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Climate change decision-support and the tolerable windows approach

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The Tolerable Windows Approach (TWA) to Integrated Assessments (IA) of global warming is based on external normative specifications of tolerable sets of climate impacts as well as proposed emission quotas and policy instruments for implementation. In a subsequent step, the complete set of admissible climate protection strategies which are compatible with these normative inputs is determined by scientific analysis. In doing so, minimum requirements concerning global and national greenhouse gas emission paths can be determined. In this paper we present the basic methodological elements of TWA, discuss its relation to more conventional approaches to IA like cost–benefit analyses, and present some preliminary results obtained by a reduced-form climate model.

Keywords: climate change, climate policy, integrated assessment, inverse modeling, uncertainty

1. Introduction: background and objectives

Increasing concerns about the potential risks involved in anthropogenic climate change over the past ten years have boosted the intensity of research efforts on all aspects of the problem and motivated an integrated analysis of their results. This paper is intended to provide a short overview of modeling approaches to integrated assessments of climate change. It also presents a new concept, the Tolerable Windows Approach (TWA), as it is adopted in a project called Integrated Assessment of Climate Protection Strategies (ICLIPS) coordinated by PIK. The approach is based on an inverse-modeling concept that derives climate-stabilization objectives from perceived unacceptable impacts and produces complete sets of permitted emission paths satisfying the corresponding climate change constraints. Initial results show that the approach is a promising new direction in integrated modeling.

The paper starts with a concise overview of the background to integrated assessment models and confirms the need for, and the policy relevance of the inverse approach. The concept of climate impact response functions, their sources and major types, and the difficulties involved in deriving them are addressed in section 2. This is followed by a presentation of the concept of TWA. Section 4 is devoted to the methodological aspects and the basic mathematical modeling tools. Results from applying the model to different specifications of two global climate windows are presented in section 5. Profound uncertainties or even downright ignorance characterize each component involved in our integrated assessment model. Section 6 outlines options to consider uncertainties in TWA. The paper ends with a short discussion of possible applications and related future development directions of the model system.

In the scientific analysis to support climate policy, various crucial components have evolved largely in isolation. Atmospheric scientists and climatologists were working on their ocean and atmospheric models. Hydrologists, ecologists, and agriculturalists attempted to assess impacts of a 2 × CO_2-equivalent climate on water supply, ecosystems, and food production. Economists and engineers were trying to work out the feasibility and costs of various emission reduction strategies. These research activities involved a diverse and often contradicting set of assumptions. Results were difficult to compare, and this has drastically reduced their policy relevance.

In the late 1980s, several research groups started to integrate various elements into a consistent framework. As the global warming problem has climbed ever higher on the social agenda, the need for policy-relevant results increased as well. Integrated assessments were conceived to be the appropriate tools to provide this service.

The traditional approach to integrated assessment modeling follows a forward direction. The analysis starts by summarizing assumptions about population growth, economic development, and other driving forces in the form of internally consistent scenarios of socio-economic development. These scenarios are then used to project emission paths for various greenhouse gases into the future. Emissions, together with atmospheric removal and chemical transformation processes, lead to changes in concentrations of those gases. Simple climate models were then used to calculate changes in various climate attributes, typically mean temperature and, in some cases, precipitation values. Data describing changing climate patterns fed impact assessments in various sectors. Using observed market values, where appropriate, or imputed values, where goods and services related to the impact sector are not traded in the market, one can come to a rough damage assessment. Direct biophysical impacts or estimated monetary damages

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can then be related to the scenario to assess the extent of climate change impacts on the assumed development patterns. There have been various attempts to package this information in the framework of a cost–benefit analysis.

Integrated assessments following the forward direction from cause to effect proved to be very useful for policy simulations. Models following this sequence are well-suited to assess environmental and socio-economic consequences of various emission-reduction strategies. The approach is less appropriate, however, if one is interested in searching for optimal policies. The objective in this case is to find the best strategy to reach an environmental or impact objective according to selected criteria. The two basic analytical frameworks here are cost–effectiveness (cost minimizing) and cost–benefit analyses.

The cost–benefit framing has major difficulties given our current state of knowledge about the climate system and impacts of climate change. First, despite a steadily increasing amount of research effort, little is known about potential impacts of climate change, especially outside the national accounts. Knowledge about the resilience and adaptive capacity of various ecosystems to climatic shifts and, especially, about the implications of the rate of climate change is still very vague. The second major difficulty involved in cost–benefit analysis is related to the monetary evaluation of non-market impacts, i.e., positive or negative changes in natural or social impact areas not directly involved in market transactions.

In addition to the above difficulties, questions raised by the policy process also point to the need of a novel approach. Policymakers would like to know the magnitude and kind of climate change entailing undesirable impacts in order to put appropriate policies in place. Article 2 of the Framework Convention on Climate Change, the most important political document on the issue so far, also invokes this requirement. It calls for the need “to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”. Framing the central question for climate policy this way, two immediate practical questions follow: where is the level of dangerous interference with the climate system, that is, at what level should greenhouse gas concentrations be stabilized? Given the stabilization target, what is the optimal emission trajectory to achieve that objective? These questions have given rise to a new family of analyses. They start from the damage/impact side and proceed backwards. This technique has become known as the inverse approach.

Various attempts have been made over the past few years to explore these questions. Working Group I of the Second Assessment Report prepared by the Intergovernmental Panel on Climate Change (IPCC) has developed emission paths leading to stabilization of atmospheric concentrations of greenhouse gases at different levels. Wigley, Richels and Edmonds (WRE) have defined a set of alternative emission paths [58] leading to the same stabilization levels in concentrations but involving slightly different total emission budgets and, more importantly, different time schedules of actual emission reductions. WRE have shown that these alternative paths achieve the same long-term environmental objective as those of IPCC WGI, but at a much lower cost. It is widely debated what are the interim implications of the alternative paths and what are the short-term policy measures required to guarantee the implementability of the tail end of the WRE paths.

While searching for an optimal emission strategy towards a stabilization target has provided useful insights, its policy relevance is limited by the fact that concentration targets are not real decision variables.

Taking the inverse analysis a step further, the Scientific Advisory Council on Global Change to the Federal Government of Germany (WBGU) has defined the climate protection target in climatic terms [51]. The council argued that most ecosystems as we know them today and other life-supporting environmental systems relied upon by humanity have evolved in the geological period of the late Quaternary. According to this argument, dangerous anthropogenic interference with the climate system cannot be excluded beyond a level where human emissions force climate out of the range that characterized this evolution window. The last interglacial maximum of the global mean temperature is estimated to be 16.1 °C. The council added half a degree tolerance to that and defined the upper limit for global mean temperature at 16.6 °C. The second constraint on anthropogenic climate change, as defined by WBGU, is derived from expert judgement. To allow natural and socio-economic systems to adapt to changes in climate, the council assumes that the rate of change should not exceed 0.2 °C per decade.

As the above thresholds involve normative judgements, they should be open to scientific and political discussion. The relevance of climate history at geological time scales for today’s societies and ecosystems, for example, is heavily debated. Nevertheless, an additional interesting feature of the WBGU analysis is the so-called tolerable windows approach, an inverse computation technique aimed at deriving complete sets of possible emission paths which would keep the global climate within a pre-defined window. This approach has become the conceptual cornerstone of the ICLIPS project at PIK with the objective to specify climate protection goals on the basis of socially defined intolerable impacts.

The TWA was applied for the first time at the occasion of the First Conference of the Parties to the Framework Convention on Climate Change in Berlin in 1995 [51,52]. A comparable approach, the “safe landing analysis” concept [2], was developed during a series of workshops organized by the National Institute for Public Health and Environment (RIVM), Bilthoven, and the Delft University of Technology, and formally presented in 1996. In the meantime, the general concept underlying both approaches, which are similar but by no means identical, has been put in practice by several research groups all over the world [1,3,21,32,45,59]. However, up to now a broad and indepth discussion of the basic methodological elements of the TWA was missing so far, although some important issues have been already discussed in [31] and [47]. The purpose of the present paper is to fill the remaining gap.

2. Climate impact response functions

One important feature of the ICLIPS project is that it makes an explicit attempt to derive climate protection objectives from possible impacts of climate change which societies may want to prevent or avoid. Best available information from sectoral and regional climate impact assessments are synthesized in the form of climate impact response functions. Impact sectors include socio-economic areas and components of the natural environment highly valued by humans which are assumed to be sensitive to changes in climate. Response functions indicate how these systems react to climate change. They contain simple representations of highly aggregated information and are usually derived from detailed impact assessment studies. They can be formally presented as $I \equiv I(C, S)$, where I indicates the impact, C embraces the relevant climatic variables (e.g., annual mean temperatures, seasonal temperatures) and S represents the significant socio-economic variables (e.g., GDP/capita, inequality indicators, poverty).

A closer look at the various impact areas reveals two major types of systemic responses to climate change. Some systems are characterized by a smooth or “regular” response function within plausible intervals of relevant climatic variables. The tolerable level of climate change forcing in the particular system depends on the perception and judgement of social actors, especially those directly affected. In this case, it is a social decision problem to demarcate beyond which level implications of climate change become perceived as dangerous. This implies a level of maximum permitted anthropogenic forcing of the global climate system.

The second type of climate change impacts can be characterized by discontinuous or “singular” response functions. These systems are assumed to undergo a phase change beyond a given forcing. This level of forcing implies a threshold at which the system would switch from one qualitative behavior to another. Here the social decision problem is whether human societies would want to refrain from crossing such thresholds.

Turning to systems characterized by smooth response functions, it is important to distinguish between impact sectors dominated by human management (such as agriculture, agroforestry) and those dominated by natural biogeochemical processes (natural ecosystems, hydrology). The profound difference between the two cases is related to the fact that the vulnerability of sectors under the influence of human management is changing over time as it is closely associated with the development level, institutional capacities, and technological capabilities of human society. Natural systems, in contrast, have a more or less constant climate sensitivity, although management practices to help adaptation are conceivable.

The special difficulty involved in the assessment of climate impacts and hence in the formulation of response functions for managed systems is the need to distinguish between the biophysical sensitivity and socio-economic vulnerability of these systems. Taking agriculture as an example, biophysical sensitivity is primarily climate-driven. Phases of crop growth, the amount of yield, or the risk of crop failure heavily depend on the vagaries of the weather. A persistent shift in weather patterns as manifestation of global climate change will, ceteris paribus, inevitably affect yields and risks of crop failure. Orthogonal to this axis, socio-economic vulnerability of the society behind this agricultural system is largely development-dependent. The vulnerability concept combines two components: to what extent is society affected by implications of climate change in the first place, and what is the adaptive capacity of the society to respond to and mitigate impacts of climate change.

Underlying arguments about changing socio-economic vulnerability are simple. One is historical: the agricultural sectors in developed countries of North America and Western Europe are much less sensitive to climate fluctuations today than they were 50–100 years ago. The other argument is cross-sectional: in today’s world economy, agriculturalists, particularly small and subsistence farmers, in poor countries are much more affected by weather fluctuations than their counterparts in rich countries. Vulnerability is reduced as institutional capacity and financial resources (e.g., alternative sources of income, commercial insurance, state support) are more readily available in rich societies. In spite of this plausible relationship, it remains a major challenge to define and assess vulnerability of various impact sectors of future societies with respect to climate change.

The issue is further complicated by the capacity of managed systems to adapt to shifting weather patterns. In this respect, it is useful to distinguish between autonomous adaptation and deliberate adaptation. The first one takes place automatically and is largely cost-less. Switching to a different cultivar of the same crop which is better suited to higher July temperatures, for example, is a case of autonomous adaptation. Even changing the capital stock instigated by the need to switch to a different crop could easily be accommodated within the regular investment–renewal cycle of agricultural capital. Many adaptation measures, nevertheless, would require deliberate action and the associated price may be high. Securing water supply by keeping the guaranteed minimum flow at the same level under changing temperature and precipitation regimes would require additional water storage facilities. Financial and environmental costs of such measures could be substantial even for rich societies. Costs of these deliberate adaptation measures would nonetheless significantly depend on whether they are undertaken as preemptive measures (before negative impacts become apparent) or in a reactive mode (after much damage and degradation have already occurred).

Ongoing research in the ICLIPS project attempts to formulate climate response functions for agriculture, human health, water resources, sea level rise, and natural ecosystems.

While some systems are assumed to be characterized by smooth response functions within plausible ranges of climatic attributes, they can also involve discontinuous changes. In some regions, for example, boreal forest may become unviable beyond a certain level of warming. This does not imply, however, that boreal forests as ecosystem will disappear everywhere in the Northern Latitudes.

Many components of the Earth's geophysical system have shown major qualitative changes and these are well detectable in the Earth's geological history. New results indicate that some of these changes occurred in a split of a second by geological time measures. While the exact mechanisms of these changes are still poorly understood, there is increasing concern that anthropogenic greenhouse forcing could trigger such changes in the future. Examples of these changes include the North Atlantic deep-water formation, the so-called conveyor belt phenomenon delivering huge amounts of heat to the Northeast Atlantic and keeping Western and Northern Europe much warmer than they would be without this ocean current. Additional examples include the South Asian monsoon patterns, sea-ice albedo, and breakdown of ice shields.

Information synthesized in both types of climate impact response functions will be used by policymakers and various social actors. These functions should help them make their judgements about tolerable impact levels in various sectors and various regions with respect to climate change. This information is then used to define permitted climate windows. Tolerable climate windows define changes permitted in climatic attributes such as temperature, rate of temperature change, precipitation, rate of precipitation change, sea level rise, rate of sea level rise. They serve as an input to an integrated climate–economy model used in inverse mode to derive permitted ranges of emission paths that keep the climate system within the tolerable window(s). The integrated model and the concept behind it is discussed in the following sections.

3. Conceptual aspects of the tolerable windows approach

In a nutshell, the *tolerable windows approach* can be summarized as follows: Based on a set of pre-defined constraints (*guardrails*) that exclude intolerable climate change on the one hand, and unacceptable mitigation measures on the other, the admissible scope for action is sought by investigating the dynamic cause–effect relationships between society and environment. In a subsequent step, a single climate protection strategy may be selected by taking into account additional criteria. This can be achieved, for instance, by applying quantitative policy optimization methods (like cost–effectiveness models), by referring to soft criteria and qualitative arguments (like an intuitive interpretation of the precautionary principle) or by seeking for a compromise in a negotiation process.

In the following, it is assumed that the approach is applied to support a specific policymaker (or a policy making body acting collectively), i.e., a unitary actor seeking scientific advice in the negotiation process of the Framework Convention on Climate Change. In addition, we assume that the respective decision-maker would like to design actively the climate protection strategy that he finally will have to defend politically and that he would feel responsible for the outcomes of such a strategy if it were implemented. Due to this, his political judgements will primarily focus on these outcomes, but the chosen strategy has to be defined in terms relevant to induce mitigation options, e.g., as a time-path of carbon taxes. Unfortunately, the dynamic links which describe the respective dependencies are highly complex. In general, the policymaker will therefore ask for scientific advice in order to assess the outcomes of the strategy that he is willing to propose.

A possible way to proceed in this situation is to specify some test policies and to evaluate the respective physical, ecological, economic, and social consequences by using integrated assessment models. The disadvantage of this "policy evaluation approach" [16] is that in general the respective iterative "trial and error" process will be very time-consuming. Therefore, scientists often try to define independently several conceivable scenarios with the aim of reflecting different political standpoints. Although very useful in order to get first insights into the issue (cf. the investigation of the IPCC scenarios [14–16]), this procedure is of restricted value for active policy design due to the limited number (e.g., six in the case of the IPCC IS92 scenarios) of the investigated policy paths.

A promising alternative therefore is to define the goals beforehand and to determine the pertinent policies by applying appropriate computer models. Respective exercises in the past have focused on deriving policy paths that are optimal according to a selected criterion. The basic analytical framework here is Cost–Benefit (welfare maximizing) Analysis (CBA), which is able to determine a single (with respect to the selected criterion) optimal policy path. At first sight, this is what policymakers are asking for. Yet, due to the applied aggregation across regions, time, and impacts, problems may arise when such an optimal policy path is investigated in detail with respect to its regional, temporal and sectoral implications.

For instance, if we followed the optimal path proposed by the DICE model [27], we would have to adapt within 500 years to a global mean temperature increase that is projected to be 6.2 °C above the pre-industrial level. Nordhaus points out that "while we have only the foggiest idea of what this would imply in terms of ecological, economic, and social outcomes, it would make most thoughtful people – even economists – nervous to induce such a large environmental change" [27, p. 322]. It is therefore not surprising that some policymakers would refrain from following this policy path till the very end.

The difficulties involved in policy paths resulting from even carefully formulated CBAs of the climate problem are analyzed in detail elsewhere [12]. Here we simply note that – beside the well-known technical problems such as monetizing environmental goods, which are outside the national accounts, and the need to quantify unknown damages and costs (at least by subjective probability distributions) – some of the difficulties can be related to normative judgements that enter traditional applications of cost–benefit analysis due to the necessity of aggregating across agents, time, and impact categories.

In addition, it should be emphasized that cost–benefit analysis seeks to maximize global welfare, which is different from the "childlike longing for a world in which every problem has a solution and that solution is an unalloyed good" [37, p. 21]. Especially, since we have to assume that active climate policy will involve "cruel choices" [37], some policymakers will ask for an approach that provides the opportunity to exclude outcomes which they judge as intolerable, even if this procedure leads to policy paths that are suboptimal according to traditional economic criteria.

From a social-science perspective, mainly two different response strategies to this request are conceivable. On the one hand, one could emphasize that maximizing global welfare should be the goal of every benevolent policymaker and that therefore the best currently available cost–benefit model should be used. Admitting that shortcomings exist, the promise is that open questions will be resolved soon. On the other hand, one could stress that some severe problems exist, yet emphasize that applying cost–benefit analysis could yield valuable insights in spite of them [46]. This perspective comes close to that of Railton who stated that cost–benefit analysis should be "used as an information-yielding device, a way of generating and bringing together within a quantified scheme a great deal of data about how people are likely to be affected by alternative choices" [36]. In this case, additional approaches to the climate-change issue like the TWA are welcome in order to get as much insight as possible. These approaches are perceived as complementary to CBA, not as complete replacements. CBA therefore has no priority and choices different from traditionally calculated cost–benefit paths are not regarded as necessarily irrational.

In the subsequent parts of this paper we assume that the policymaker seeking advice is not willing to accept the application of CBA as the sole decision criteria, either because of deviating normative judgements with respect to fundamental or technical aspects of CBA or because of the perception that the currently available scientific knowledge is insufficient for quantitative decision making based solely on CBA.

It should be emphasized that here we are interested in practical policy advice at the level of individual policymakers who will participate in an ensuing negotiation process.

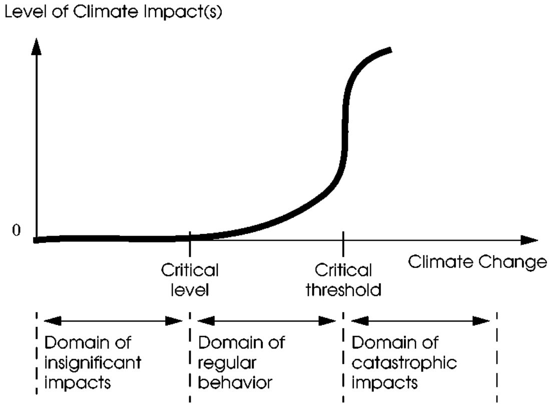

Figure 1. Scientific perception of climate change. To simplify the discussion, only one impact dimension is indicated, although all relevant categories should be obviously taken into account in a multidimensional way.

This pragmatic point of view is completely different from the task we would face if we had to advise a benevolent "world manager". In the latter case, we would have to integrate all necessary normative judgements in the framework that tries to resolve the respective social-choice problem without any possibility of referring to a negotiation process. For a detailed discussion of the relative merits of different frameworks (CBA, cost–effectiveness analysis, TWA) see [12]. Note that the TWA may be well suited even in the social-choice case, although here we focus on its application with a view to a negotiation process solely.

Considering the numerous difficulties involved in calculating climate change damage functions, Cost–Effectiveness Analysis (CEA, i.e., cost-minimizing subject to pre-defined constraints) has been proposed as a valuable complement to CBA (cf. [16, p. 151]). In a nutshell, an ideal cost–effectiveness analysis would be characterized by the following recipe (cf. figure 1): first, identify the *critical level* of climate change "below which harmful effects which are judged to be significant ... do not occur according to present knowledge" (compare with the definition of critical loads for sulphur and nitrogen as given in [25] and [26] and to that of critical levels discussed in [24]), and second, determine a specific climate protection strategy by minimizing the cost of mitigation measures that are necessary to stay below the critical level. Unfortunately, our current knowledge is not sufficient to specify a critical level that takes into account *all* relevant impact categories and it is not clear whether a non-zero level exists at all in the case of global climate change, even if adaptation opportunities are considered. From this point of view, the situation is therefore similar to that of health-related consequences of air pollution ([22, p. 43] and references therein), in which the problems of the so-called "myth of thresholds" (in the sense of critical levels) also have to be dealt with.

Due to this, it is sensible to focus on the other extreme, i.e., seeking to determine the *critical thresholds* (cf. figure 1) that characterize catastrophic climate change (like run-away greenhouse effect, disintegration of the West Antarctic ice shield, shut-down of the conveyor belt, perpetuation of El Niño, etc.). At present, there is increasing concern that emissions of greenhouse gases can trigger rapid and catastrophic climate change, e.g., due to a possible instability of the thermohaline circulation [34,35]. There are even attempts at identifying the respective threshold quantitatively [42]. A promising strategy therefore is to identify those climate protections strategies that limit the risks of crossing these thresholds to an acceptable confidence level.

The basic framework here is related to risk aversion. In the context of global change it might be called "pessimization" [38] since it takes into account the possibility that "all the climatic dice roll the wrong way" (cf. [16, p. 207], where some of the conceivable climate catastrophes are discussed). The notion of excluding at least the extremely risky strategies is one of the roots of the TWA, which was proposed by the German Advisory Council on Global Change [51,52]. For the sake of clarity, it is important to note that although analyses to identify scientific thresholds (in the sense of figure 1) can be useful guides in the climate change decision process, the decision to avoid crossing them is a normative one and not a scientific task in the strict sense.

In addition, a major misinterpretation of the bundle of all climate protection strategies that seek to exclude catastrophic climate change would be to expect that the outcomes of these strategies would be completely tolerable. One has to take into account also the domain of regular behavior (figure 1), in which significant impacts might occur. It is therefore legitimate that – even in the case of a continuous and smooth change of climate impacts – policymakers specify levels of climate change and of the respective impacts that they are not willing to accept and which they would like to exclude by defining appropriate guardrails. These guardrails, which may be lower (stricter) than the scientific thresholds, are therefore defined in the course of a normative judgement conducted by the policymakers themselves.

Framing the decision process in this way raises the question: Why are policymakers willing to accept climate change at all if no range of harmless climate change can currently be identified? This might be conceived as hardly defendable, especially if categories like human health are taken into account. The rationale – beside the impossibility of influencing climate change that has been already induced – is that sharp emission reductions could endanger the economic basis of welfare currently enjoyed, which could also indirectly lead to health risks. Implicitly, benefits (i.e., avoided climate damage) and costs (i.e., welfare losses due to mitigation measures) are therefore traded off. Protagonists of an exclusive application of cost–benefit analysis (or other approaches like decision analysis) would consequently argue that CBA should be used to identify the welfare-optimal path and – as a by-product – the acceptable limiting value located in the domain of regular climate change. We mention the fact that traditional CBA would not only allow health risks to be traded off in terms of costs and benefits but in addition would allow increasing health risks for parts of the population to be compensated by gains in other fields.

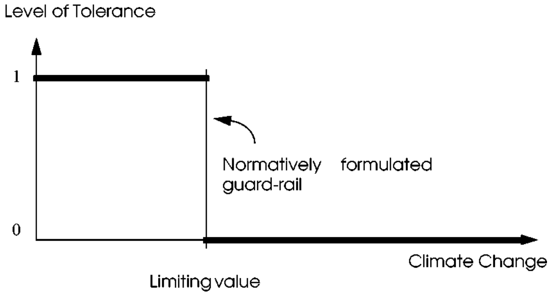

Figure 2. Normative perception underlying the cost–effectiveness approach to climate change. To simplify the discussion, only one impact dimension is indicated, although all relevant categories should be obviously taken into account in a multidimensional way.

Guardrails specified by policymakers without referring to a definitive criterion are certainly not universally valid. They reflect a normative judgement based on the policymaker's current qualitative and quantitative knowledge about the issue. After fixing the limiting values in this way, decision support could proceed in different ways.

If the policymaker regards every (possible) consequence of climate change lying within the range defined by the guardrail to be equally tolerable and *a priori* acceptable, a sensible strategy will be to use the cost–effectiveness approach (cf. figure 2). In that case, we have to be aware of the following peculiarity of this approach. In general, minimizing climate change mitigation costs will eventually lead to a situation, in which the guardrail is touched, in the sense that the level of climate change will coincide with the level defined by the guardrail at some point(s) in time. We assume here and in the following, that the guardrail can be modeled mathematically by some kind of "$\leqslant$" inequality. This is the case, for instance, in the concentration stabilization exercises (e.g., [20]) and it does not present a problem as long as the guardrails are actually regarded as separating *purely* tolerable and intolerable outcomes, respectively.

However, normative perceptions deviating from that sketched in figure 2 are equally conceivable. Figure 3 therefore depicts an exemplary tolerance function which is more general. The guardrails are used (only) to exclude outcomes which are *a priori* and explicitly judged to be intolerable according to the present knowledge of the policymaker. Thus, a forced revision of this setting would be perceived as regrettable, but it is not excluded under all circumstances. Next to the specified guardrail, a domain of indecision (cf. figure 3) may be located, i.e., policymakers are unable or unwilling to specify without additional information whether they regard outcomes in this domain as tolerable or not. Finally, at least for some climate impact categories, a domain of *a priori* tolerance (figure 3) may be identified which characterizes moderate climate change that is considered to be tolerable (with respect to this category),

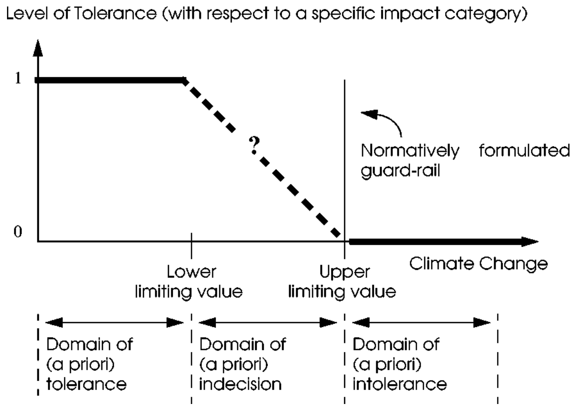

Figure 3. Normative perception of climate change (general case). To simplify the discussion, only one impact dimension is indicated, although all relevant categories should be obviously taken into account in a multidimensional way.

for instance, due to the availability of sufficient and cheap adaptation measures.

Whether or not a non-vanishing common domain of tolerance exists, when *all* pertinent impact categories are taken into account simultaneously, depends on the smallest value of the various *lower* limiting values, since already an intolerable outcome in *one* impact category is sufficient to characterize the corresponding climate change level as intolerable. This behavior differs from that of the common domain of intolerance, where tolerable outcomes in some impact categories do not destroy the overall intolerance. Mathematically, the common domain of tolerance is the intersection of all category-specific domains of tolerance, whereas the common domain of intolerance is obtained by constructing the union of all domains of intolerance. Due to this asymmetry, it is reasonable to investigate the case where at least one of the tolerance functions belonging to different impact categories possesses a *lower* limiting value (see figure 3) equal to zero, for example with respect to an increase of health-related risks.

In the following, we will therefore discuss the case where the domain of *a priori* tolerance (figure 3) vanishes for at least one pertinent impact category, i.e., for that category we only have to deal with the "domain of indecision" and with that of "*a priori* intolerance" separated from another by a normatively formulated guardrail. In this situation, cost–effectiveness analysis can be applied once again in order to determine cost-minimal paths with respect to the pre-defined *upper* limiting value (in the sense of figure 3). However, as the degree of tolerance is now undefined for all climate change values below the limiting value, these levels of climate change cannot be treated as equally tolerable anymore, which is in sharp contrast to the situation depicted in figure 2. As we have indicated above, one typical feature of cost–effectiveness analysis is that cost–efficient strategies tend to be extreme policy paths in the sense that eventually one of the guardrails will be touched. But this may not be the best strategy when the guardrails are borders of intolerance, i.e., *upper* limiting values in the sense of figure 3 as all climate impacts below the upper limiting value would be neglected completely.

In addition to applying the cost–effectiveness approach, which minimizes mitigation costs subject to climate change constraints, the policymaker may therefore be interested in just the opposite, i.e., in minimizing climate change as long as this does not violate guardrails defined in terms of unacceptable mitigation costs. As long as one solely focuses on "no-regret potentials" [16, p. 271], or as long as one takes into account only the "first order" mitigation costs of more ambitious mitigation measures (e.g., the amount of money required for restructuring the energy systems), this may be regarded as a very appealing strategy. Yet if one considers the indirect effects as well, and if these effects are described in physical terms (like health-related risks), one faces ethical problems similar to those involved in the cost–effectiveness strategy. Minimizing climate change subject to cost constraints is an approach which favors the environment by completely neglecting socio-economic impacts below the value that defines "unaffordable costs", whereas cost–effectiveness is one that favors the economy by neglecting climate change impacts below the chosen climate guardrail. Both approaches deliver interesting results, which should be considered to be extreme in a symmetric sense. The approaches therefore are complements rather than alternatives.

A further possibility is to take into account both aspects (cost and damage) simultaneously. In principle, one way would be to refer to CBA and/or to multicriteria analysis (if trade-offs should be depicted explicitly) either in their traditional form or enhanced by taking into account the pre-defined guardrails as constraints that exclude those domains where welfare losses amount to infinity. Yet, we have assumed at the beginning of the discussion that the policymaker seeking for scientific advice is interested in complementary approaches. A supplementary way to proceed is to abstain intentionally from calculating a single (preferable) path (or a set of vector-optimal paths if multicriteria analysis were applied). This may be motivated, for example, by the perception that the currently available scientific knowledge is insufficient to identify optimal paths quantitatively.

However, doing so is not identical with neglecting scientific insights and existing knowledge completely. The challenge is to provide a framework which takes into account the current knowledge without being forced to carry out a complete accounting of all conceivable climate damages and mitigation costs. Especially with respect to some impacts of climate change, large parts of the problem that may be the crucial ones (like the possible consequences of climate instabilities) are still to be investigated and therefore are not known either in a deterministic or in a statistical sense. In addition, this framework should allow necessary normative choices to be made as explicitly as possible.

The tolerable windows approach represents a first step in this direction. Initially, the policymaker defines guardrails which exclude intolerable climate change impacts as well as unacceptable socio-economic consequences of greenhouse gas mitigation. Then, a scientific assessment tries to identify all policy paths (e.g., in terms of time-dependent emission rates or emission taxes) that are not explicitly intolerable. The resulting set of climate protection strategies admissible in this sense characterizes a valuable pre-selection of policy paths relevant for the further negotiation process, in which the policymaker will participate.

It should be emphasized that the tolerable windows approach therefore does not exclude the search for a collectively acceptable policy path by resolving the "indecision (domain)" still involved in the definition of the guardrails. In accordance with the point of view expressed in the contribution of Working Group III of the IPCC [16, chapter 2], it intentionally leaves this decision to the negotiation process. The approach seeks to combine pre-defined normative settings and available scientific knowledge in the forefield of these negotiation processes in order to identify the maneuvering room of the respective policymaker. Hopefully, being provided with whole bundles of possible and not evidently intolerable strategies will help policymakers to exhibit sufficient flexibility to participate efficiently in the Conferences of the Parties to the Framework Convention on Climate Change.

4. Methodological aspects of the tolerable windows approach

Up to now, we have explained the conceptual prerequisites for applying the TWA. From a methodological point of view, the challenge now is to transform the oversimplified static and one-dimensional concept (cf. figure 4) into a dynamic one that takes into account various dimensions of climate change impacts and of socio-economic consequences of mitigation measures.

As a starting point for the following detailed mathematical description – which may be skipped by readers primarily interested in the results – we assume that the current state of scientific knowledge is represented with sufficient precision by an appropriately chosen dynamic model that comprises partial models for all systems (socio-economy, atmospheric composition, climate and impact) relevant for the global climate change issue, and their interconnections, in an integrated way. In addition, we assume that the behavior of the overall system is described sufficiently by the time evolution of a vector of pertinent *state variables* denoted by $\boldsymbol{x}(t)$ including, for instance, Gross Domestic Product (GDP), greenhouse gas concentrations, global mean temperature, and agricultural yield. Obviously, the respective evolution depends on the chosen climate protection strategy (e.g., expressed by the emissions themselves or by that of the emission reduction rates) that is modeled by specifying the components of a *control vector* $\boldsymbol{u}(t)$ as a function of time t. For the moment, we neglect all uncertainties involved and assume that the relationship between $\boldsymbol{x}(t) \in \mathbb{R}^n$ (Euclidean n-space) and $\boldsymbol{u}(t) \in \mathbb{R}^m$ can be described by a deterministic dynamic model given by an appropriately chosen set of differential equations denoted as

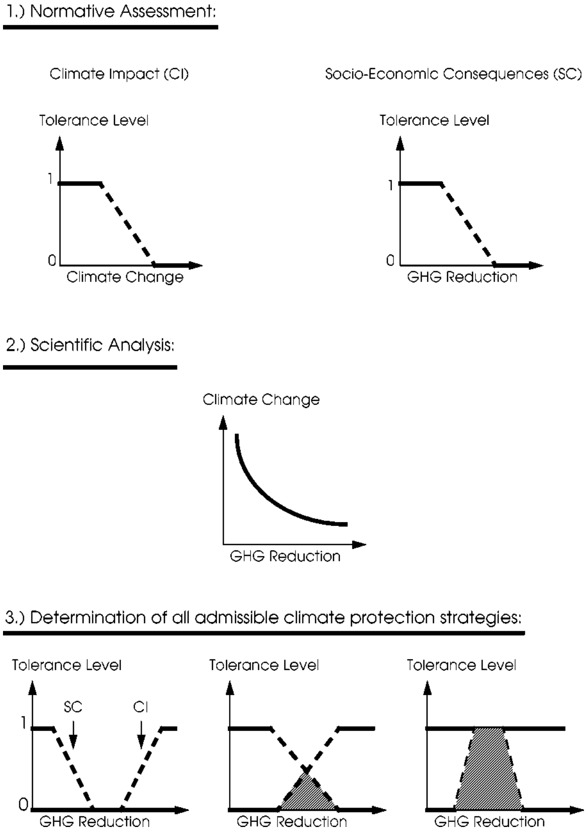

Figure 4. Static sketch of the tolerable windows approach. First, normative constraints are defined with respect to climate impacts as well as to the socio-economic consequences of mitigation measures by taking into account available scientific information. In a subsequent step, the relevant parts of the Earth's system are analyzed in order to determine all admissible climate protection strategies in terms of the necessary GreenHouse-Gas (GHG) emission reduction. The resulting set is empty, if the guardrails are defined too ambitiously (left variant). Otherwise, the result is an entire set of possible climate protection strategies (middle and right variant). It should be emphasized that the dashed lines are used in order to indicate that the respective relationships are not known quantitatively. They do *not* represent a linear relationship, which would obviously result in curved dashed lines in the third series of graphs.

$$\dot{\boldsymbol{x}} \equiv \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x}(t) = \boldsymbol{f}\big(\boldsymbol{x}(t), \boldsymbol{u}(t), t\big) \tag{1}$$

with respective initial conditions

$$\boldsymbol{x}(t = 0) = \boldsymbol{x}_0. \tag{2}$$

In general, the constraints defined by the policymaker will impose restrictions on certain state variables (e.g., maximum loss of agricultural yield or loss of GDP). Due to the nature of the climate problem, it may also be necessary to impose restrictions on some control variables as well (e.g., the rate of emission reduction). Together, the respective constraints can be modeled as a set of K adequately chosen inequalities

$$\begin{aligned} h_1\bigl(\boldsymbol{x}(t), \boldsymbol{u}(t), t\bigr) &\leqslant 0, \\ &\vdots \\ h_i\bigl(\boldsymbol{x}(t), \boldsymbol{u}(t), t\bigr) &\leqslant 0, \\ &\vdots \\ h_K\bigl(\boldsymbol{x}(t), \boldsymbol{u}(t), t\bigr) &\leqslant 0, \end{aligned} \tag{3}$$

or in vector form,

$$\boldsymbol{h}\bigl(\boldsymbol{x}(t), \boldsymbol{u}(t), t\bigr) \leqslant \boldsymbol{0} \quad \forall t \in [0, t_e], \tag{4}$$

where, in general, one externally defined constraint corresponds to one inequality. In practice, we will choose a finite and fixed value for the final point in time t_e, which is sufficiently large so that the normative decisions are represented appropriately.

Let $\mathcal{W}_i(t) \subseteq \mathbb{R}^n \times \mathbb{R}^m$ denote the (possibly time-dependent) inner domain of the combined state-and-control space as delimited by the ith inequality. Then the *tolerable windows* are simply defined as projections of the high-dimensional set

$$\begin{aligned} \mathcal{W}(t) &\equiv \bigcap_{i=1}^{K} \mathcal{W}_i(t) \\ &= \bigcap_{i=1}^{K} \bigl\{ \bigl(\boldsymbol{x}(t), \boldsymbol{u}(t)\bigr) \mid h_i\bigl(\boldsymbol{x}(t), \boldsymbol{u}(t), t\bigr) \leqslant 0 \bigr\} \\ &\subseteq \mathbb{R}^n \times \mathbb{R}^m \end{aligned} \tag{5}$$

onto subspaces (of $\mathbb{R}^n \times \mathbb{R}^m$) spanned by variables that are involved in the definitions of the guardrails, cf. [39]. These projections are called tolerable windows even when they are not closed subsets or when the windows so-defined are time-dependent. They constitute the fundamental elements on which the TWA is based, cf. [47].

Due to the very important issue of adaptation possibilities [61], often normative settings will not only involve state variables. They may take into account the rate of change in these variables $\dot{\boldsymbol{x}}(t)$ (e.g., rate of temperature change) as well. But this case is already implicitly included in the mathematical description discussed so far, as according to (1) the entity $\dot{\boldsymbol{x}}(t)$ can be easily replaced by the function $\boldsymbol{f}(\boldsymbol{x}(t), \boldsymbol{u}(t), t)$, which depends on state and control variables solely. Guardrails that would involve the rate of change in state variables explicitly therefore can be redefined and then described in terms of $\boldsymbol{h}(\boldsymbol{x}(t), \boldsymbol{u}(t), t) \leqslant \boldsymbol{0}$ as well, as long as $\boldsymbol{f}$ is appropriately taken into account in the concrete definition of $\boldsymbol{h}$. In the following parts of this section, we assume that the inequalities are formulated in the standard form so-defined.

It should be noted that although the initial characterization of the TWA focused on the two extreme sides (climate change impacts and socio-economic consequences of mitigation measures) there is no need to exclude normative settings with respect to intermediate points involved in the chain of cause and effect that connects both sides. Actually, as long as it is difficult to specify most climate impacts quantitatively, appropriate proxy variables like global mean temperature may be used as substitutes which reflect our restricted knowledge. In addition, it should be emphasized that it is up to the policymaker to decide which variables should be included in the definitions of the guardrails. Therefore, the state variables may be local impact variables as well as global indicators of climate change; they may be related to single countries or to quantities aggregated across countries (e.g., global GDP). The guardrails may restrict impacts in different dimensions separately or they can be applied to combined functions of different impact variables in order to allow some degree of compensation across impacts or consequences. It is even possible to allow some kind of trade-off between quantifiable costs and damage, either restricted to specific sectors like human health or even across sectors, so that aspects of conventional CBA can be well included in the framework if the policymaker is asking for them. In all cases in which state and control variables are combined in a purely algebraic way (like aggregation across impacts, aggregation across agents, and compensation of costs and avoided damage), the respective relationships can be easily taken into account by an appropriate definition of the components of $\boldsymbol{h}(\boldsymbol{x}(t), \boldsymbol{u}(t), t)$.

In summary, the goal of the tolerable windows approach as presented here may be described as follows:

Identify all climate protections strategies, i.e., the set of all admissible (piecewise continuous) control paths $\boldsymbol{u}(\cdot)$, that obey simultaneously the predefined constraints (4) subject to the dynamical constraints (1) with initial conditions (2). (Here and in the following we use the notation as explained in [33, pp. xvii–xx].) We intentionally allow the control path to exhibit a finite number of discontinuities (of the first kind), since instantaneous changes in control variables, like carbon taxes, are conceivable and should therefore not be excluded.

In contrast to optimal-control problems, we are not interested in one (optimal) path solely, but in a whole family of admissible paths. Since the respective non-uniqueness is unfamiliar, we would like to embed our initial problem in the framework of the "theory of differential inclusions" (e.g., [4,5,8,18]) that is designed exactly to deal with this kind of dynamical non-uniqueness and that provides appropriate definitions, a consistent theoretical background (e.g., theorems of existence), and even some useful approximate solution methods.

Suppose that the different components of the vector $\boldsymbol{h}(\boldsymbol{x}(t), \boldsymbol{u}(t), t)$ are arranged in the following way. The first $\widetilde{K}$ components – summarized by the vector $\boldsymbol{h}'(\boldsymbol{x}(t), \boldsymbol{u}(t), t)$ – involve control variables explicitly. The remaining inequalities – combined to form the vector $\boldsymbol{h}''(\boldsymbol{x}(t), t)$ – impose restrictions on state variables, solely. (Note: the prime and double prime are only used to mark the different components of $\boldsymbol{h}$. They do not denote a derivative.) We then denote the set

$$\mathcal{U}\big(\boldsymbol{x}(t),t\big) \equiv \big\{\boldsymbol{u}(t) \mid \boldsymbol{h}'\big(\boldsymbol{x}(t),\boldsymbol{u}(t),t\big) \leqslant \mathbf{0}\big\} \tag{6}$$

as the time-dependent and possibly state-dependent *control domain*. In addition, we define the time-dependent set

$$\mathcal{D}(t) \equiv \big\{\boldsymbol{x}(t) \mid \boldsymbol{h}''\big(\boldsymbol{x}(t),t\big) \leqslant \mathbf{0}\big\} \tag{7}$$

that represents pure *phase constraints*.

The state trajectories $\boldsymbol{x}(\cdot)$ that are solutions of the multidimensional differential equation (1) subject to the specified constraints (4) satisfy the following *differential inclusion*:

$$\begin{aligned} &\dot{\boldsymbol{x}}(t) \in \mathcal{F}\big(\boldsymbol{x}(t),t\big) \quad \text{with} \\ &\quad \mathcal{F}\big(\boldsymbol{x}(t),t\big) \equiv \big\{\boldsymbol{f}\big(\boldsymbol{x}(t),\boldsymbol{u}(t),t\big) \mid \boldsymbol{u}(t) \in \mathcal{U}\big(\boldsymbol{x}(t),t\big)\big\} \\ &\quad \text{subject to } \boldsymbol{x}(t) \in \mathcal{D}(t) \wedge \boldsymbol{x}(t=0) = \boldsymbol{x}_0. \end{aligned} \tag{8}$$

Framing the problem in this way emphasizes the set-valued character (in the function space) of the solution we are looking for. Since different possibilities exist to define what should be considered as a solution of this differential inclusion, we proceed in introducing some fundamental notions of the theory of differential inclusion.

An (isolated) state trajectory $\boldsymbol{x}(\cdot)$ that starts from $\boldsymbol{x}_0$ and that fulfills the differential inclusion (8) subject to the given constraints is called an *admissible trajectory* driven by a corresponding, not necessarily unique, *admissible control path* $\boldsymbol{u}(\cdot)$. The most comprehensive solution of the differential inclusion would be provided by the *bundle of all admissible trajectories* $\mathcal{S}(\boldsymbol{x}_0)$ which corresponds to an underlying *bundle of admissible control paths*, i.e., the set of all admissible climate protection strategies. Unfortunately, a complete and exact determination of these bundles is hardly feasible at the current stage of the theory, or as Deimling states, "usually it will be impossible but also not necessary to know all solutions" [8, p. 77]. Besides this, even if it were simple to determine these bundles, they would have to be described in rather abstract function spaces, so that at least for policy advice these bundles would have to be expressed in a simpler way, i.e., by emphasizing special aspects (e.g., appropriate projections onto subspaces or sufficient and necessary conditions, respectively) of the bundle of admissible control paths. Our solving strategy therefore focuses directly on the determination of these special aspects.

We have proposed a comprehensible method to describe a subset of the bundles via parameterized control paths. Although simple, the method has already provided some interesting insights in the form of sufficient conditions for admissible control strategies [47].

Here, we would like to focus on the derivation of necessary conditions. The basic concept is to determine the (*integral state*) *funnel* [8, p. 84], which is given by

$$\begin{aligned} \Gamma(\boldsymbol{x}_0) &\equiv \big\{\big(t,\boldsymbol{x}(t)\big) \mid t \in [0,t_e],\ \boldsymbol{x}(\cdot) \in \mathcal{S}(\boldsymbol{x}_0)\big\} \\ &\subseteq [0,t_e] \times \mathbb{R}^n. \end{aligned} \tag{9}$$

The funnel is therefore defined as being nothing else as the picture that we get if we plot all admissible trajectories simultaneously. Fortunately, it is possible to derive the boundaries of the funnel without actually knowing the most comprehensive solution $\mathcal{S}(\boldsymbol{x}_0)$. The subtle difference between the funnel and the bundle of the admissible trajectories is that in the latter case the different trajectories are emphasized whereas in the first case the set of admissible points is determined. We therefore are not further interested in the trajectories themselves, but in calculating the admissible states. This simplifies the task extremely. The intersection of $\Gamma(\boldsymbol{x}_0)$ by a hyperplane $t = \tau,\ \tau \in [0,t_e]$, gives the *admissible phase domain*. It should be noted that this domain contains all states $\boldsymbol{x}(\tau)$ that can be reached by applying an admissible control in $[0,\tau]$ and for which an admissible future exists in $[\tau,t_e]$.

Obviously, the admissible domain is in general a time-dependent subset of a high-dimensional phase space. Yet, we are often not actually interested in this domain itself but in projections of this domain onto pertinent subspaces related to crucial variables. These projections are called *admissible windows* in the framework of the TWA.

It is possible to extend the definitions discussed so far in order to take into account aspects of the solutions with respect to control variables as well. As the corresponding definitions (*control funnel*, *admissible control domain*) are straightforward extensions, we can avoid a detailed discussion. Here we only like to mention, that it is usual to call pertinent projections of the admissible control domain admissible windows as well and that this notion will be used even if the subspaces on which the domains are projected are spanned by state and control variables together. For each tolerable window (see above), a corresponding admissible window may be derived that reflects the restrictions imposed upon the state and control variables by taking into account all guardrails simultaneously. It should be noted that the admissible windows so-defined are in general time-dependent, so that a final visual presentation will provide them, for example, in a stroboscopic way or by applying video techniques.

Another way to stress this time-dependent feature is to select one component of the state vector or of the control vector (e.g., the rate of global CO_2 emissions), solely, and to determine the projection of the funnel onto a plane that is defined by the time axis and the axis of the respective variable. These projections are called *necessary corridors*. It is important to realize that these corridors do not contain the full information captured in the admissible trajectory and control path bundle, respectively. Rather they present necessary conditions for trajectories and for control paths to be admissible. Therefore, every trajectory and every control path that leaves the respective corridor is obviously not admissible. However, not any arbitrary trajectory (or path) lying completely within the corridor is necessarily admissible. This important feature should be kept in mind whenever corridors are presented.

We abstain from discussing the numerical methods which were used to derive the corridors that are presented in the following. We have done this elsewhere [47] so that we can focus on presenting the results without further ado.

5. First results

This section illustrates our approach by a rather simple example based on a tolerable *climate* window originally formulated by the German Advisory Council on Global Change (WBGU) [51,52]. The window is specified in terms of restrictions for the global mean temperature T and for its rate of change DT. Besides these temperature constraints we want to employ limits for the sea-level rise S and its rate DS. Generalizing the functional form of the council's window we write in case of global warming, i.e., for temperatures above the preindustrial level,

$$\begin{aligned} T &\leqslant T_{\max}, \\ DT &\leqslant \begin{cases} DT_{\max} & \text{if } T \leqslant T_{\text{trans}}, \\ DT_{\max} \cdot \sqrt{\frac{T_{\max}-T}{T_{\max}-T_{\text{trans}}}} & \text{else,} \end{cases} \\ S &\leqslant S_{\max}, \\ DS &\leqslant DS_{\max}, \end{aligned} \tag{10}$$

with parameters $DT_{\max}$, $DS_{\max}$ for the maximal rate, $T_{\max}$, $S_{\max}$ for the absolute value, and T_{trans} for the transition value from linear to non-linear behavior of the underlying generalized response function. In this study, we will make five different assumptions concerning the tolerable climate window with parameters given in table 1. The council's window, indicated by the name "WBGU" is based on considerations of the climate history over the last 120,000 years and some expert estimates on potential climate impacts [51,52,61].

According to the methodological discussion in the previous section, it is not sufficient to specify the maximally tolerable climate change only. As a further constraint, we have to set upper limits for the burden imposed by climate change mitigation measures. In order to include this constraint in our analysis, we initially specify a maximum rate of emission reduction of 10%/yr [47]. This restriction is arbitrary and only meant as an example, as no one seriously asserts that emissions can be halved in seven-year periods. Strictly speaking, it would be necessary to explore such constraints in terms of socially relevant indicators like welfare or private consumption losses by using an adequate socio-economy–energy model (see discussion at the end of this section).

Table 1
Parameter values for the climate window defined by equation (10). Dashes indicate that the corresponding constraint is not effective.

Name	$DT_{\max}$ (°C/dec)	$T_{\max}$ (°C)	T_{trans} (°C)	$S_{\max}$ (cm) rel. to 1990	$DS_{\max}$ (cm/dec)
WBGU	0.2	16.6	15.6	–	–
WBGU SLR	0.2	16.6	15.6	30.0	3.0
LARGE	0.3	17.6	16.6	–	–
LARGE SL	0.3	17.6	16.6	30.0	–
LARGE SLR	0.3	17.6	16.6	30.0	3.0

The coupled climate and greenhouse-gas cycle model (called ICM) currently implemented in the model framework consists of four basic submodules. The model includes basically all important GreenHouse Gases (GHG), i.e., CO_2, CH_4, N_2O, halocarbons, tropospheric and stratospheric O_3, and stratospheric water vapor. In addition, it takes into account the radiative effects of aerosols originating from SO_2 emissions and from biomass burning. The input of ICM consists of emission paths for CO_2, CH_4, N_2O, CFC11, CFC12, HCFC22, HFC134a, and SO_2. The emission profile of each GHG can either be included by specification of a scenario or be used as a control variable. For the investigation in this paper we have used one control variable, i.e., a single homogeneous rate of emission reduction for CO_2, CH_4, N_2O, and SO_2. The output is given by transient global-mean temperature, rate of temperature change, global-mean sea-level rise, and rate of sea-level rise. The carbon cycle is modeled according to a reduced-form approach developed by Svirezhev and Brovkin [43,44] that explicitly takes into account carbon pools in dead and living biomass and in the ocean. The circulation of the residual greenhouse gases and the related radiative forcings are simulated by means of reduced-form models that are similar to the corresponding parts of MAGICC [28,40,53–55,57] (cf. [17]). The climate module (in the strict sense) and the module that computes the sea-level rise due to the thermal expansion of the ocean are given by simple impulse–response models similar to that described by Hasselmann et al. [11]. The other sea-level rise components (related to glaciers, Greenland, and Antarctica) are calculated according to Wigley and Raper [56] and Warrick and Oerlemans [50]. The next version of the model will include regionalized climate variables according to their role in regional vulnerability to climate change [15]. For more details of the model see [47,49].

In order to compute successively necessary representations of the set of emission profiles compatible with the five different climate windows specified by equation (10) and table 1, we have developed an effective numerical algorithm [47]. The algorithm is based on the analogy between the general Hamilton–Bellman–Jacobi equation [30] and the equation for the boundary of the entire tube of solutions [29] and is in principle equally applicable to more general problems stated in terms of differential inclusions.

Figures 5 and 6 depict various aspects of the solutions for the five windows investigated here. The figures show necessary corridors for the CO_2-equivalent greenhouse gas concentrations, global mean temperature, sea-level rise relative to 1990, and global energy and cement-related CO_2 emissions. In case of temperature constraints alone, the white area (outside the corridor) is forbidden. Additional prohibitions due to the constraints in sea-level

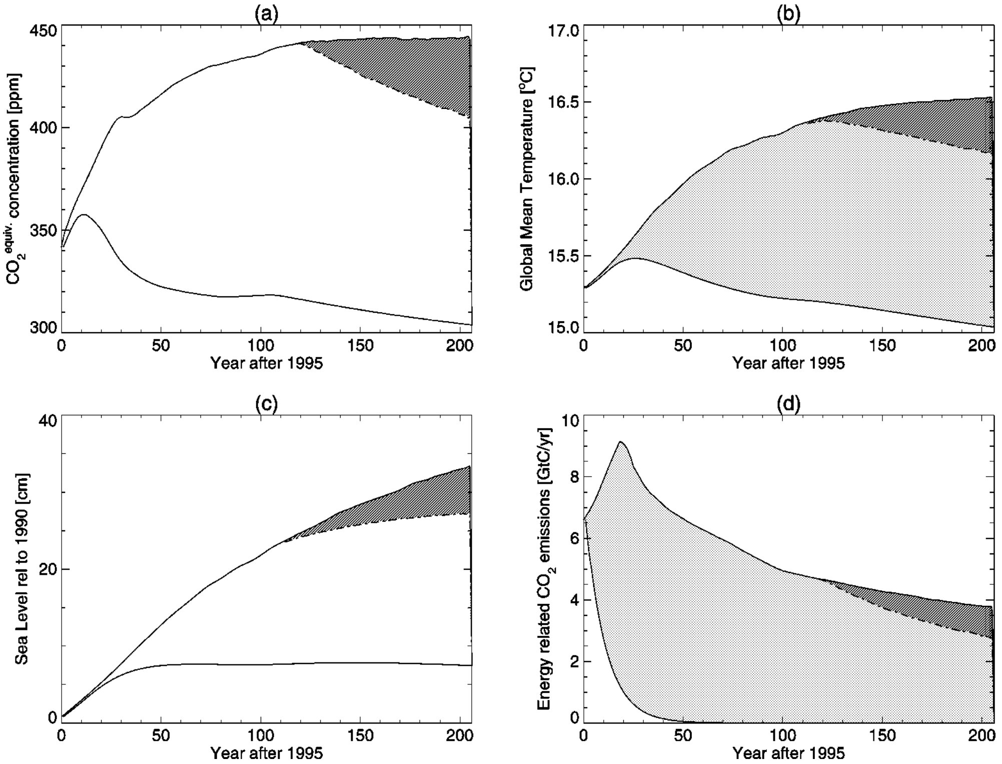

Figure 5. Corridors for the WBGU temperature constraints as originally set by the German Advisory Council on Global Change. If no restriction is made for the sea level, the corridor is given by the union of the two shaded areas. In case of constraints for the magnitude of sea-level rise, the domain shaded in dark grey, is forbidden as well.

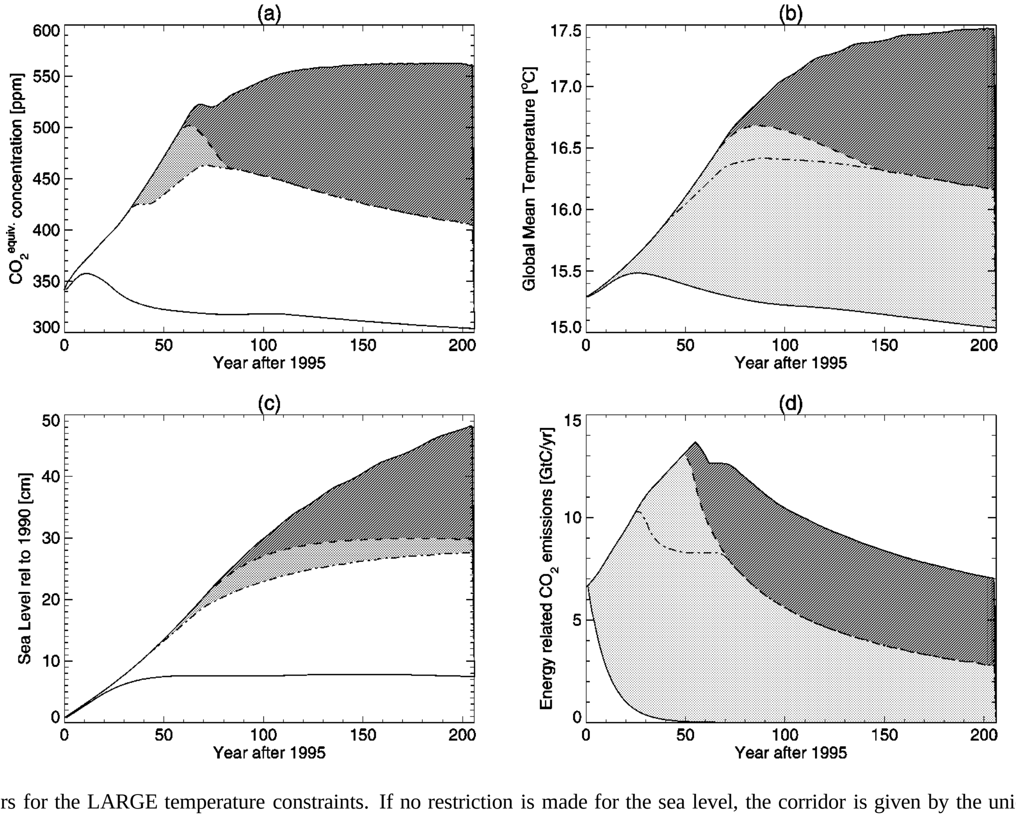

Figure 6. Corridors for the LARGE temperature constraints. If no restriction is made for the sea level, the corridor is given by the union of all shaded areas. In case of restrictions on the magnitude of sea-level rise the dark area is forbidden. Additionally, in case of constraints for the rate of sea-level rise, the domain shaded in medium grey is forbidden as well.

rise are encoded by the dark (magnitude only) and by dark and medium gray shaded areas (magnitude and rate of rise), respectively. The projection of the funnel onto the emissions subspace might be called the CO_2 emission corridor (compare [2] where the concept of emission corridors is presented for the first time). As the results have been obtained by simultaneously reducing CO_2, SO_2, CH_4, and N_2O by the same percentage rate, the corridors for the other trace gases (i.e., for CH_4 and N_2O) can be obtained by a simple scaling procedure. In the initial phase, i.e., until reduction is started, greenhouse gas emissions are assumed to follow the IS92a scenario of IPCC [13]. Land use change emissions are extrapolated from historical records and halocarbon emissions are treated according to the updated IPCC scenarios [14]. The depicted corridors and projections represent *necessary* conditions for the time evolution of the respective variable to fulfill the specified socio-economic and climatic constraints.

The main results for the WBGU domain (figure 5) are:

(a) Considering only CO_2 emissions related to energy and cement production, effective emission reduction has to commence in 2017 at the latest due to the limitation in the rate of temperature change. The longer the reduction is delayed, the longer it has to last with a higher rate.

(b) The restriction on the magnitude of sea-level rise becomes effective only after 2115. The rate of sea-level rise chosen here has no influence on the emissions corridor.

(c) If there is no restriction on sea-level rise, a simple analysis of the climate model yields the maximal admissible equilibrium CO_2-equivalent concentration at 442 ppm. Yet within the time horizon investigated in this paper, the concentration can be slightly higher, i.e., about 450 ppm. With restrictions on the sea level, however, admissible concentrations are much lower: after reaching its absolute maximum of 441 ppm in 2110, the concentration definitely has to decrease continuously to 405 ppm in 2200. Note that due to the long-term melting effects of the Antarctic and Greenland ice shields there is no climatic equilibrium if general sea-level rise is restricted. Similarly, global mean temperature declines from 16.4 °C in 2115 to ca. 16.2 °C in 2200.

The LARGE window of tolerable temperatures (figure 6) implies the following main differences in the results:

(a) The latest time to start reductions shifts to 2053 without sea level constraints, to 2047 with a limit on the absolute amount of sea-level rise, and to 2024 with restrictions on the rate of sea-level rise. Note, however, that in the case of sea-level constraints, long-term emission constraints are equal to those of the WBGU temperature domain, i.e., emissions have to be less than 2.8 GtC/yr in 2200.

Table 2

Maximal achievable energy and cement-related CO_2 emissions for the five different climate windows as defined in equation (10) and table 1.

CO_2 emissions in GtC/yr	2030	2050	2100	2200
WBGU	7.4	6.4	4.9	3.8
WBGU SLR	7.4	6.4	4.9	2.8
LARGE	11.6	13.7	10.2	7.0
LARGE SL	11.6	11.5	5.3	2.8
LARGE SLR	8.8	8.3	5.3	2.8

(b) The equilibrium concentration without sea-level restrictions amounts to 556 ppm which will not be exceeded within the next 200 years.

(c) If emission profiles are chosen appropriately and emissions are not restricted due to sea-level rise, it is possible to keep emissions rather high (approximately 12.5 GtC/yr) far into the next century. However, this requires emissions to be stabilized not later than in 2035. Similarly, in case of constraints on the rate of rise, emissions can be stabilized at about 8.3 GtC/yr if they are frozen beyond 2007.

Table 2 summarizes our main results in terms of the maximum energy- and cement-related CO_2 emissions for the different assumptions on tolerable windows. As one can see, short term emission reduction is needed only if either the rate of temperature change or the rate of sea-level rise has to be restricted. Limitations on the absolute values are important only in the long term.

A general consensus in the integrated assessment community holds that, with a view to the complexity of issues involved in the climate change and our ignorance about its many aspects, the best integrated models can offer to policymakers is insights about the nature, basic relationships, and key dynamic features of the problem. Especially, since we have not taken into account various important uncertainties, for example concerning the sensitivity of the climate model, the results should be taken as preliminary only.

In order to be most comprehensible, the results presented here are based on investigating a rather restricted part (emissions, concentrations, and climatic aspects only) of the complex chain of causes and effects that relates socio-economic activities with climate impacts. A comprehensive analysis would therefore take into account climate impacts as well as various indicators of socio-economic development.

Accordingly, the current version of the ICLIPS model embodies a multi-regional Ramsey-type optimal growth economic model [48] so that restrictions, which reflect the limited resilience of societies with respect to climate change mitigation measures, can be imposed on the following economic indicators (for the global average and/or for each region separately):

- cumulative welfare and/or utility loss (relative to the optimal development that would be projected in a world without climate change);

- transient welfare and/or utility loss;
- transient and/or cumulative GDP loss;
- transient and/or cumulative per capita income loss.

Furthermore, a minimum annual per capita income/consumption increase (relative to the absolute values of the preceding year) can be prescribed as well as a minimum annual per capita GDP increase. Finally, intergenerational equity concerns can be formulated, for example, by enforcing intergenerationally equal cumulative utility or per capita income losses and an intergenerationally equal per capita income/consumption increase, respectively.

For the sake of brevity, we abstain from presenting results of corridor calculations that take into account some of these indicators explicitly, since we have done this already [48].

The normative definition of guardrails concerning the other extreme of the chain of causes and effects – the climate impacts – can be carried out on the basis of regional climate impact response functions. The response functions included in the ICLIPS model are derived from complex process oriented climate impact models fed with regional patterns of climate change, which are provided by general circulation models.

The ICLIPS model currently encompasses regional response functions for the following impact categories (for numerical examples see [47]):

- water availability;
- natural vegetation;
- nature reserves;
- agricultural yield.

Aggregation of regional impacts is a normative question that should, in the line of the approach, be resolved by the policymaker seeking for scientific advice (compare the "trade-off" problem discussion in [31]). The approach (and the ICLIPS model implementing it) is therefore open for various settings ranging from limiting regional impacts, that is focusing on "hot spots", to imposing constraints on the cumulative effects only. It is possible to define minimum regional standards and to impose simultaneously a restriction for the cumulative effect by taking into account positive impacts. The latter case is very important, as it is easily conceivable that regional impacts are still below their maximum values although the combination of all impacts is regarded to be intolerable.

6. Tolerable windows and uncertainty: a methodological outlook

Up to now, we have presented a purely deterministic version of the tolerable windows approach. Although it provides some important insights, such a version can only be considered as a first example and introduction to the tolerable windows concept. With respect to global climate change issues, uncertainty is omnipresent (cf. [14,16,41]). Integrating uncertainty is therefore a major task in the further development of the TWA (cf. [9,19,23,60]). In order to draw attention to this problem and in order to provide further clarification on TWA, we would like to discuss some of the most important aspects related to tolerable windows and uncertainty. Of course, this discussion is meant only as a methodological outlook and it is therefore far from being exhaustive. The proposed methods are promising but not yet realized in numerical form.

Up to now, some aspects of the large uncertainties inherent in the elements of the climate and the socio-economic system have been incorporated in integrated assessment models mainly by applying one of the following methods: sensitivity analysis, stochastic modeling or decision analysis (cf. [16, pp. 389; 41]).

Sensitivity analysis (in the strict sense) tries to determine the implications of uncertainties in major input variables or model parameters. In the simplest version, the sensitivity of model results related to a small variation (e.g., by 10%) in one of the uncertain model inputs is investigated successively for each of these inputs. This reveals the model sensitivity due to variations per se. If the uncertainty in the inputs is quantifiable, e.g., by appropriate probability distributions or by bounded uncertainty ranges, one can calculate results for an extreme choice (e.g., 10th and 90th percentile or boundary values, respectively) for each uncertain input, which yields the sensitivity due to changes in inputs over plausible ranges.

Stochastic modeling generalizes the sensitivity analysis idea by investigating the combined effect of all uncertain inputs, rather than focusing on each uncertain input separately. This is done by sampling objective – or, if these are not available, subjective – probability distributions that have to be provided for each major uncertain input. By applying Monte Carlo methods, the results related to a multitude of different possible combinations of inputs are calculated. The final analysis of these results then derives a probability distribution for each model output variable, which indicates the possible range of outcomes of different plausible policy paths that *could* occur in the future.

In order to determine what climate protection strategy *should* be chosen under uncertainty, *Decision Analysis* (DA) is proposed by some authors (see the evaluation of this method in [16]). Prerequisites for applying the method are the focus on a single actor, a limited number of decision alternatives, a consistent valuation of possible outcomes (in a common unit, e.g., in monetary terms), and the precondition that uncertainties are quantifiable.

Assessing the usefulness of DA, especially with respect to uncertainty, we have to take into account that objective probabilities have not been established for many inputs to decision making. Subjective probabilities may conceivably be used to replace them, but it makes a worldwide agreement difficult to achieve [16, p. 65]. Due to these (and other) shortcomings, authors of chapter 2 of the IPCC Second Assessment Report [16, p. 65] suggest that "decision analysis cannot serve as the primary basis for international climate decision making" and, in addition, they mention, that "without an effective quantitative approach to decision optimization, climate change decision-makers will have to rely on negotiation to choose their responses to the problem". As we have already discussed, this does not mean that methods like DA are useless. Being an information-yielding instead of a decision-making tool [36], DA can provide useful insights. DA especially "may help keep the information content of the climate change problem within the cognitive limits of decision-makers" [16, p. 65]. But DA or (in the deterministic case) CBA is not the only tool provided for decision-support. There are other approaches, with a different focus. One of these approaches is the TWA as described in this paper. In order to outline the conceivable incorporation of uncertainty aspects in the framework of the tolerable windows approach, the following three types of uncertainty should be distinguished, cf. [7]:

(a) ignorance, where we cannot (quantitatively) specify the uncertainty at all;

(b) uncertainty (in the strict sense), where the available information is not sufficient to justify assignments of probabilities, but where the uncertainty range is bounded;

(c) risk, where uncertainty can be described by probability distribution functions.

Stylized examples, related to the climate change issue, are: (1) the possibility of a "runaway greenhouse" effect [16], (2) the climate sensitivity parameter, which is assumed to be in the range of 1.5–4.5 °C [14], and (3) changes in the risk of flooding due to sea-level rise [6].

A characteristic feature of traditional approaches to climate change decision making is that these approaches try to identify one (often the apparently best) solution of the problem. This leads to very sophisticated model structures, but reduces the opportunity to incorporate uncertainty appropriately. For instance, CBA works with "best guesses" (sometimes investigated by sensitivity analysis) only, and even DA can only deal with "risky" situations in the above defined sense. One promise concerning the still-to-be-developed non-deterministic version of the tolerable windows approach is to take into account appropriately each of the different aspects of uncertainty.

(a) With respect to ignorance, it might be sensible to seek for identifying at least the "borders of ignorance", cf. [10]. In this sense, it can be a prudent strategy to flee those domains of future climate change, where possible climate catastrophes are conceivable, even though they are not yet describable in quantitative terms. As a guideline to define those climate states that seem to be "safe", appropriate paleoclimatological records can be used. This is one rationale that underlies the definition of the WBGU climate window [51]. An interpretation of the precautionary principle allows a moderate climate evolution but not arbitrarily large climate change, e.g., by defining a maximal change of 2 °C. This poses questions about the range of emission paths which obey this (normative) threshold. As has been shown, this kind of question and the determination of the related policy strategies can already be tackled by the deterministic version of the TWA.

(b) Dealing with uncertainty (in the strict sense) can be likewise addressed by the tolerable windows approach. Actually, the investigation of dynamical systems with partially unknown but bounded input variables or parameter values is one of the fast evolving and promising parts of the theory of differential inclusions, which builds the mathematical background of the TWA (cf. [18]). One possibility to do so is to require that the guardrails are not violated even in the worst case. But, instead of specifying scenarios of "worst-case" parameter combinations beforehand, as it is done often in connection with policy evaluation methods ("best-case", "mean-case", "worst-case"), these combinations should be revealed as a result of the investigation. In addition, it is preferable to determine the set of all admissible policy paths even for the case of uncertain future disturbances, i.e., under "counteraction", and not only for *uncertain* input *parameters* (which are defined to be unknown quantitatively but which are time independent).

(c) Reliable objective or uncontroversial subjective probability distributions can be obtained for some uncertain inputs. This additional information should be incorporated in the analysis. In this case, often the notion of strict binding guardrails must be abandoned, either because the (upper limiting) values (cf. figure 3) that define the borders of some tolerable windows are (in a scientific sense) uncertain themselves or due to the spread of uncertainty caused by uncertain inputs. Strict compliance with guardrails may then be replaced by the requirement that the restrictions are violated with a probability of less than x% only, where the setting of x is part of the normative setting of the guardrail by the policymaker who seeks scientific advice. The last but not the least, it will be very interesting to introduce the opportunity of learning in the framework of the TWA, too.

7. Summary and future plans

Increasing concerns about the potential risks involved in anthropogenic climate change over the past ten years have boosted the intensity of research efforts on all aspects of the problem and motivated an integrated analysis of the climate change issue. In order to support the international decision-making community, these integrated assessment models were embedded in different decision-support concepts yielding policy evaluation or policy optimization (e.g., cost–benefit analysis and cost–effectiveness analysis) models. Although these methods have provided useful insights into the issue, they do not cover all conceivable questions that may be posed by policymakers. The latter may be interested in framing their climate protection strategies on the basis of normative settings that express their normative judgements with respect to the outcomes of the climate protection strategy they are willing to propose. Bringing together these normative judgements, which may deviate from judgements included in traditional cost–benefit analyses, with the available scientific knowledge about the systems that are involved in the climate change issue is the aim of a new complementary decision-support concept: the tolerable windows approach. This approach is based on an inverse modeling concept that derives the set of all admissible climate protection strategies from perceived intolerable climate impacts as well as from unacceptable consequences of emission mitigation measures.

The analytical tools are based on the theory of differential inclusions that appropriately takes into account the dynamic aspects of the entire problem, e.g., restrictions on the rate of change of climate or socio-economic conditions. From this point of view, the TWA may be considered as a dynamic generalization of the critical loads concept, which proved very successful in the negotiation process of the Second Sulphur Protocol. The solution methods are suitable for providing necessary descriptions for the set of all admissible emission paths, i.e., for all emission paths which are compatible with the tolerable windows. The boundaries of the tube of all admissible paths are calculated for different climate windows. The corridors so determined are by no means “safe” corridors. Although each admissible path lies within the corridor, not any arbitrary trajectory lying within the limits of the corridor is necessarily admissible. The required insight into the internal structure of the corridors may be gained by realizing an appropriate parameterization of the emission profiles.

The main result gained by the example tolerable-windows exercise is that restrictions on the rate of temperature change or on the rate of sea-level rise favor short term emission reductions whereas limitations on the absolute values of temperature change and sea-level rise are important only in the long term.

A general consensus in the integrated assessment community holds that, with a view to the complexity of the climate change issue and our ignorance about its many aspects, the best integrated models can offer to policymakers are insights about the nature, basic relationships, and key dynamic features of the problem.

This paper has shown that, even in its early phase of development, the TWA can make a useful contribution to the debate and provide valuable information for the policy process in its search for appropriate management strategies. In order to enhance the usefulness of the approach, future extensions will focus on an explicit treatment of uncertain features of the global climate change issue. In addition, the concept will be extended to allow a temporary violation of the guardrails as well as the definition of maximal tolerable probabilities for violating some of them.

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