CLIMATE POLICY IN LIGHT OF CLIMATE SCIENCE: THE ICLIPS PROJECT

FERENC L. TOTH

Potsdam Institute for Climate Impact Research, Telegrafenberg, D-14473 Potsdam, Germany
and International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria
E-mail: toth@iiasa.ac.at

Abstract. The paper introduces the Tolerable Windows Approach (TWA) as a decision analytical framework for addressing global climate change. It is implemented as an integrated assessment model (IAM) developed in the project on Integrated Assessment of Climate Protection Strategies (ICLIPS). The background and the main objectives of the project are described and its relationships to other current integrated assessment efforts are elucidated. Key features of the TWA are compared with those of cost-benefit and cost-effectiveness frameworks. An overview of the ICLIPS IAM framework is provided together with its methodological foundations. Main features of the individual models are presented, covering the climate, the aggregated economic, and the impact models. Additional components of the framework include dynamic mitigation cost functions and an agriculture/land-use model (both incorporated into the fully integrated ICLIPS climate-economy model) as well as a global multi-region, multi-sector, dynamic general equilibrium model.

1. Introduction

The generally recognized intricate features of global climate change and the emerging need for policy response have triggered a host of research activities over the past decade. One cluster of efforts attempts to adopt and improve traditional decision-analytical frameworks. Examples include the early applications of cost-benefit analysis by Nordhaus (1992, 1994) and Cline (1992). Another array of research involves a series of new efforts to create frameworks specifically tailored to the climate change problem and focusing on selected aspects of it. For example, uncertainty has attracted considerable attention and is the key concern in the contributions by Dowlatabadi and Morgan (1993a,b, 2000) and by the group at the University of Cambridge (Hope et al., 1993; Plambeck and Hope, 1996; Plambeck et al., 1997).

All these frameworks involve integrated assessment models (IAMs) that combine models of the most relevant components of the society-biosphere interactions. IAMs have come a long way from emerging and later trendy gadgets to instruments generally recognized as useful sources of scientific insights for climate policy. Initial efforts by a handful of research groups (Edmonds and Reilly, 1985; Rotmans, 1990; Manne and Richels, 1992; Alcamo, 1994) were boosted by a series of three workshops held at the International Institute for Applied Systems Analysis (IIASA)

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in Laxenburg, Austria, between 1992 and 1996 (see Kaya et al., 1993; Nakicenovic et al., 1994, of which selected papers were revised and published in Nakicenovic et al., 1995; and Nakicenovic et al., 1996). Working Group III of the Second Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) acknowledged the rising importance of IAMs by devoting a chapter to them. The excellent survey by Weyant et al. (1996) was a very insightful chapter of that IPCC report. The development of the new IPCC emissions scenarios (IPCC, 2000) drew heavily on IAMs, and several chapters in the volumes by Working Groups II and III in the IPCC Third Assessment Report review contributions from an increasing number of IAMs.

This special issue of Climatic Change presents a new decision analytical framework and the associated, relatively new member of the IAM family. This framework and model have been developed in the project on Integrated Assessment of Climate Protection Strategies (ICLIPS), together with a series of other concepts and models, also presented in the papers that follow. The origins stem from a simple carbon budget calculation prepared by the German Advisory Council on Global Change (WBGU, 1995) to establish long-term paths for anthropogenic carbon dioxide (CO_2) emissions. Subsequent publications present the preliminary conceptual framework (Petschel-Held and Schellnhuber, 1998; Petschel-Held et al., 1999), still emphasizing the unidirectional ‘backward induction’ concept. The initial modeling experiments (Toth et al., 1997; Bruckner et al., 1999) involve the first cases of simultaneous specification of climate change (environmental) and emission reduction (cost) constraints.

This introductory paper starts with a short presentation of some fundamental conceptual issues and clarifies the relationship of the TWA to other widely used approaches. The paper then provides a brief overview of the project, its main objectives, the core modeling concept, and its implementation in the form of an IAM. The intention is to locate the ICLIPS project and its components and products on the map of current integrated assessment models and projects. The second part of this introduction provides an overview of the material presented in the papers in this special issue. The application of the ICLIPS model in decision-making processes and the presentation of the results from the IAM and from its main components are left to those papers.

2. Project Background: Modeling Climate Policy

The main objectives of the ICLIPS project include developing an integrated assessment framework based on the Tolerable Windows Approach, or TWA (also known as the guardrail or inverse approach), building modules and related tools for the IAM, and conducting policy analyses to advise policymakers on response strategies to global climate change. The core concept of the ICLIPS project is the TWA. It is based on an inverse modeling concept that derives climate protection strategies from perceived unacceptable impacts of climate change as well as from intolerable socioeconomic implications of mitigation measures and produces complete sets of solutions in a multidimensional state-control space, of which permitted carbon emission paths are the most relevant for policymaking. The TWA seeks to investigate implications of and trade-offs among several constraints related to different domains in the climate-society system. But why do we need a new decision-analytical framework in the first place?

Integrated Assessment Models (IAMs) developed in climate change research incorporate the full cycle of anthropogenic greenhouse gas (GHG) emissions, the options and costs of their mitigation, the resulting climate change, its impacts, and the related options and costs of adaptation. IAMs are traditionally classified into two main groups: policy evaluation models and policy optimization models. Examples of policy evaluation models include IMAGE (Integrated Model to Assess the Greenhouse Effect; Alcamo et al., 1998) or the more recent exploratory modeling technique developed to find robust strategies (Lempert and Schlesinger, 2000; Lempert et al., 2000). Simulation models take user-defined assumptions about a specific course of future policy (e.g., determining the emissions as drivers) and calculate the implications of the specified policy for all explicitly modeled variables of interest to the policymaker: temperature change, ecosystem and agricultural yield changes, sea-level rise, etc. Simulation models cannot say anything directly about the optimality features (environmental effectiveness, cost efficiency, social equity) of the user-defined scenarios, but offer the user the opportunity to compare any number of his or her scenarios and conclude the policy implications. Although simulation models do not perform optimization, they can take note of cost efficiency and some models even assess social equity in gross terms (e.g., Yohe and Jacobsen, 1999; Yohe et al., 2000).

Policy optimization models restrict the range of externally defined parameters (but still concatenate them into a scenario) by separating key policy variables that control the evolution of the climate-economy system (typically emission levels or, for example, carbon tax levels that influence emissions) and determine the values of these policy variables in an optimization procedure according to clearly defined objectives. In a cost-benefit framework, like the DICE/RICE (Dynamic/Regional Integrated Model of Climate and the Economy) family of models (Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000), the criterion for optimal policy is an equalized marginal cost of mitigation (the opportunity cost in terms of what societies give up for reducing GHG emissions by an additional unit) and the marginal benefit of mitigation (the climate change damage, expressed in monetary terms, avoided by an additional unit of emission reduction). As a result, a cost-benefit model determines optimal values for both emissions and impacts. In a cost-effectiveness framework, the acceptable impact is specified as an environmental target (typically in terms of CO_2-equivalent concentrations), and the optimization is restricted to finding the least-cost emission path to reach that target (see Wigley et al., 1996; Manne and Richels, 1997; Valverde and Webster, 1999; Yohe and

Jacobsen, 1999; Tol, 1999a). Optimization models are typically concerned with global optima and tend to pay less attention to equity concerns, like the widely diverging implications for specific regions pertaining to both impacts of climate change and the costs of mitigation.

Morgan et al. (1999) discuss six basic assumptions of conventional policy analysis tools (including the single-problem/single-actor perspective, manageable impacts valued at the margin, known and static exogenously determined values, exponential discounting as an adequate representation of decision making, modest and manageable uncertainties, linear system properties) and their validity with a view to the special features of global change problems. They conclude that 'conventional tools of policy analysis, routinely applied, can lead to wrong or silly answers in studies of global change. To avoid such failures, analysts ... must think much more carefully about the assumptions ... ' (p. 278). Morgan and his co-authors suggest that more attention should be devoted to devising new analytical strategies to overcome the prevailing difficulties.

The inverse approach can be taken as a policy exploration framework that incorporates elements of the policy evaluation and policy optimization frameworks. It can be used as a policy evaluation model by specifying assumptions about the future evolution of exogenous (scenario) variables to track their implications for GHG emissions, climate change, and impacts in sectors for which climate impact response functions (CIRFs) are available. It can also be used as a policy optimization model in cost-effectiveness mode to identify the least-cost emission path under an externally specified climate change or impact constraint. Nonetheless, the distinctive feature of the tolerable windows framework is its ability to demarcate a range of permitted emission paths according to externally specified combinations of impact and mitigation cost ceilings. Yohe (1999) casts the TWA in the context of the decision-analytical frameworks applied in recent years to help thinking about climate policy. He observes that the relative strengths and weaknesses of the different frameworks ensure that the combined contributions provide really valuable policy insights, and new approaches like the TWA can contribute to them.

From a narrow economic perspective, global cost-benefit analysis appears to be the policy analytical framework to provide guidance for an efficient policy. The difficulties of setting up, calibrating, and interpreting the results of a global cost-benefit model have been widely discussed (Munasinghe et al., 1996; O'Riordan, 1997; Portney, 1998; Toth, 1998a) over the last decade.

The problems start with estimating the marginal cost function. Fossil fuels and the products and services produced using them are widely traded in all national economies as well as internationally. Accordingly, one needs to estimate not only the direct but also the indirect and induced effects of any emission reduction policy in terms of changes in relative prices and the corresponding shifts in demand and supply. Global multi-region and multi-sector general equilibrium models are the appropriate tools to provide these cost estimates. The problem is that as resource endowments and technologies change, intersectoral relationships within regions and international trade flows among regions will inevitably alter over time. These changes are difficult to predict and work into these models. As a result, cost estimates derived from general equilibrium models become increasingly unreliable beyond three or four decades into the future.

To provide marginal cost estimates at the century scale, economists have adopted aggregated energy-economy models (like the MiniCAM/GCAM model family, see Edmonds et al., 1994; 1996a) or extended production functions (like the MERGE model, see Manne et al., 1995; or the Connecticut model, see Yohe and Wallace, 1996; Yohe and Jacobsen, 1999). These aggregated representations provide the basis for assessing the impacts of technological development on the long-term evolution of carbon emission reduction costs. Globally aggregated marginal cost functions nevertheless may hide large regional differences in the actual mitigation burden. In principle, the differences in the regional marginal costs could be reduced by implementing flexibility mechanisms (like emission trading or joint implementation as established in the Kyoto Protocol to the United Nations Framework Convention on Climate Change [UNFCCC]). However, the associated transaction costs (of which we do not have reliable estimates) and the need for hedging against possible implementation failures and the associated penalties might significantly reduce the cost-saving benefits of flexible mechanisms.

There seems to be a consensus in the analytical community that the estimation of a global benefit function poses much greater difficulties. The marginal benefit curve is traditionally derived by estimating the damages avoided by incremental emission reduction efforts. Similar to the global cost function, the globally aggregated marginal benefit curve is likely to hide huge regional differences. Some regions are expected to gain from a modest magnitude of warming (Smith et al., 2001), while other regions seem to be on a losing track from the beginning. Other broadly shared concerns are that establishing a marginal benefit function requires all impacts to be evaluated in monetary terms and that some mechanism (typically discounting) is needed to make those monetary values comparable across time. This is highly controversial irrespective of whether we estimate the benefit function at the globally aggregated level or at regional or national scales.

Even if it were possible to find a generally acceptable solution to the above problems, the actual benefit curve should also reflect the very different risk perceptions and risk-taking behavior of different societies. This is partly related to the current situation and to future expectations about the adaptive capacity to cope with the disturbances caused by the changing climate. Another part of this problem is rooted in the widely differing attitudes toward risk in different cultures (Douglas, 1985; Baron et al., 1993).

The applicability of well-established analytical frameworks like cost-benefit analysis and routinely used procedures like discounting costs and benefits arising in different time periods at market-based discount rates to their present values have been challenged and debated in the literature for over a decade. A collection of essays edited by Portney and Weyant (1999) presents the diversity of the positions leading economists take on this subject; see Toth (2000a) for a short overview. Bradford (1999) points out that using the positive net benefit as the sole criterion for implementing or rejecting a project is not sufficient in any public policy dilemma. Even if the cost-benefit test fails, the project may still be worth implementing if the redistribution effect favors those social groups whose support is politically desirable. Bradford also indicates that the compensation test underpinning the cost-benefit analysis is difficult to conceive of as being operational in the climate change context because the transfers involve many generations over time and many nations and sub-national social groups across space. Nevertheless, the cost-benefit analysis of climate change must make clear the distributions of gains and losses over time and across space. Even if a strict cost-benefit test of the policy fails, the emission reduction should be favored if beneficiaries (presumably distant in time and place from those who need to carry the burden) are likely to be poor. Bradford notes two difficulties associated with cost-benefit analysis. First, the distribution of gains and losses of specific groups should be based on the discounted consumption values as indicators but the effects cannot be reliably added together. Second, monetary valuation of non-market goods and ecosystem services is the most serious problem.

The decades- or even centuries-long delay between incurring the emission reduction costs and redeeming the resulting benefits due to the inertia of the climate system, the rather asymmetric uncertainty positions (in which relatively reliable cost assessments stand out against highly uncertain benefit estimates), and the need to discount for both lead to a relatively modest GHG abatement as the efficient policy emerging from a cost-benefit framework. Nordhaus (1997) notes that along the economically efficient emission path ‘the long-run global average temperature rises sharply. After 500 years, it is projected to increase 6.2 °C over the 1900 global climate. 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. Given the potential for unintended and potentially disastrous consequences, it would be sensible to consider alternative approaches to global warming policies’ (Nordhaus, 1997, p. 322).

Nordhaus then explores alternative approaches: changing the discount rate in the cost-benefit model, introducing limits to the increase in global mean temperature, greenhouse gas concentrations, and global emissions in selected years – these are different versions of the cost-effectiveness framework. After evaluating the environmental effectiveness and the economic efficiency of various alternatives, he concludes that ‘[t]he best approach will be to identify the long-term objective and to take specific steps to override market decisions or conventional cost-benefit tests so as to achieve these long-term goals’ (Nordhaus, 1997, p. 327).

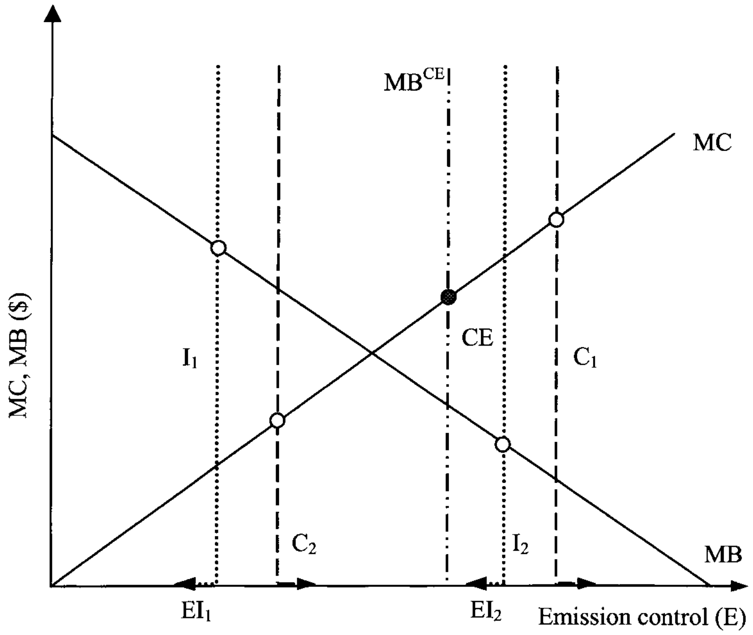
In summary, conceptual and practical difficulties associated with applying traditional decision analytical frameworks (like cost-benefit or cost-effectiveness analysis) to climate change call for new techniques that better reflect the special features of anthropogenic climate change. The tolerable windows or inverse approach is a recent attempt at expanding the analytical arsenal to provide insights for climate policy mainly at the global and national levels. The inverse approach gives special attention to the long-term nature and dynamics of the climate problem and to the associated far-future implications of climate change, and it derives policy insights from perceived unacceptable impacts and costs of climate protection rather than by balancing costs and benefits of climate policy at the margin.

3. The TWA in the Context of Other Decision Analytical Frameworks

In reviewing the difficulties of applying cost-benefit analysis to the climate change problem and especially the problems of establishing the marginal benefit curve, Portney (1998) suggests that an alternative to the generally used damage function approach might be to conduct a survey of the current generation about their willingness to pay to reduce the threat of climate change in the future. One impediment in this proposition is that it is difficult for the respondents to know what they would actually be buying. Portney proposes to make available the best scientific information we currently have about the possible impacts of climate change to alleviate this information problem. This is exactly the strategy followed in the ICLIPS project by developing climate impact response functions for climate-sensitive sectors. This formulation and the option of specifying the cost constraint in terms of the upper limit to loss in current consumption any generation may need to endure are also in line with the arguments by Lind and Schuler (1998) concerning the appropriate way to evaluate intergenerational equity.

The difficulties associated with establishing marginal benefit curves for global climate change led many analysts to abandon the cost-benefit framework and use cost-effectiveness analysis instead. This approach will not produce the economically efficient policy of controlling GHG emissions to equate its marginal costs with its marginal benefits, but it can lead to the least-cost strategy for reaching an externally defined target. The cost-effectiveness framework has been successfully used to provide guidance for environmental regulation, technology and personal safety regulations, and other public policy issues in many countries. Cost estimates of different emission paths to reach the same concentration targets by pursuing different implementation strategies are the best-known examples in climate change (Wigley et al., 1996; Ha-Duong et al., 1997; Manne and Richels, 1999).

One key consideration in developing the TWA is the following. It is always difficult (and often controversial) to account for all costs and benefits of even a relatively small, local/regional environmental project where the economic, social, and cultural characteristics of the affected communities are likely to be much more homogeneous than is the case for a pervasive global risk like climate change. Moreover, climate policy at the national scale cuts across many other sectoral policies ranging from energy, agriculture, regional development, transport, and forestry all the way to industrial development and foreign trade policies. This suggests that



MC = Marginal cost
MB = Marginal benefit
CE = Cost-effective optimum
MB^{CE} = Marginal benefit under cost effectiveness

Unacceptable impacts: I_1, I_2
Unacceptable costs: C_1, C_2
Emission Control: EI_1, EI_2

Figure 1. The relationship between the cost-benefit, cost-effectiveness, and the tolerable windows frameworks.

there might be substantial value in establishing a field of GHG emission paths that satisfies some basic climate-related concerns and permits the selection of the actual emission path to follow within the field by observing additional concerns that were not explicitly represented in the climate policy model.

The relationships among the cost-benefit, cost-effectiveness, and tolerable windows frameworks are illustrated in Figure 1. It is important to emphasize that the figure shows only the conceptual linkages of the three frameworks rather than actually modeled relationships. In TWA we do not know the exact positions of the marginal cost and marginal benefit curves. The curves in Figure 1 serve to show that the user-specified impact and cost limits can be lower or higher than the cost-benefit optimum. Moreover, Figure 1 presents a static sketch of the TWA. Bruckner et al. (2003) present the mathematical specification of the comprehensive dynamic model.

The economically efficient solution is provided by cost-benefit analysis at the intersection of the marginal cost and marginal benefit curves. Cost-effectiveness analysis is characterized by a vertical marginal benefit curve, and the associated marginal cost will be provided by its intersection with the lowest marginal cost curve. (For visual clarity, only one marginal cost curve is depicted in Figure 1.) Cost-effectiveness attempts to get around the problem that no good measure of the benefit function exists and therefore it is not possible to find an efficient allocation (equating marginal costs and marginal benefits). The vertical damage function (MB^{CE}) represents the environmental (impact or damage) target, and its intersection with the lowest-lying marginal cost curve denotes the associated cost. Note that Figure 1 provides a highly simplified picture because only two parameterized constraints are considered. TWA analyses with the ICLIPS model provide the opportunity to explore the effects of variations of many more parameters.

The TWA is based on the recognition that we can say something about the benefits (avoided damages), but not enough to specify them in the form of a marginal benefit function. The ICLIPS framework includes impact response functions in terms of physical units that portray the changes induced in a given impact sector by incremental climate change and increases in carbon concentration. The social decision problem is then to settle on the maximum acceptable climate change impact. Any impact beyond this level is unacceptable. Two independent cases are illustrated by the vertical lines I_1 and I_2 and the connected arrows in Figure 1. Each case corresponds to the willingness to accept any amount of damage between zero and the marginal benefit equivalent to the specified total damage. The hypothetical judgment behind I_2 illustrates the social unacceptability of climate change impacts that result if the level of emission control is less than EI_2. In contrast, the judgment behind I_1 implicitly assumes that the society can cope with a larger amount of climate change and unacceptable impacts loom beyond a much lower level of minimum reduction (EI_1).

The associated social decision on the cost side is similar: what is the society's maximum willingness to pay for climate change mitigation? Again, two independent cases are represented by the vertical lines C_1 and C_2 and the connected arrows in Figure 1. Each case corresponds to the willingness to pay for mitigation any amount between zero and the marginal cost equivalent of the specified total cost. The hypothetical judgment behind C_2 implies a much lower willingness to pay for climate protection than the social decision associated with C_1.

It is easy to see from the figure that, while the cost-benefit and cost-effectiveness frameworks lead to single optimum points, different types of outcomes can emerge from the tolerable windows specifications. A whole range of feasible emission strategies exist for the combinations of $I_1 + C_1$, $I_1 + C_2$, $I_2 + C_1$; that is, whenever the marginal benefits representing the specified unacceptable impact levels are located to the left of the marginal costs corresponding to the specified unacceptable mitigation cost levels. In contrast, not a single emission path (thus no emission corridor) exists for the combination $I_2 + C_2$. This situation corresponds to the social decision in which the level of climate change impact the society is willing to accept is too low compared to its willingness to pay for avoiding it. In accidental cases the specified I and C levels may coincide. This would lead to a single feasible emission path. This path would be equivalent to the cost-effectiveness outcome of the specified environmental constraint, but it would not necessarily coincide with the cost-benefit optimum.

Another important distinctive feature of the cost-benefit and cost-effectiveness frameworks, on the one hand, and the TWA, on the other, is that the first two would always imply reaching the actually specified environmental and cost limits. By specifying the range of feasible policy options in terms of upper limits to impacts and costs, the actually chosen emission paths (recall that the choice among the feasible ones is based on non-climatic considerations) may well lie inside the corridor so that neither the impact nor the cost limits will be reached. These paths are clearly sub-optimal in a purely climate-policy sense, but they may represent a sort of joint optimum with respect to the non-climatic objectives considered in combination with the specified climate change constraints.

The ability to demarcate the field of all permitted emissions paths under a given set of constraints is much more important and characteristic of the inverse approach than the speculation about possibly looming disasters if a path is chosen that would temporarily leave the corridor by a marginal amount, thereby generating an infinitesimal surpassing of the most binding impact constraint. The problem of infinitesimal threshold crossing characterizes any environmental policy analysis conceived in the vein of cost-effectiveness. No matter how much better the actual quality of drinking water is relative to the specified quality standards, there is no bonus to earn. However, even a slight violation of the prescribed standard would trigger penalties although the health implications are uncertain but presumably negligible.

The TWA contains cost-effectiveness as a special case. Several papers in this special issue present results in which not only carbon emission corridors but also the least-cost paths within the corridor are discussed. Therefore the relationship of the TWA to the concept of a cost-effective optimum in a cost-effectiveness framework needs some additional explanation. Although there are constraints imposed on the implementation costs that might be incurred in any given time period by any region, the concept of cost-effectiveness still remains relevant in the tolerable windows analysis. The cost-minimizing emission path really takes the climate system to the specified impact limit and it is really the least-cost path that stays within the climate constraints. This is not the optimal policy in the traditional cost-effectiveness sense because it does not minimize mitigation costs across the board by equating marginal costs across all regions over the entire time horizon. (Such a global optimization would in principle allow some regions suffering excessive costs, whereas in the TWA analysis upper limits are set to the costs any region might need to endure.) However, it is optimal with respect to the entire set of the user-specified normative constraints, including those that foreclose imposing extreme burden on some regions or some generations for the sake of the overall cost-minimization.

‘Zero damage within, infinite damage outside the emission corridor’ is not the appropriate interpretation of the TWA framework. The emphasis is on the level of unacceptable damage outside the corridor. The actual damage inside the corridor varies, of course, according to which permitted emission path is chosen. But the very essence of the TWA is that the choice of the emission path within the corridor is not based on minimizing the mitigation cost, the damage, or the cost-benefit ratio of the most binding constraint. The choice inside the corridor is assumed to be driven by non-climatic considerations that are impractical or outright impossible to include in a comprehensive integrated assessment model. The differences between the opportunity costs of those policy options may well exceed the strictly climate-related cost differences across the permitted emission path. Hence this ‘underdetermined’ climate policy space is likely to provide useful flexibility in the broader policy context.

In the intended applications of the ICLIPS integrated assessment framework, model users specify the minimum requirements for climate protection, including, in particular, the maximum acceptable impacts of climate change and the maximum acceptable cost of mitigation. The resulting emission corridor is a ‘relaxed’ cost-effectiveness strategy field because the ‘target’ (the maximum acceptable impact) is not necessarily reached, and it is a relaxed cost-benefit outcome because benefits need not be specified in monetary terms and not necessarily equalized with costs at the margin. But the main distinctive feature is that the inverse approach provides a range of policy options (a set of emission paths) whereas both cost-benefit and cost-effectiveness analyses produce single optimal paths.

Several authors comment on the conceptual design and practical features of the TWA. Dowlatabadi (1999) emphasizes the purposeful search for threshold relationships between climate conditions and life systems as a prominent characteristic. Yohe (2000) calls attention to the importance of adaptation opportunities in defining the acceptable climate change limits. He discusses three types of adaptation: response to short-term fluctuations, reaction to long-term change, and activity switching. A crucial distinction to be made in discussing adaptation is between biophysical sensitivity to climate change (and the associated ‘virtual thresholds’) and the actual socioeconomic vulnerability (determined by social, economic, technological, and other factors) that crucially shape the actual tolerability levels.

Toth et al. (1997) present a preliminary version of the ICLIPS IAM to calculate emission corridors for environmental constraints defined in terms of the magnitude and rate of global mean temperature change as proposed by the German Advisory Council on Global Change (WBGU). The climate change limits proposed by the Council are largely based on past climate-ecosystem relationships. In his appraisal of this effort, Dowlatabadi (2000) highlights that ‘the current distribution of ecosystems can neither be defined in terms of an equilibrium, nor is it an optimum in traditional sense of the term’ (p. 392). This observation clearly points to the potential deficiencies of the current climate impact response functions (van

Minnen et al., 2000; Füssel et al., 2003) and indicates the need for using the new class of dynamic global vegetation models in innovative ways to develop their next generation.

Dowlatabadi (2000) also calls attention to the regional climatic anomalies and oscillations that indicate the non-trivial nature of defining temperature/climate guardrails and that make forward-looking adaptive control less reliable. His analysis of the modified WBGU target with the ICAM-3 model leads to two classes of conclusions. First, future versions of the ICLIPS model need to incorporate a systematic treatment of uncertainties, the baseline emissions and controls of non-CO_2 GHGs, and the possible socioeconomic thresholds associated with too stringent emission reductions. The version of the ICLIPS model presented in this special issue indeed incorporates a scenario-based, fully dynamic treatment of non-CO_2 GHGs and the possibility to explore emission corridors under the same impact and cost constraints but under different non-CO_2 scenarios, as well as the possibility to explicitly specify the maximum level of acceptable social costs of emission reductions.

The second class of conclusions is related to the analytical framework. Rigorous implementation of the inverse calculation is difficult, even with innovative modeling techniques, if the underlying analytical framework is not purposefully designed in that vein. Specifically, Dowlatabadi's results with the ICAM-3 model indicate high probabilities of exceeding the specified temperature targets (which are actually stricter than the original WBGU targets) and high probabilities of exorbitant regional reduction costs. There are two main reasons for this result. The first is the endogenous forward-looking stipulation of the mitigation policy in ICAM-3. While there are many useful insights emerging from this model formulation, it differs profoundly from the TWA, in which non-permitted paths can be identified even if they lie inside the corridor. The second reason for the possibility of missing the target is the policy instrument used in ICAM-3. If the regional marginal reduction cost curves are uncertain, then a tax-based system may well miss the quantity target. That is why the policy mechanism implemented in the current version of the ICLIPS aggregated economic model (Leimbach and Toth, 2003) is a quantity-based, cap-and-trade system. Finally, the user-defined willingness to pay for climate protection is as important a decision variable in determining the permitted range of emission paths as the acceptable environmental impacts.

The TWA does not claim exclusive truth, of course. On the contrary, its proponents always emphasize that it is intended to provide an integrated assessment framework to think about long-term targets for climate policy and to provide broad-brushed near- and medium-term implications of different long-term targets. The exploration of options for near-term policies and measures in the ICLIPS framework has been assigned to an analytical tool that is more suitable to do the job: a detailed multi-region and multi-sector model of the world economy (see Klepper and Springer, 2003). Yohe (1999) correctly notes that it is impossible to define the acceptable impact limits with knife-edge certainty, therefore the TWA should be taken as a tool to assess ‘opportunity costs of adding increasingly restricted constraints to the construction of the target window’ (p. 290). This interpretation corresponds entirely to the definition of the TWA as a policy exploration framework. Several papers in this special issue present results of how different impact and cost limits determine the existence and shape of the emission corridor. Yohe also underlines the strengths of the TWA (no need to monetize impacts, possibility to include distributional issues, directing attention to the most binding targets and adaptation options, etc.). Finally, Yohe notes two deficiencies: the silence of the TWA about the implementing institutions and about the design of a mitigation policy. In addition to its possible use by national government agencies in preparations for negotiating long-term climate change targets, one can envision the use of the ICLIPS integrated assessment model directly in the negotiating fora established under the UNFCCC – for example, the Subsidiary Body for Scientific and Technical Advice, SBSTA – or indirectly in a preparatory activity that could take the form of a participatory integrated assessment, for example, a Policy Exercise. Details of the mitigation policy design are clearly beyond the scope of the ICLIPS framework, but the concept of the emission corridor points toward a quantity-based policy instrument as the implementation mechanism.

Whatever form a practical application of the ICLIPS model takes, it always consists of three steps. The first step is to solicit the climate-change-related constraints from the participating social actors. The most convenient way to explore what might be the limits to manageable climate change impacts is to use the impact response functions for the impact sectors of concern. Limits to the social costs of emission reductions also need to be specified. This is the normative or social decision part of the exercise. The second step is to apply the model to check whether there exists a corridor of long-term emission paths that satisfy the specified policy constraints. The third step is to formulate additional (secondary) climate-related concerns or, more typically, general non-climatic but mitigation-related targets, policy concerns, or hypotheses, and to select among the permitted paths accordingly. This step also involves supplementary runs of the ICLIPS model. The full cycle can then be repeated in several rounds in which model users can explore the implications of what they want in terms of acceptable/unacceptable climate change impacts and what they can get given their willingness to sacrifice a fraction of their income in terms of acceptable mitigation costs. This iterative application process reinforces the TWA as a policy exploration framework.

Some of the ‘additional concerns’ solicited and analyzed in step 3 above are rather obvious and can be easily implemented with the integrated model. Additional information about the least-cost path, for example, can be extracted from any given model run. Leimbach and Toth (2003) present total and discounted costs, burden-sharing implications, permit trade flows, and other relevant information about selected emission paths within the corridor. They also demonstrate the ability of the ICLIPS model to illustrate how the CO_2 emission corridor would change under different assumptions about non-CO_2 emissions even if the same impact and cost constraints are used.

A key point in Dowlatabadi's (2000) critique defines an important future task: the TWA needs to be complemented with a systematic procedure to explore the effects of various types of uncertainties on the derived emission corridors for any set of externally defined impacts and cost limits. The TWA is certainly not a panacea in climate policy analysis. It is intended to complement existing decision analytical frameworks by combining some features of cost-benefit, cost-effectiveness, and multi-criteria analyses. As Dowlatabadi (2000) observes, the TWA is 'asking explicit questions often implicitly assumed to be easy to answer in the past' (p. 406).

To sum up, the tolerable windows approach has some aspects in common with cost-benefit and cost-effectiveness analysis, but there are some key distinctive features as well. Among these features, the most important ones include the clear distinction between normative, value-laden decisions about what constitute acceptable levels of climate change impacts and mitigation burdens, and the scientific, model-based analyses of their implications; the representation of climate change impacts in natural units (biogeophysical indicators of the response of the impact sector to gradual climatic and carbon change forcing) rather than in monetary units (being sensitive to controversial valuation techniques); and the computation of the field of permitted emission trajectories satisfying the user-specified normative constraints rather than a single optimal path.

4. The ICLIPS IAM: Overview and Comprehensive Results

The TWA concept is operationalized in the form of the ICLIPS IAM. Key features of this model framework are presented in Figure 2. The core of the ICLIPS framework is a fully integrated climate-economy model, incorporating results from technological development and agriculture/land-use modeling. The framework also includes impact assessment tools and a detailed model of the world economy. Figure 2 also includes pointers to papers in this special issue dealing with the different models in detail.

The core model of the ICLIPS framework combines a reduced-form greenhouse-gas and climate model and a highly aggregated economic model. In forward mode, the model can simulate how different GHG emissions pathways affect climate and produce biophysical changes in selected impact sectors across the world. In inverse mode, the model generates permitted corridors for future carbon emissions that would keep the climate system within tolerable ranges at acceptable costs, both specified externally by model users, eventually policymakers. To help the users make these arduous choices, the project has also developed pilot climate impact response functions (CIRFs) that indicate how a particular climate-sensitive sector reacts to changes in relevant climatic attributes across a plausible range.

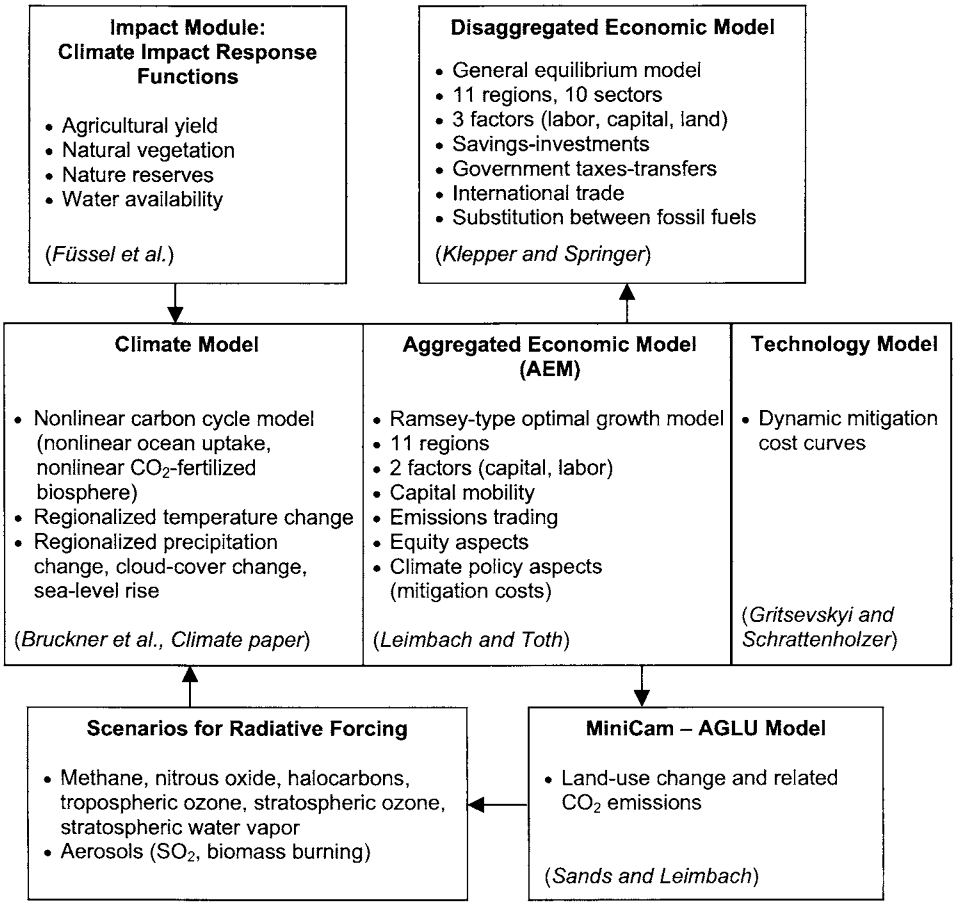


Figure 2. The ICLIPS IAM framework. Note: Names in parentheses refer to papers in this special issue devoted to the specific models.

The first paper in this special issue by Toth et al. (*Integrated Assessment of Long-term Climate Policies: Part 1 – Model Presentation*) provides an overview of the ICLIPS modeling framework. Members of the core team at the Potsdam Institute for Climate Impact Research (PIK) present the key features of the main model components and the modes of operation: policy simulation in forward mode and corridor calculation in inverse mode. The paper discusses the difficulties associated with finding a reasonable compromise between natural processes (atmospheric GHG accumulation and decay, the inertia of the climate system and the resulting long-delayed effects) and socioeconomic processes (development, GHG emissions, technological progress, land-use and land-cover changes) in terms of the length of the time horizon and the temporal and spatial resolution as well as their settlement in the ICLIPS model. Simple case studies of climate change impacts on agricultural yields and the implications of limits to acceptable climate-induced changes in yields for the corridor of permitted long-term carbon emissions are presented to illustrate the operation of the ICLIPS IAM in forward and inverse mode.

The second paper by the same writing team (*Integrated Assessment of Long-term Climate Policies: Part 2 – Model Results and Uncertainty Analysis*) starts with the detailed presentation of a corridor assessment. This case study draws on CIRFs that assess the effects of incremental climate change on ecosystems in nature reserves around the world. Hypothetical but plausible social choices regarding the acceptable magnitude of ecosystem transformation (impact constraint) and endurable mitigation expenditures (cost constraints) are defined and the resulting corridors for long-term carbon emissions are presented. An additional series of model runs serves the purposes of an uncertainty analysis. The authors explore how the variations of some crucial model variables affect the maneuvering room of long-term climate policy as determined by the existence and the shape of the corridor of permitted emissions.

An important characteristic of the inverse approach or TWA is the intention to support climate change decision making by clearly separating risk perception, value judgments, and associated uncertainties, on the one hand, and scientific analysis and related uncertainties, on the other. Accordingly, a TWA application always involves a 'decision step' (the explicit formulation of normative constraints or 'guardrails' that delineate unacceptable climate change impacts and mitigation costs) and an 'analysis step' (the model-based scientific analysis of the global climate-economy system to obtain the corridor of all emission paths that satisfy the pre-defined constraints).

The mathematically correct procedure to obtain the bundle of all permitted emission paths would require a complete inversion of an appropriately formulated integrated assessment model. This is not yet possible given the current state of the pertinent mathematical theory and numerical methods. Nevertheless, as the paper by Bruckner et al. (*Methodological Aspects of the Tolerable Windows Approach*) shows, useful results, like emission corridors depicting important properties of the most comprehensive solution, can be obtained without knowing the bundle of all admissible emission paths beforehand.

The attempt to identify the main characteristics of a *whole family of admissible emission paths* is fundamentally different from the methodological issues involved in applying traditional approaches to integrated assessment. Policy evaluation and policy optimization methods primarily deal with *a single emission path* either by investigating the consequences of a pre-defined scenario or by deriving the (usually unique) optimal emission path that maximizes welfare (as in cost-benefit analyses) or minimizes mitigation costs subject to climatic constraints (as in cost-effectiveness analyses). Another way to look at this relationship is to consider the marginal cost and marginal benefit curves. The cost-benefit rule implies that the optimal level of mitigation is at the point where the two curves intersect. The TWA relaxes this optimality rule. It lets the user specify the level beyond which costs and damages become unacceptable. Recall the relationship between cost-benefit analysis, cost-effectiveness analysis, and the TWA illustrated in Figure 1.

The inverse approach takes the form of a 'relaxed' control problem in the sense that a multitude of permitted control paths is sought (rather than a single optimal path) leading to a set-valued problem. To handle the set-valued character of the solution sought by the TWA, the basic methodological problem is reformulated in terms of the *theory of differential inclusions*. This theory has been developed specifically to deal with the above dynamical non-uniqueness. It provides appropriate definitions, a consistent theoretical background (e.g., theorems of existence), and even some solution methods that are applicable as long as the underlying climate and economy models remain relatively simple.

For large-scale models, the ICLIPS framework includes a transparent and generally applicable method to derive emission *corridors*. The basic idea is to sequentially maximize (minimize) the amount of emissions in order to calculate the upper (lower) bound of the emission corridor for a series of interesting points over time. The respective intertemporal optimization has to take into account simultaneously the pre-defined environmental, climatic, social, and economic constraints as well as the dynamic relationships connecting climate impacts, climate, and society. The corridor calculation problem is therefore formulated as a series of optimal control problems that can be solved by well-established numerical algorithms applied routinely in standard intertemporal optimization tasks. Framing the corridor calculation problem this way considerably enhances the comprehensibility of the TWA. Moreover, this procedure emphasizes that the TWA is a general concept that can be operationalized by different numerical methods and (integrated assessment) models.

Ever since the signing of the UNFCCC in 1992, scientists and policymakers alike have been pondering the meaning of its Article 2: what constitutes a 'dangerous anthropogenic interference with the climate system' (see for example, Moss, 1995; Parry et al., 1996). In preparing its Second Assessment Report, the IPCC devoted a special conference to the topic (IPCC, 1994) and its synthesis document attempted to summarize the most important findings in the spirit of Article 2 (IPCC, 1995). The question of 'dangerous anthropogenic interference' is also one of the nine policy-relevant scientific questions addressed by the Synthesis Report of the IPCC's Third Assessment (IPCC, 2001). Traditional climate impact assessments study effects of a $2 \times CO_2$-equivalent climate on selected sectors in relatively small regions. They are very useful for giving some broad estimates of the risks, but they are not very helpful in providing clues for answering the 'dangerous interference' question. Neither can their results be used in the context of the inverse approach as required by the ICLIPS IAM. There is clearly a need for alternative formulations of climate impact assessments in order to make them more policy relevant. Recent work by Mendelsohn and Schlesinger (1999), Mendelsohn et al. (1999), Tol (1999b,c), and Nordhaus and Boyer (2000) represent efforts in rather different directions. The contribution by the ICLIPS project to alleviating this problem is the development and implementation of the concept of CIRFs.

According to the definition (Toth et al., 2000), a CIRF describes how a particular climate-sensitive sector responds to changes in relevant climatic attributes across a whole range of plausible climate change patterns under a broad diversity of socioeconomic conditions. Füssel et al. (*Climate Impact Response Functions as Impact Tools in the Tolerable Windows Approach*) present a detailed description of the procedure for deriving CIRFs. The procedure starts with applying the scaled scenario approach to concisely describe future climate states while taking into account the spatial and seasonal variability in the climate anomalies as simulated in transient general circulation model (GCM) experiments. The resulting representative samples of future climate states or scenarios are used as input to drive simulation runs of sectoral impact models. This leads to a CIRF that denotes a kind of dose-response relationship between a small number of climatic variables, on the one hand, and an indicator of sectoral impacts of climate change, on the other. CIRFs thus constitute an efficient way of representing simulated impacts of climate change across a wide range of plausible futures. It is important to note that the CIRFs developed so far and presented in this special issue consider only the biophysical processes of climate impacts. The next big research task will be the development of the socioeconomic dimensions of CIRFs in order to properly account for features of vulnerability and processes of adaptation in all impact sectors where adaptation is conceivable.

Füssel et al. first define the most important requirements for modeling climate change impacts in the context of the TWA as implemented in the ICLIPS IAM. The discussion focuses on the different application modes of CIRFs, on the climatic input to the respective impact models, and on the choice of the appropriate impact indicators. The paper then presents exemplary CIRFs for natural vegetation, agriculture, and water availability that cover a wide range of spatial and thematic aggregation levels. Relevant aspects of a CIRF to be used in the forward and inverse mode are visualized by response surface diagrams, impact isoline diagrams, and balance diagrams. The authors also report the results of selected sensitivity tests conducted to assess the effects of different climate scenarios and aggregation levels on the CIRFs, and on the admissible climate windows derived from them.

CIRFs can be used off-line to study the relationships between incremental climate change and the response of a given impact sector at different levels of spatial aggregation. However, in the ICLIPS framework they are most typically used to define maximum acceptable levels of sectoral impacts in different regions. This ultimately determines the constraints for the respective climate variables of the integrated climate-economy model. To derive the corridor of permitted future carbon emissions, the boundaries of the corridor need to be determined by successively solving a multitude of dynamic optimization problems subject to pre-defined intertemporal constraints. The resulting enormous computational burden excludes the application of complex GCMs. Therefore, the climate system can only be represented by highly aggregated reduced-form models that are numerically efficient and reproduce the results of GCMs with sufficient accuracy.

The paper by Bruckner et al. (*Climate System Modeling in the Framework of the Tolerable Windows Approach: The ICLIPS Climate Model*) demonstrates that the climate model developed for the ICLIPS IAM fulfils both requirements. The ICLIPS climate model provides data for important climate variables. The model takes into account all major greenhouse gases (CO_2, CH_4, N_2O, halocarbons, SF_6, tropospheric and stratospheric O_3, and stratospheric water vapor) as well as the radiative effects of aerosols originating from SO_2 emissions and from biomass burning. The model produces transient patterns for temperature, precipitation, and cloudiness change supplemented by transient information about various factors (thermal expansion of the ocean, melting of glaciers and ice sheets) leading to sea-level rise.

The biogeochemical modules convert emissions into concentrations whereby CO_2, well-mixed gases with well-defined lifetimes, aerosols, and not directly emitted gases are treated differently. The radiative transfer modules calculate radiative forcing values from concentrations. The climate module (in the strict sense) translates radiative forcing into temperature, precipitation, and cloud-cover change. Finally, sea-level rise modules calculate sea-level change from thermal expansion of oceans and ice melting. The scales and complexity of the ICLIPS climate model are comparable to those of the MAGICC model (Hulme et al., 1995) or the reduced-form model by Schlesinger and Jiang (1991).

In contrast to most optimizing IAMs, the intertemporally optimizing ICLIPS model includes carbon cycle and non-CO_2 chemistry as well as climate (in the strict sense) and sea-level rise modules that reflect the state-of-the-art understanding of the dynamical behavior of the systems involved. In addition to descriptions of all modules mentioned, Bruckner and his colleagues present climate change pathways resulting from a set of IPCC scenarios published in the Special Report on Emissions Scenarios (IPCC, 2000) and examples of ‘reachable climate domains’ defined as feasible combinations of values of at least two model variables under given restrictions for plausible emission scenarios.

Similarly to all other IAMs, GHG emissions provide a well-defined interface between the economic and the climate systems in the ICLIPS framework. The full impact of these emissions on the climate system, however, will manifest itself over decades or even centuries. Portraying the dynamics of the economic system over such time spans is meaningful only in highly aggregated models. Leimbach and Toth (*Economic Development and Emission Control over the Long Term: The ICLIPS Aggregated Economic Model*) present a Ramsey-type optimal growth model that has been developed as the suitable economic model to be coupled directly to the ICLIPS climate model.

The economic growth path is determined by exogenous population and endogenous investment dynamics, as well as by assumptions on productivity change implemented in a technological diffusion model. According to this diffusion model, developing countries close the productivity gap to the most developed countries at different speeds. The model is calibrated for 11 world regions, thereby focusing on interregional linkages that influence the economic growth paths. There are two types of interregional linkages: intertemporal trade and capital mobility. Global capital flows balance out in each period, but regions might build up net foreign assets. Assets are valued at a globally averaged rate of return on capital. To avoid unrealistic magnitudes of capital transfer, all regions are prescribed to have zero net foreign assets in the final period (i.e., in the year 2135).

Climate policy triggers another type of interregional linkage in the model in the form of emission permit trading. The model determines the volume of traded and allocated emission rights at each time step endogenously. This results in a more efficient solution than could be obtained from models with a fixed amount of emission rights to be allocated. However, the initial share of each region in the total budget is pre-defined by a particular allocation principle. It is a combination of the grandfathering and the equal per capita allocation principles, with a smooth transition from the former to the latter. The point in time when the equal per capita principle becomes fully effective can be exogenously defined. The model allows the implementation of emission ceilings as well as the temporal divergence of obtaining and paying for the permits. With the integration of emission trading, intertemporal trade mainly functions as its balance counterpart (i.e., as payment for emission permit imports/exports). The economic model is nested within a master problem to obtain an equilibrium solution. Within the master problem, the welfare weights of the regions are adjusted to offset intertemporal trade balance deficits which might cause an unreasonable redistribution of income.

5. The ICLIPS Framework: Additional Components

Probably the most ferociously debated issue in climate change mitigation over the past few years has been the timing of various mitigation actions. Several factors influence the relationships between the near-term and long-term mitigation portfolio, but the central thread of the debate revolves around technological development. How ambitious should near-term emission reductions be in order to trigger the development of low-carbon, non-carbon, and energy-efficiency technologies that will decrease the reduction costs decades later? Is it efficient or wasteful to undertake massive reductions in the near term when technologies improve rapidly and there is a non-negligible risk of premature lock-in to inefficient technologies? Finally, how much 'doing' is needed for 'learning' about emerging technologies to drive down their costs? Recent attempts to come to grips with these questions include those of Grubb (1997), Schneider and Goulder (1997), Goulder and Schneider (1999), and Gruebler and Messner (1998).

Traditional approaches to the problem of establishing mitigation cost curves assume static relationships between the magnitude and the costs of carbon reduction over time and do not provide regional details. An explicit evaluation of uncertainties is usually omitted as well. In most cases, carbon mitigation costs are incorporated in a ‘generic’ form without any real comparison of the assumptions behind the baseline scenarios and their variants. This largely explains the wide spread of estimates of carbon reduction costs in the literature, as demonstrated by recent comprehensive surveys of mitigation costs by Hourcade et al. (2001), Barker et al. (2001), and Toth et al. (2001).

The paper by Gritsevskyi and Schrattenholzer (*Costs of Reducing Carbon Emissions: An Integrated Modeling Framework Approach*) presents a new approach to estimating dynamic regional carbon mitigation cost functions. The procedure is based on the integrated modeling framework developed at IIASA. The authors consider processes of technological changes in energy systems over the long term in the context of macroeconomic models and establish relatively simple relationships between mitigation actions, technological changes, and their effects on economic development. They use the IIASA scenario database, which contains a number of mitigation cases based on a multitude of scenario runs, and derive dynamic carbon mitigation cost curves through statistical analyses of available data from iterations with the MESSAGE-MACRO model. This global model operates at the level of eleven world regions and includes detailed information on several hundred technologies. It can consistently explore complex emission reduction policy questions by combining the virtues of energy system models and macroeconomic models.

The regionalization, calibration, and underlying assumptions of the IIASA dynamic mitigation cost functions and the ICLIPS aggregated economic model are harmonized to the maximum possible extent. This permits the full integration of the cost functions into the ICLIPS IAM. The carbon emission corridors presented in several papers in this special issue are all derived with the benefit of insights and parameters from the IIASA effort to model technological learning.

Besides fossil energy, changes in land use and land cover and activities in different sectors of agriculture are also important sources and potential sinks of GHGs. It is therefore essential to consider the most important processes governing emissions in land use and agriculture. Instead of venturing into the development of a new model, the ICLIPS project adopted the Agriculture and Land Use (AgLU) model developed as part of the MiniCAM system by the Battelle Pacific Northwest National Laboratory in Washington, D.C. (Edmonds et al., 1996b). The contribution by Sands and Leimbach (*Modeling Agriculture and Land Use in an Integrated Assessment Framework*) explains the main features of this module and how the original model was modified to fit into the ICLIPS framework.

The AgLU module of the ICLIPS framework is designed to simulate carbon emissions from land-use change. As energy prices rise, commercial biomass expands its share of land. The model provides estimates of carbon emissions from land-use change over the next century in response to changing populations, incomes, and agricultural technologies. It can evaluate the role of commercial biomass and its impact on land use in a carbon-constrained world.

The model allocates land to crops, pasture, or forests in the eleven world regions of the ICLIPS model according to the economic return from each land use. Economic return is calculated as crop revenue per hectare less costs of production. Land allocation is affected by the demand for agricultural products, which is driven by population growth and economic development as computed by the ICLIPS aggregated economic model. Land allocation may also be affected by changes in yield due to technical change, or by carbon mitigation scenarios that provide an incentive for biomass crops. Carbon densities are applied to each land-use category to provide an estimate of the carbon stock during each 15-year time step. Carbon emissions from land-use change are calculated as the difference in carbon stock between periods.

Specific routines are provided to couple the AgLU module with the ICLIPS core model. The latter is programmed in a different language and runs on a different hardware platform. At run-time, AgLU is called from ICLIPS' core model iteratively, receiving data on population development, gross domestic product growth, and carbon price evolution. The resulting emissions profiles for CO_2 are sent back to the core model, changing the total GHG emissions in forward mode and modifying the shape of the emission corridor in inverse mode. Convergence is reached after a few iterations.

The inverse approach as analytical framework and the ICLIPS IAM as modeling tool are developed to serve the main objective of the project: to provide policy-relevant insights for long-term climate policy. The emission corridors computed by the ICLIPS model contain all permitted century-long emission paths under a given set of constraints. However, when it comes to implementation, more detailed information is needed about the relative short- to medium-term virtues of 'promising' or 'interesting' long-term paths. The Dynamic Applied Regional Trade (DART) model developed and presented by Klepper and Springer (*Climate Protection Strategies: International Allocation and Distribution Effects*) for the ICLIPS project serves this objective. It is a useful addition to the group of medium-term models that have been extensively used recently to estimate the costs of different medium term emission reduction policies, including the Kyoto Protocol (see the G-Cubed model by McKibbin et al., 1999; the MS-MRT model by Bernstein et al., 1999a,b; the Oxford Global Macroeconomic and Energy Model by Cooper et al., 1999; the GREEN model by van der Mensbrugghe, 1998; and many others).

DART is a global, recursive-dynamic, multi-region, multi-sector computable general equilibrium (CGE) model. It disaggregates the world economy into 11 regions and 10 sectors. The regions are linked by bilateral trade flows. The economic structure is fully specified for each region and incorporates production, consumption, investment, and governmental activity. All markets are perfectly competitive. A detailed model of the energy sector allows substitutions between fossil fuels with different carbon intensities in the production and consumption patterns of the private agents. The model dynamics are characterized by off-steady state growth. This specification is especially important for the analyzed time span of about 40 years for regions like China, Africa, Latin America, and some Asian countries.

The DART model is calibrated regionally for different parameters like exogenous technological progress, savings rates, population growth rate, and the growth rate of human capital. For the initial period, the CGE model is calibrated on the Global Trade Analysis Project (GTAP) database version 3 for 1992 (McDougall, 1997). This GTAP data set is adjusted for primary energy flow data from the International Energy Agency (IEA, 1997a–c), which provide statistics on physical fossil fuel flows and prices for industrial and household demand. The CO_2 emissions stemming from the use of fossil fuels over the simulation horizon are calibrated on the projections of the 'back to coal' scenario by IIASA and the World Energy Council (Nakicenovic et al., 1998) for each type of fossil fuel. This scenario is the most carbon-intensive one among those energy projections and thus represents the least favorable case for an international climate protection policy. Worldwide GHG emissions start from around 6 gigatons of carbon (GtC) in 1993 and rise up to 12 GtC in 2030.

To the greatest extent possible, the calibration and scenario assumptions of the DART model are harmonized with the ICLIPS IAM. Nevertheless, there are limits to the extent of this harmonization. The present version of the DART model assumes across-the-board technological improvement for the economy as a whole but does not include autonomous energy efficiency improvement, cost decline due to learning-by-doing, or backstop technologies. Mechanisms for international emission trading are not implemented either. These features of the model explain why its cost estimates tend toward the high end of the spectrum compared with results from similar models.

Klepper and Springer use the DART model for a case study based on a modified version of the proposal by the German Advisory Council on Global Change (WBGU). The Council proposes an annual CO_2 emission reduction by 3% from 2000 onward for the industrialized countries (the Klepper–Springer version starts this mitigation in 1995) and constant emissions for the developing countries after 2010. These reduction targets would keep global carbon emission nearly constant at 6 GtC over the simulation horizon until 2030. Not surprisingly, the authors find that these drastic emission reductions result in high welfare costs that amount to global welfare losses of 16% relative to the benchmark in 2030 measured in Hicksian Equivalent Variation. (This welfare measure indicates the maximum amount losers from the policy would be willing to pay in order to prevent the policy.) This global welfare loss is not equally distributed across the regions. Pacific Asian countries and India gain in terms of welfare while all other regions lose from the policy proposal by the WBGU. The emission reduction objectives can only be fulfilled through a considerable decrease in output of production, especially in the energy-intensive sectors, because adjustment potentials via expenditure switching are exhausted. Thus, the reduction in output of the energy-intensive sectors ranges between 20 and 80% relative to the benchmark in 2030.

The attempt to build the ICLIPS Aggregated Economic Model and the DART model as a harmonized model set and the modest achievements of the effort reconfirm the necessity and the difficulties of developing different but harmonized tools to address different aspects of climate policy, in this case long-term climate stabilization (ICLIPS IAM) and medium-term emission reduction (DART). One possibility might be a telescope-like model that properly blends high-resolution general equilibrium models (with increasingly aggregated sectors over time ending up with a single production function for each region beyond 70 to 80 years) and optimal growth models that keep track of the long-term intertemporal optimization features (e.g., consumption, capital accumulation, and capital transfer).

6. Closing Remarks

The ICLIPS project was implemented by an international research consortium. A core team at PIK and researchers at six partner institutes have collaborated closely for over four years. The list of partners comprises three German institutes – the Max Planck Institute for Meteorology in Hamburg (principal investigator Klaus Hasselmann), the Institute for Environmental Systems Research at the University of Kassel (Joe Alcamo), and the Kiel Institute of World Economics (Gernot Klepper) – and three others – the International Institute for Applied Systems Analysis in Laxenburg, Austria (Nebojsa Nakicenovic), the Jackson Environment Institute at the University College London in the United Kingdom (Martin Parry), and the Battelle Pacific Northwest National Laboratory in Washington, D.C. in the U.S.A. (Jae Edmonds). Papers in this special issue are written by members of this consortium and present the main components and results of the ICLIPS project.

The research activities in the ICLIPS Project have covered a broad range of scientific problems and policy issues in climate change: from impacts to mitigation strategies, from climate to economic modeling, from mathematical research to policy analysis. In addition to the models and results presented in this special issue, the ICLIPS project has involved a whole range of other events. A series of workshops brought together leading representatives of the international community to seek their advice and secure their input for the project activities (see Toth 1998b, 1999, 2000).

The start-up years of any integrated assessment project cannot produce more than an initial framework and Version 1.0 of the integrated model. Both have plenty of imperfections and rough edges. The ICLIPS project is no exception. Papers in this special issue openly discuss the current deficiencies and the many opportunities to improve the inverse approach and each model in the integrated assessment framework. Nevertheless, it is felt that the project has reached the level of maturity at which it can and should present itself to the broader peer community.

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