}\text{C}$ $\kappa = 1.14$									
$T_{\max} = 4^{\circ}\text{C}$	692	535	412	439	388	347	306	295	287
$T_{2CO_2}=4.5^{\circ}\text{C}$ $\kappa = 0.89$									
$T_{\max} = 3^{\circ}\text{C}$	556	435	341	367	326	298	268		
$T_{2CO_2}=3.5^{\circ}\text{C}$ $\kappa = 0.86$									
$T_{\max} = 2^{\circ}\text{C}$	413	328	265	287	261	243			
$T_{2CO_2}=2.5^{\circ}\text{C}$ $\kappa = 0.80$									
$T_{\max} = 3^{\circ}\text{C}$	555	412	354	254	230	220			
$T_{2CO_2}=4.5^{\circ}\text{C}$ $\kappa = 0.67$									
$T_{\max} = 2^{\circ}\text{C}$	253	196	169						
$T_{2CO_2}=3.5^{\circ}\text{C}$ $\kappa = 0.57$									
$T_{\max} = 2^{\circ}\text{C}$	145	130	119						
$T_{2CO_2}=4.5^{\circ}\text{C}$ $\kappa = 0.44$									

Figure 4: Maximum admissible cumulative emissions [GtC] in the period 2000-2100 (MACE) of the Annex I countries for all combinations of T_{\max} , $T_{2\times CO_2}$, r , t_{trans} and the assumption of two emitters with equal per capita emissions rights as of the year 2050.

Annex I countries across all 90 parameter constellations (T_{\max} , $T_{2\times CO_2}$, r , t_{trans}). Analogous to the global MACE values, the MACE values of the Annex I countries are divided into six classes ranging from very large emissions leeways (MACE > 820 GtC) over large ($570 < \text{MACE} \leq 820$ GtC), medium large ($460 < \text{MACE} \leq 570$ GtC), medium small ($340 < \text{MACE} \leq 460$ GtC), small ($220 < \text{MACE} \leq 340$ GtC) to very small (MACE < 220 GtC) emissions leeways.

There are striking differences between the sensitivity of global and Annex I emissions corridors, which can be seen clearly by comparing Fig. 3 with Fig. 4. As expressed by the change from horizontal to diagonal class boundaries, the influence of the parameters r and t_{trans} on the Annex I MACE values is much stronger than on the global MACE values. Requiring equal per capita emissions rights as of the year 2050 places a strong burden on the emissions rights of the Annex I countries in the long run. This burden limits the emissions leeway of the early stages much more, if the Annex I capabilities to reduce emissions are low. Therefore, even if distributional aspects are becoming restrictive in the long term only, a detailed discussion of the reduction capability of Annex I is necessary to assess its share of emission rights in the short run.

The emissions reduction capability of the industrial countries plays also an important role for the overall existence of a solution. The more limited the maximum admissible reduction rate of the Annex I countries is, the larger is the minimum amount of Non-Annex I emissions rights that is necessary to obtain equal per capita emissions rights in 2050. It is therefore no surprise that the parameters r and t_{trans} become as important as κ for determining the very existence of a corridor, when equal per capita emissions rights as of 2050 are required. Fig. 4 shows that the ‘no solution’ domain expands substantially to $r = 0.02$ as well as higher κ values. This highlights the important restrictions on future emissions leeways that come about by assuming two emitters with differentiated responsibilities in a future climate policy regime.

7 CONCLUSIONS

The enormous sensitivity of emissions corridors to the climate impact response parameter κ leads to results ranging from cases where any climate policy seems highly unnecessary to cases where no climate policy however severe can avoid the prespecified intolerable domain. This highlights the pervasive role of uncertainty in generating the widely different views about climate protection. The socioeconomic emissions reduction capabilities become a particular important factor, when two emitters with differentiated responsibilities in mitigating climate change are considered. The domain of the parameter space, where there is no solution to the climate change problem that observes all guardrails, is by far larger for the case of equal per capita emissions rights between industrial and developing countries as of the year 2050 than for the idealized case of a single global emitter. The equity condition is a particular strong burden for the Annex I countries, if their economic capability to reduce emissions is low. This reduction capability has to be assessed in detail when addressing the viability of ‘wait then run’ vs. ‘early action’ strategies.

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