INTEGRATED ASSESSMENT OF LONG-TERM CLIMATE POLICIES: PART 1 – MODEL PRESENTATION

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Abstract. An integrated assessment model (IAM) conceived in the vein of the inverse approach is introduced. The model is designed to help social actors in making informed judgments about climate change impact targets, mitigation costs, and implementation mechanisms. Based on these normative decisions, the model verifies whether there exist long-term future emission paths that satisfy the user-defined constraints. If they do, the model determines an emission corridor containing all permissible emission trajectories. An overview of the IAM is provided and short descriptions of the model components are presented. Forward and inverse modes of application are explained. Examples based on impacts of climate change on aggregated potential crop production in Western Europe and South Asia illustrate how the model can be applied in different modes. The examples demonstrate how the inverse approach separates social judgments shaping climate policy from the model-based analysis of their implications. The examples also show the difference in climate change tolerance between developed regions in temperate zones and less developed regions in already warm climate zones.

Keywords: climate change, integrated assessment model, tolerable windows approach, emission corridor

1. Background and Objectives

The difficulties involved in the assessment and management of climatic change are numerous: the need to simultaneously consider long-term implications of near-term actions, global processes and their local driving forces and impacts; the multiplicity of linkages to many other fundamental social, economic, and environmental issues; the profound uncertainties characterizing the science and the deep controversies involved in the policy debate. This has triggered a rich variety of analytical efforts to foster scientific understanding and help policy formulation. The project on Integrated Assessment of Climate Protection Strategies (ICLIPS) is one such attempt. The task of the present paper is to explain the motivation and objectives of the project and to provide an overview of the Integrated Assessment Model (IAM) developed to reach the objectives: how its key components are assembled and operated, what are the main modes of using the model, and what kind of results

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are produced. The conceptual foundations of the ICLIPS model and its relation to other IAMs are presented in the introductory paper to this special issue, while details of the methodology and the specific model components are presented in subsequent papers.

The Third Conference of the Parties to the United Nations Framework Convention on Climate change (UNFCCC) approved the Kyoto Protocol in December 1997 as a first step in mitigating global greenhouse gas (GHG) emissions. The Kyoto Protocol specifies near-term emission targets and outlines a series of flexible mechanisms for implementation. Over the past few years, the bulk of the scientific analyses to support the policy process at global and national levels has focused on the virtues and drawbacks of the Kyoto Protocol. Economists have been searching for the least expensive implementation options while political scientists have analyzed the legal and political intricacies of its fulfillment. Irrespective of the question whether it will be implemented or not, the Kyoto Protocol has left open the ultimate question of greenhouse gas mitigation: at what level should mankind attempt to stabilize climate change with respect to anthropogenic influence.

Over the past decade or so, integrated assessment models (IAMs) have become the most utilized tools in analyzing interactions between human activities and the global climate (see Weyant et al., 1996). Traditional applications of these models involve policy simulations (e.g., the IMAGE model, see Alcamo, 1994; Alcamo et al., 1998) and policy optimizations. The latter in turn can take the form of a global cost-benefit analysis (see Nordhaus, 1994; Nordhaus and Boyer, 2000) or cost-effectiveness analysis (e.g., the MiniCAM model, see Edmonds et al., 1996; or the MERGE model, see Manne et al., 1995). All these analytical frameworks provide useful insights into the nature of the problem and shed light on possible management strategies.

Article 2 of the UNFCCC frames the requirement for long-term climate policy in terms of an environmental objective "to prevent dangerous anthropogenic interference with the climate system". This calls for an inverse approach that provides information about possible emission strategies with respect to environmental targets. Early attempts by the Intergovernmental Panel on Climate Change (IPCC) Working Group I (IPCC, 1996) and Wigley et al. (1996) depict emission paths with respect to given concentration targets. Subsequent work takes climate change attributes (magnitude and rate of change in global mean temperature) or geophysical consequences (magnitude and rate of sea-level rise) as environmental targets (see Alcamo and Kreileman, 1996a; 1996b; Swart et al., 1998; WBGU, 1995; Toth et al., 1997; 1999) to guide long-term climate policy assessments. While these analyses provide useful insights into the stabilization issue, they are only remotely related to the ultimate concerns about climate change: its possible adverse effects.

The main objective of the project on Integrated Assessment of Climate Protection Strategies (ICLIPS) is to develop an IAM that extends the inverse approach to address this ultimate concern. The ICLIPS IAM finds its starting point in impact analysis (to define acceptable climate change impacts) and in cost estimates (to determine acceptable mitigation costs). The inverse approach is thus formulated as a kind of extended and generalized cost-benefit analysis for which two types of normative inputs are required. The first type of input is based on the use of climate impact response functions (CIRFs) that depict reactions of climate-sensitive socioeconomic and natural systems to climate change forcing. As users of the ICLIPS model, social actors can specify their willingness to accept a certain amount of climate change impacts in important sectors in their own jurisdiction. Second, the same social actors can reveal their perceptions about their society's willingness to pay for climate change mitigation in terms of acceptable burden sharing principles and implementation schemes internationally, as well as in terms of the acceptable social costs for their nations. The ICLIPS IAM can then determine whether there exists a corridor of emission paths over time that keeps the climate system within the permitted domain without exceeding the specified social costs.

If the corridor does exist, it contains all permitted emission paths that satisfy the user-specified constraints. For the given set of impact/climate and cost/equity constraints, the emission corridor can be perceived as the room to maneuver for global climate policy over the long term. If the corridor does not exist, a willingness to accept more climate change impact can be specified on the impact side. This can be conceived as a result of resource transfers to increase the adaptive capacity in the most constraining region or sector. Alternatively, willingness to pay for emission reductions can be increased or more cost-reducing flexibility instruments can be allowed on the mitigation side.

The inverse approach leaves the specification of climate change mitigation regimes up to decision makers involved in climate change policymaking at the global and national levels. The primary task of the ICLIPS model is to determine the implications of different equity principles in burden sharing and in various implementation mechanisms on the existence and shape of the emission corridor. In addition, the model can also produce cost-effective emission paths.

An overview of the ICLIPS IAM and its main components is presented in Section 2. This is followed by a concise summary of the modes of model application and the decision variables users can work with in the current version. The modeling procedures in forward and inverse mode are presented in Section 4 together with the resulting impact paths (forward mode) and emission corridors for a given impact target under different mitigation cost constraints (inverse mode). A short summary section closes the paper.

2. Model Overview

IAMs addressing the climate change problem face a number of challenges in terms of the spatial and temporal scales as well as the complexity of the processes involved. By definition, these models need to account for GHG emissions from all major sources globally and should be able to deal with climate change impacts in relevant sectors in sufficient regional details relevant for at least national level policymakers. The atmospheric residence times of most GHGs and the inertia of the atmosphere-ocean-terrestrial biosphere system demands long-term analysis extending over centuries. In contrast, assessments of socioeconomic and technological development patterns, the resulting GHG emissions and mitigation costs are highly uncertain beyond a few decades into the future and policy attention is also focused on actions to undertake in the next decade or two. Complexities range from highly non-linear processes in the earth system, the possibility for some components to function both as a source and sink (depending on changes in land use and land cover, for example) as well as the intricacies involved in instruments and implementation mechanisms of various mitigation options.

To face these challenges, the ICLIPS IAM is implemented as a tightly interconnected system of models built on a platform of harmonized assumptions (see Figure 1). The core of this model system is a fully Integrated Climate-Economy Model. Its two main components are the Aggregated Economic Model and the ICLIPS Climate Model. The integrated model is driven by exogenous scenarios that include socioeconomic components like population growth, technological development, and emissions of GHGs not explicitly modeled in the Aggregated Economic Model. It is also linked to the impact module that consists of a set of Climate Impact Response Functions.

The ICLIPS Integrated Climate-Economy Model and the related modules are useful to analyze long-term climate policy options. Typical model runs cover 100 to 200 years. For near-term strategies, however, the insights from this model are limited due to the highly aggregated characterization of the economic activities. A more disaggregated model is required to explore near-term implications of different long-term options in detail. A global multi-regional and multi-sectoral general equilibrium model has been developed to provide this function (see Klepper and Springer, 2003). It is a multi-sectoral recursive-dynamic model based on the Global Trade Analysis Project (GTAP) database (Hertel, 1995).

2.1. THE ICLIPS CLIMATE MODEL

The ICLIPS Climate Model is a computationally efficient reduced-form model that mimics the behavior of sophisticated coupled atmosphere-ocean general circulation models (GCMs) combined with three-dimensional models of the carbon cycle. The radiative forcing modules cover all important GHGs: carbon-dioxide, methane, nitrous-oxide, sulfur hexafluoride, halocarbons, tropospheric and stratospheric ozone, and stratospheric water vapor as well as aerosols originating from SO_2 and biomass burning. The model produces regionalized temperature, precipitation, and cloud cover changes in two steps. Global mean temperature change is computed first and it is subsequently used to scale static spatial patters of climate anomalies, derived from GCM forcing experiment by applying empirical orthogonal function (EOF) analysis.

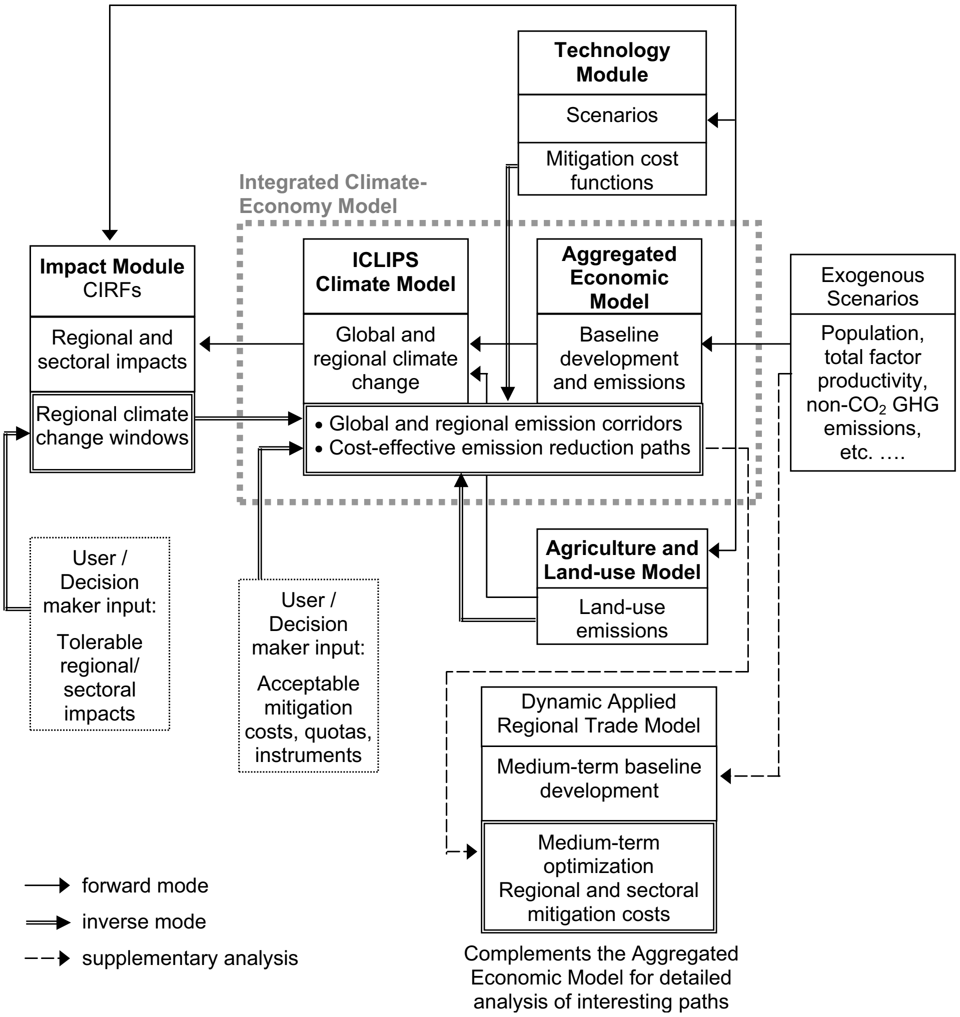

Figure 1. The structure and modes of application of the ICLIPS Integrated Assessment Framework. Note: CIRFs = Climate Impact Response Functions.

The core component of the climate model is a seven-box carbon cycle model developed at the Max Planck Institute for Meteorology in Hamburg. It consists of a differential impulse-response representation of the three-dimensional Hamburg Model of the Ocean Carbon Cycle (HAMOCC) extended into the non-linear high-CO_2 domain by an explicit treatment of the chemistry governing the CO_2 uptake by the ocean surface, and a nonlinear impulse model of the terrestrial biosphere's CO_2 fertilization.

The main application of this climate model in the ICLIPS framework entails deriving permitted emission corridors in the inverse model runs. However, the model can also be used in stand-alone mode for different purposes. The first possibility is to run the climate model in forward mode to assess patterns of climate change generated by a given emission scenario. The results can then be used as input to the Climate Impact Response Functions to determine the associated sectoral and regional biophysical impacts. The second possibility is to determine so-called “reachable climate domains” that represent all possible combinations of selected climate and atmospheric parameters (for example, changes in CO_2 concentrations and global mean temperature). Bruckner et al. (2003) present the ICLIPS Climate Model in detail.

2.2. THE ICLIPS AGGREGATED ECONOMIC MODEL

The Aggregated Economic Model is a Ramsey-type optimal growth model. It describes the most essential elements of the long-term economic development process, the investment and capital accumulation cycle, in an endogenous way. A Cobb-Douglas production function denotes the transformation of the input factors capital and labor into regional gross product at the macroeconomic scale. Labor availability is derived from exogenous demographic scenarios. Scenario-specified total factor productivity parameters describe the combined improvements in capital and labor efficiency.

The global economy is split into eleven regions. Although this makes the data acquisition and scenario specification more complicated, it permits a better description of various aspects of the dynamics relevant to the problem. First, the model can cope with the varying starting conditions and development patterns of different regions and depicts essential growth dynamics elements that result from interregional relations. Second, the differing potentials and interests in the realization of climate policy requirements can be made clear. The model aggregates regional utility functions into a global welfare function by establishing welfare weights in a way consistent with modern welfare economics. The Aggregated Economic Model allows for the mobility of capital and intertemporal trade as well as trading of GHG emission rights among regions. The initial distribution of emission rights has a decisive influence on the volume of emission permit trade and on the regional costs of climate policies. These macroeconomic costs are determined on the basis of completely integrated dynamic mitigation cost functions.

A large part of the input data for the model (population, carbon intensities, energy efficiency improvements, initial values for gross domestic product and capital stock) is based on the IIASA Reference Scenario F (Gritsevskyi and Schrattenholzer, 2003). This scenario is similar to the A2 scenario of the World Energy Council (WEC) (see Nakicenovic et al., 1998) and resembles the IPCC SRES A1FI scenario (IPCC, 2000). The Reference Scenario F largely extrapolates current economic, technological, and environmental trends. Additional requirements for the empirical foundation arise from estimation/calibration of the Cobb-Douglas production functions and the regional depreciation rates of the capital stock. While the parameters of the production function are mainly adjusted to reproduce the growth patterns of the reference scenario, aggregated capital stock parameters are calibrated from historical time series of investments in different categories of capital (see Leimbach and Toth, 2003).

The technology module is linked to the Aggregated Economic Model via harmonized assumptions about the baseline socioeconomic development (population numbers and regional distribution, regional economic growth) and the resulting baseline CO_2 emissions. The technology module produces dynamic mitigation cost curves that are fully integrated into the economic model as dynamic cost functions. They express the relationships between cumulative GDP losses relative to their baseline values as a function of cumulative carbon reductions up to a future point in time relative to the baseline emissions. In addition to the scenarios and data sets mentioned above, the IIASA scenario database is used to derive carbon mitigation cost functions via statistical analyses (see Gritsevskyi and Schrattenholzer, 2003).

A tightly integrated component of the Aggregated Economic Model is the Agriculture and Land-use Module. It is a properly adopted version of the land-use and agriculture component of the MiniCAM model (see Edmonds et al., 1996). It simulates land-use changes and the resulting carbon emissions. Various forms of land use (crops, biomass, pasture, forests, and unmanaged) compete for the suitable cultivation areas. The distribution takes place according to the economic returns from each land-use type in each region. Additionally, carbon policies, represented by positive carbon prices, create an incentive for the production of commercial biomass. Carbon densities are applied to each land-use category to provide an estimate of the carbon stock during each time period. Carbon emissions from land-use change are then calculated as the difference in carbon stocks between periods.

The bulk of the data for the Agriculture and Land-use Model is obtained from the summary land-use data compiled by the World Resources Institute (WRI, 1992). It is used to set up the 1990 land allocations. The Food and Agriculture Organization (FAO) food balance data for 1990 are aggregated into broad food categories to estimate the demand for agricultural products. Per capita income data that, along with population, drive the demand for agricultural products are exchanged between the economic model and the land-use module (see Sands and Leimbach, 2003).

2.3. THE ICLIPS IMPACT MODULE

The Impact Module consists of a series of regionalized Climate Impact Response Functions (CIRFs). These functions show the magnitude of climate change impacts in natural vegetation, nature protection areas, forests, agricultural yields, and water availability. Due to computational restrictions and data limitations, the integrated climate-economy model distinguishes a few world regions only. This level of detail is sufficient for reproducing important features of the dynamics of the climate system and the economic system. Meaningful assessments of climate change impacts, however, generally require a finer spatial resolution. CIRFs have been developed in order to incorporate information from geographically explicit impact models into the integrated ICLIPS model without impairing its computational efficiency. The impact functions are based on multiple runs of sophisticated sector-specific impact models for a sample of plausible future climate states.

Modified versions of the BIOME 1 vegetation model (Prentice et al., 1992), the FAO crop suitability model (Leemans and van den Born, 1994; FAO, 1981), and the WaterGAP hydrological model (Döll et al., 1999) are applied for assessing climate impacts on natural vegetation, crop production, and water availability, respectively. The model applications use soil information and quasi-daily data for temperature, precipitation, and cloudiness as an input. The BIOME model and the FAO model also consider the direct effect of atmospheric CO_2 on plant physiology. All models are globally applicable whereby a spatial resolution of 0.5 degree latitude by 0.5 degree longitude is used for the computations. Results are typically presented at the level of single countries or groups thereof.

The climatic input to the impact models is constructed by a scaled scenario approach that efficiently uses maximum information from GCM experiments. Spatial patterns of anomalies in various pertinent climate variables are scaled to the change in global mean temperature. The anomaly patterns are derived from transient forcing experiments with coupled GCMs. These climate scenarios consistently allow for the spatial and seasonal variability in the simulated climate change signal. CIRFs may be used in ‘forward’ mode to assess the impacts of specific emission scenarios, in ‘overview’ mode to visualize the impacts for a wide range of climatic futures, and in ‘inverse’ mode to determine the ‘tolerable’ set of climate states that is compatible with a pre-defined impact guardrail (see Füssel et al., 2003).

3. Model Applications

The Integrated Climate-Economy Model can be used in “forward” mode as a policy simulation model. Driven by exogenous assumptions about demographics, productivity increases, and other determinants, the economic model produces baseline development patterns and CO_2 emissions. Combined with exogenously specified emissions of non-CO_2 GHGs, and accounting for land-use related emissions computed by the land-use module, the climate model calculates concentrations of all GHGs, the resulting radiative forcing and climate change patterns. Based on the regionalized climate change patterns, the impact model can be used to determine the resulting changes in the impact sectors for which regionalized CIRFs are available.

The novel feature of the ICLIPS IAM, however, is apparent when used in “inverse” mode. Normative judgments manifested in the form of social decisions are taken as input to a dynamic control problem. The first objective is to determine whether there exist GHG emission paths which satisfy the externally defined constraints on the acceptable climate change impacts and mitigation costs. If such paths exist, the model determines an emission corridor including all paths permitted under the given constraints. It is not possible to identify each permitted

TABLE I

Specification of normative constraints for an inverse analysis with the ICLIPS framework

Impact	Climate	Economy
Maximal change in global and/or regional ...	Maximal ...	Maximal global and/or regional ...
- nature reserves	- global mean temperature change	- emission reduction rate
- biome type	- rate of global mean temperature change	- transient and/or cumulative GDP loss (relative to the reference case)
- total forest area	- regional temperature change	- transient and/or cumulative per capita consumption loss
- stable forest area	- global mean sea-level rise	- transient and/or cumulative welfare loss
- agricultural yield	- rate of global mean sea-level rise	- deviation of income losses of different generations
- area suitable for agriculture		Minimal global and/or regional increase in per capita consumption
- water availability		Maximal regional export and/or import of emission permits
		Transition time to allocation of emission rights on equal per capita basis

individual path directly because there is an infinite number of them. The corridor represents an “envelop” of all permitted paths. It is important to note that any emission path that leaves the corridor is known to violate one of the constraints. However, not all arbitrary paths within the corridor are necessarily permitted paths.

The most delicate user-made decisions in the inverse mode concern the question what constitutes a tolerable climate change impact. The left column in Table I lists the impact sectors for which CIRFs are currently available. As explained in Section 2.3 above, CIRFs describe the relationships between the gradually increasing forcing through a climate change pattern and an appropriate indicator of the impact sector’s response. These biogeophysical relationships are derived from state-of-the-art impact models. Nevertheless, they provide only part of the picture. Detailed knowledge of the affected impact sector and good understanding and real life experience of the surrounding socioeconomic conditions are required to make an informed judgment about the level of climate change- induced impacts with which the given sector or region can cope.

The judgment of social actors concerning the acceptable degree of change in the impact sector determines the tolerable level of regional climate change. This, in turn, corresponds to a given level of global climate change. It follows from the global nature of the climate problem and from the immanent logic of the inverse approach that for a given analysis the tightest sectoral or regional impact limitation will determine the global climate change constraints. It is also possible to ignore the impact functions and to define acceptable changes directly in climatic terms, as shown in the middle column of Table I. In fact, the first analyses conducted with the ICLIPS IAM are based on restrictions prescribed for the change in global mean temperature and for the rate of temperature change and thus explore the implications of constraints defined in the climate domain (Toth et al., 1997).

The second set of user-specified constraints concerns the “willingness to pay” for climate protection. This corresponds to a globally uniform or regionally differentiated income, welfare, and/or consumption loss due to the diversion of resources from consumption and investments to emission mitigation. These cost considerations cannot be separated from the contentious issue of burden sharing across regions and generations. The Aggregated Economic Model is formulated in such a way that emission rights are allocated according to the actual emissions in the starting year (grandfathering principle) and they can be set on a transition path towards an allocation according to other burden-sharing principles (equal per capita relative to the population in a pre-specified year, equal per unit of GDP, etc.). The year by which the user-specified principle of the emission rights allocation becomes fully effective can also be decided by the user. The model determines and works with a linear transition between the two end-points.

Intergenerational burden sharing can be specified uniformly (welfare or consumption losses should not exceed a user-specified percentage for any generation) or it can be differentiated. The model considers the user-specified values for inter- and intragenerational equity preferences in the calculation of the actual emission corridors for regions over time. The economic model allows the implementation of the prescribed climate change constraint by using global trade of emission rights. The model user can specify upper limits for regional exports and/or regional imports of emission permits for all regions uniformly or for selected regions variably. Possibilities for user input related to the acceptable costs and mechanisms of emission reduction are listed in the right column of Table I.

4. Selected Results

The ICLIPS integrated assessment framework presented above is developed for use in national-level climate policy discussions or in international climate negotiations. In order to test the applicability of the framework, the modeling team has defined and implemented a large number of test cases. As indicated in the previous section, the integrated model can be applied in two different modes that are denoted as 'forward' and 'inverse' analysis, respectively. In this section, we present illustrative examples of both application modes. For a more comprehensive and systematic application of the ICLIPS IAM, see the next paper by Toth et al. (2003).

4.1. FORWARD MODE

There is a great deal of flexibility in using the ICLIPS model in forward mode. The first option is to define a consistent set of values for the exogenous variables of the Aggregated Economic Model in the form of a new scenario or calibrate those variables to an already existing scenario. In either case, the economic model will provide the baseline development patters, regional consumption and emission paths, and other key indicators in the absence of climate policy and ignoring climate change damages. This scenario definition and calibration procedure is indispensable for creating the reference paths against which the magnitude of the required emission reductions and the related costs are measured in inverse mode.

The second option is to take the GHG emission projections from any scenario, use them as direct input to the ICLIPS Climate Model and take the resulting climate change patterns as input to the impact models to establish impact trajectories. Selected emission paths from the IPCC SRES are used in the present subsection to illustrate results from applications in forward mode. The IIASA F (similar to the IPCC A1FI) scenario serves as the basis for model calibration and therefore it is the foundation of the baseline development and emission patterns underlying the illustrative applications in inverse mode presented in the next section.

The forward analysis presented in this section is based on the second option above. It starts from specific emission scenarios for greenhouse gases and aerosol precursors. In the first step, the ICLIPS Climate Model computes the corresponding trajectories for the atmospheric concentrations of all greenhouse gases and for all important climate variables. In the second step, the impacts on various climate-sensitive sectors are determined by using the respective Climate Impact Response Functions.

In the present example, we assess the effects of climate and CO_2 change on crop yields in two regions for five emission scenarios specified by the IPCC SRES team (IPCC, 2000). The wide range of plausible future CO_2 emissions (in the absence of specific climate protection measures) is covered by the four so-called marker scenarios (A1, A2, B1, and B2) and by an additional coal-intensive scenario (A1C). The IPCC emission scenarios are taken because they exhibit a broad range of plausible future economic development and emission paths.

The agricultural impact functions are derived from an adopted version of the FAO crop suitability model. The model estimates the rainfed yields of 19 important crops for each 0.5° by 0.5° grid cell of the land surface based on local soil and climate data and the CO_2 concentration. The focus of the crop model is on annual crops that are used as staple food. Some other crops that are regionally important (e.g., grape-vine in parts of Europe) are therefore not considered. Regional climate change scenarios are computed by using the scaled scenario approach that combines the aggregated results of the ICLIPS Climate Model with climate change patterns derived from various GCM experiments. The results presented here are based on climate projections from the HadCM2 model.

We use an aggregated indicator to represent the performance of the most important crops in a country under current and future climate conditions. In the first step, the simulated yields for each crop are made comparable by expressing them as percentage of the maximum crop-specific yield (under optimal climate and soil conditions). In the second step, the normalized yield figures are weighted with the current acreage of the respective crop in the country. The so-defined indicator describes the sensitivity of the presently important crops to climatic changes, assuming an optimal timing of agricultural activities. (See Füssel et al., 2003 for details of the impact model and the chosen indicator.)

Figure 2 presents simulation results for the indicator ‘weighted crop performance’ (expressed as a percentage of the baseline value in the reference period 1961-1990). The region ‘Western Europe’ (Figure 2a) refers to the European Union and the European Free Trade Association states whereas ‘South Asia’ (Figure 2b) comprises the countries south of the Himalayas (most importantly India). Both regions show an initial increase in their agricultural potential under all scenarios due to the positive direct effects of enhanced atmospheric CO_2 levels on crop growth. The results for later periods are dominated by the adverse effects of changing climatic conditions. Aggregated losses in the year 2100 (the time horizon of the SRES scenarios) amount to 6% in Western Europe and to 21% in South Asia. In summary, both the initial increases and the later decrease in Western Europe appear to be relatively small compared to the long-term decrease in South Asia.

4.2. INVERSE MODE

The distinctive feature of the ICLIPS IAM is its applicability in inverse mode. The model determines the maneuvering space for global climate policy subject to ‘guardrails’ defined for the tolerable amount of climate change, acceptable mitigation costs, and feasible burden sharing principles. These guardrails aim at operationalizing the objective of the UN Framework Convention on Climate Change stated in its Article 2. They are supposed to be specified by decision makers from different regions who are involved in the formulation of a global climate policy regime. For the examples presented below and for other illustrations in this special issue, the authors define the cases to be investigated on the basis of discussions in the policy arena but without particular reference to any official statement or agreement.

The inverse analysis presented here is based on the crop yield simulations described above. For the sake of simplicity, we assume that decision makers in both investigated regions consider a decrease in aggregated crop yields by more than 10% in their respective home regions unacceptable. This is admittedly an arbitrary

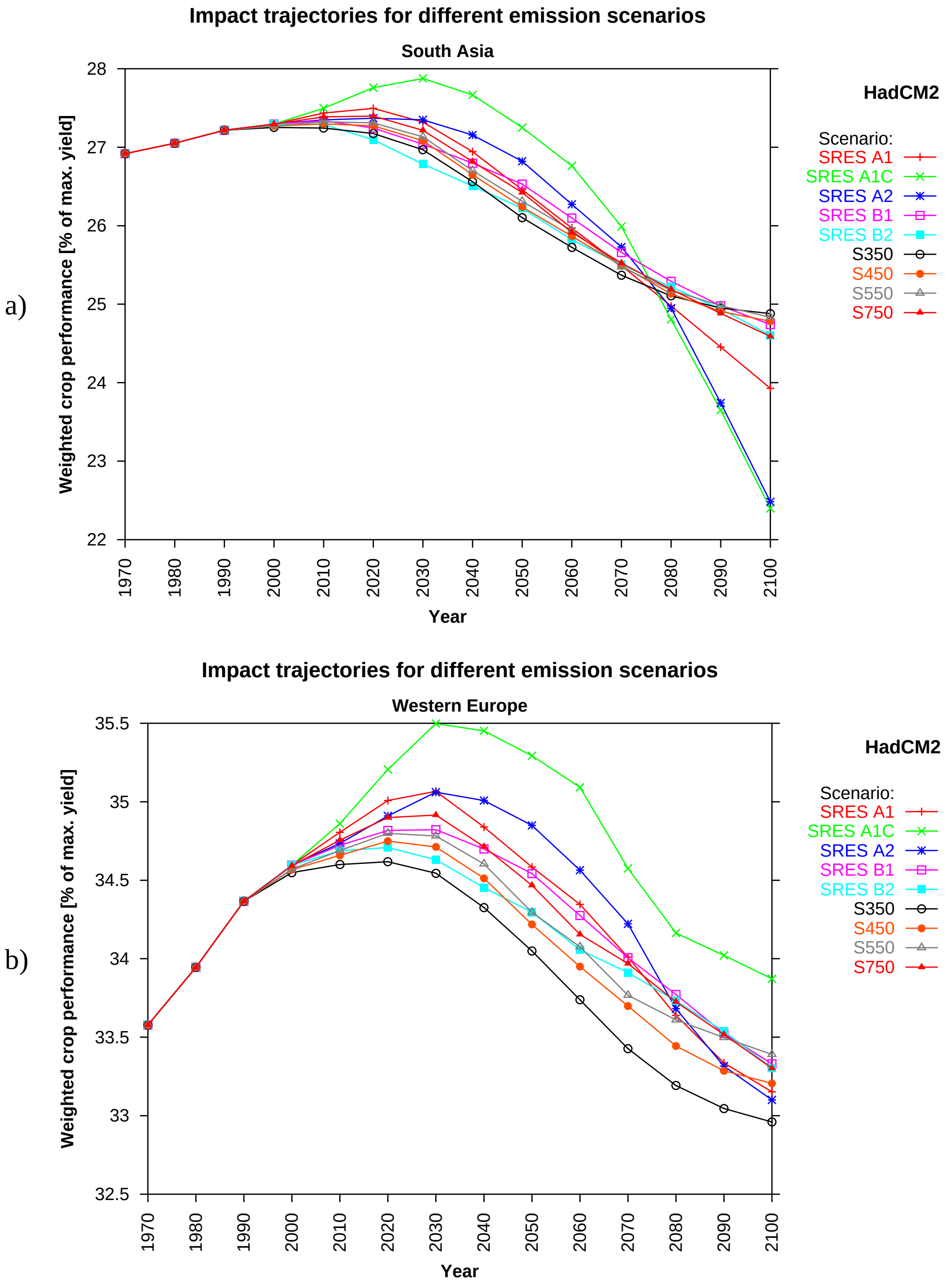

Figure 2. Weighted crop performance indices for Western Europe (panel a) and South Asia (panel b). Note the different scales used in the two panels due to the differing ranges depicted.

number and serves only our purpose to illustrate the application of the ICLIPS framework. The underlying assumption might be that this is the magnitude of yield loss that can be counterbalanced by technological (cultivation techniques, fertilizers) or socioeconomic (food import) adaptation measures.

Figure 2 shows that the 10% acceptable yield-loss limit is violated in South Asia by the end of the 21st century under all surveyed emission scenarios. The loss-of-yield limit for Western Europe, in contrast, is not exceeded before the 22nd century. Since the default time horizon for inverse analyses with the ICLIPS model is the year 2200, the impact guardrail for Western Europe becomes effective in the corridor calculations.

The limit to the acceptable climate change impacts defined in terms of a 10% yield-loss is only part of the social choice to guide climate policy. Another important part is the decision about the endurable mitigation costs. We express this socioeconomic limitation as a deviation from the baseline consumption path. The constraint applied here refers to a maximum annual consumption loss of 2% that is experienced by any world region at any time, relative to the reference scenario without climate policy targets. Income effects of climate change impacts are not considered explicitly in the ICLIPS model. The user-defined maximum impact values determine the tolerance boundaries, but no attempt is made to define monetary damage functions. The advantage of this model formulation is that one can avoid the controversial issues involved in monetary valuation while the clear shortcoming is that the model cannot say anything about climate change damages associated with permitted emission paths inside the tolerable emission corridor. The latter is the price one has to pay in the inverse approach for focusing the analysis on the most crucial ultimate questions of long-term climate policy.

Besides the specification of guardrails, some additional assumptions have to be made in an inverse analysis. We simply report the settings applied in this exercise and refer the reader to Leimbach and Toth (2003) for details. There are no caps on the trading of emission rights between different regions. Their initial allocation follows a smooth transition path from the ‘grandfathering’ principle to an ‘equal per capita’ allocation (based on the 1990 population figures) by the year 2050. Since dynamic mitigation cost functions are only available for energy-related CO_2 emissions until 2100 in the present version of the ICLIPS economic model, emissions of other gases have to be either prescribed or linked to CO_2. We assume that non-CO_2 greenhouse gas emissions remain constant at their current levels whereas non-energy CO_2 emissions follow the IPCC IS92a scenario. SO_2 emissions are linked to energy-related CO_2 emissions whereby an autonomous desulfurization rate of 1.25%/year is applied. All emissions remain constant after the year 2105 in the reference scenario as well as in the policy runs.

Figure 3 shows global emission corridors derived by inverse applications of the integrated ICLIPS model. Figure 3a refers to the application of the loss-of-yield constraint in Western Europe whereby the income loss in any region at any time period is limited to 2%. For this weak impact constraint, the upper boundary of the necessary emission corridor (shown in bold) equals the baseline emission scenario. The term "necessary corridor" emphasizes the fact that any path leaving the corridor is known to violate at least one of the pre-defined constraints.

It follows from the formulation of the inverse modeling technique that an emission trajectory along the upper boundary of the corridor would produce a cumulative emission that pushes the climate system outside the permitted range. Altogether, the comparatively weak impact constraint permits a wide range of policy options. Additional information on feasible paths and trade-offs between early and late emission reductions can be derived from the paths that define the boundaries of the necessary corridor and from the sufficient corridor. Figure 3a shows a sufficient emission corridor delineated by dashed lines. It is defined in such a way that its boundaries are permitted emission paths themselves and they are at any point in time equidistant to the boundaries of the necessary emission corridor. The paths defining the boundaries of the sufficient corridor are "optimal" in the sense that each permitted path that transgresses the boundary at some time to the outside must, in turn, deviate toward the center of the corridor at another point in time.

Figure 3b shows emission corridors based on the loss-of-yield constraint in South Asia. Since no feasible solution exists for the original specification of the acceptable mitigation costs, we had to relax the cost constraint. The diagram shows emission corridors for maximal regional income losses of 4%, 5%, and 10%. As a higher willingness to pay increases the flexibility of emission reductions, it affects both the upper and the lower boundary of the corridor.

The boundaries of each corridor are defined by the trajectories which maximize or minimize emissions at a specific point in time. These paths also indicate the inner structure of the corridor. Three of them are shown for the 4% income-loss corridor in Figure 3b in dotted lines: the paths that maximize emissions in 2030 and 2080, respectively, and the one minimizing emissions in 2090. Trajectories that follow the upper boundary of the corridor for some time need to take a sharp turn and imply emission reductions at the highest rate permitted by the constraints on acceptable mitigation costs. Once again, boundaries of the necessary corridors themselves are not permitted emission paths.

Figure 3 reconfirms the results of many impact assessment studies (see Gitay et al., 2001) that detrimental impacts of climate change will first hit regions in the already warm climatic zones. Even if we completely ignore all opportunities for socioeconomic adaptation, there is not much reason to worry about agricultural yield impacts in Western Europe. Changing biophysical conditions will lead to a less than 10% loss in the potential yields. In contrast, the initially defined limit for climate mitigation expenditures (2% income loss) is not sufficient to craft a global emission strategy that would prevent India crossing the 10% yield-loss threshold. The critical question in this case is whether it would be economically possible and institutionally feasible to boost adaptive capacities in India so that it can cope with higher magnitudes of yield losses or it would be really necessary and politically

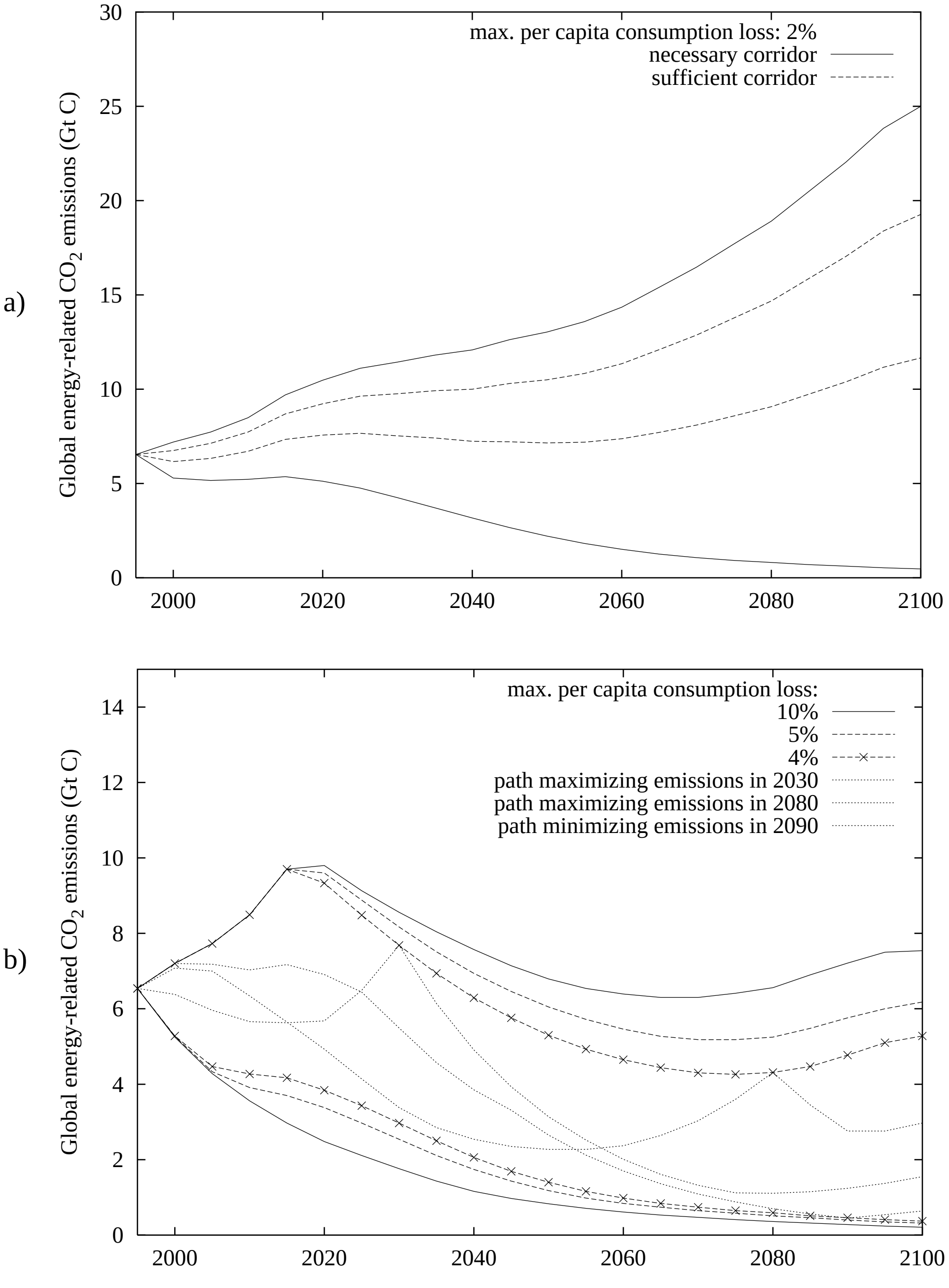

Figure 3. Global industrial CO_2-emission corridor for a 10% loss-of-yield constraint (see text for explanations); Panel a: Western Europe; boundaries for 2% income loss (bold) and sufficient corridor for 2% income loss (dashed); Panel b: South Asia; boundaries for 4%, 5%, and 10% income loss, inner structure of the 4% corridor.

feasible to increase climate mitigation outlays to the level that can arrest climate change at the level that prevents crossing the specified impact threshold. This dilemma draws the attention to the importance of better understanding and appropriate representation of adaptation options and processes in the ICLIPS framework in the future. It also illustrates the immense difficulties negotiators will face when trying to agree on an impact-based target for stabilizing GHG concentrations.

5. Concluding Remarks

This paper presents an overview of the ICLIPS IAM. In addition to traditional policy simulation and cost effectiveness analyses, it is suitable to plot a stratagem for long-term climate policy. This leaves room for searching for emission paths that accommodate additional concerns within a permitted range demarcated by commonly agreed climate-related primary criteria. These secondary concerns can range from differences in risk perception and risk acceptance to searching for compromise in political negotiations.

When used in inverse mode, the ICLIPS IAM can easily determine whether there exists an emission corridor that obeys the impact constraints specified by social actors from a given region for a certain impact sector (in our examples: agricultural yields in Western Europe and South Asia). The model can also be used to explore at which combinations of impact and mitigation cost constraints would emission corridors emerge or vanish altogether. This tool, however, cannot replace the perceptions and verdicts of social actors about acceptable risks and affordable costs within regions and about the feasibility of resource transfers across regions to foster adaptation.

It is important to note that the Climate Impact Response Functions available in the current ICLIPS framework incorporate only biogeophysical relationships. Their applications by social actors draw heavily on the users’ assumptions about future changes in the socioeconomic dimensions that will affect the vulnerability of future societies to the estimated biophysical impacts of climate change. The next crucial step is therefore to develop the socioeconomic components of the impact functions so that they can support social actors in making better informed choices about the dangerous and thus unacceptable impacts of climate change.

Probably the most crucial concern in building an IAM and in interpreting its results is related to the treatment of uncertainties. The ICLIPS model largely follows the practice prevailing in recent integrated assessments. The integrated model as well as its main modules can undergo systematic sensitivity tests by varying one key model parameter after another across a plausible range and observing how the fundamental output variables change as a result. In this respect, our observations are rather similar to those of other integrated assessment modelers: climate sensitivity is the most important model parameter, aerosol emissions is the main scenario variable shaping model results in the climate model, while technological development and discount rates are the most important model parameters, and productivity improvements and population growth are the key scenario-based sources of uncertainties in the economic model.

A special kind of uncertainty is associated with the linkage between the regional impact functions and global climate change. The first part of the problem stems from the uncertainties inherent in the sectoral impact models we adopted. The impact functions clearly inherit the uncertainty features of those models. The scaled scenario approach is adopted in deriving Climate Impact Response Functions, but uncertainties about the linkages between global and regional climate change are independent of the scaled scenario approach (see Cubasch et al., 2001). The source of the uncertainty in this respect is the generally assumed linear relationship between global and regional climate change. Nonetheless, the inverse procedure of tracing the acceptable regional climate change impacts to tolerable global climate windows helps identify the impact sectors and geographical regions that impose the tightest limitations on the global emission corridors. Reducing the uncertainties about these sectors and regions is crucial, because they largely influence the stabilization target and the permissible range of emission paths. The ICLIPS framework can help pinpoint the most binding impact constraints and the associated emission limits.

Another way to relax the tightest sectoral or regional tolerable impacts might be to increase their tolerance by helping them to adapt and endure more regional climate change. This possibility is more obvious in the case of climate-sensitive socioeconomic sectors (like the construction industry or human health) and intensely managed ecosystems (like agriculture) than in the case of natural ecosystems. Uncertainties related to the options and scope for adaptation are increasingly explored (Smit et al., 2001). Uncertainties concerning the choice of acceptable magnitudes of ecosystem transformation are explored in the next paper of this issue.

The inverse analysis presented in this paper also illustrates the relationship between the Tolerable Windows Approach and other types of multi-attribute approaches. The key distinctive feature of the TWA is its intention to demarcate the full range of available emission policy options on the basis of multiple management criteria. In contracts, multi-attribute decision analysis seeks a single optimal outcome by maximizing expected utility at each decision node (decision making point) in a sequential process. The precondition to this procedure is that all decision criteria and all important attributes are specified. All possible outcomes need to be evaluated in terms of utilities and probabilities need to be assigned to the possible outcomes of the “chance” nodes. As a result, part of the uncertainties surrounding the problem is incorporated in the model structure. Accordingly, any model revision, like the introduction of an additional attribute or objective, requires a major revision of the model itself.

The TWA concentrates on a few key attributes (e.g., acceptable impacts and costs) and provides an envelop for future action. Which course should be taken within the envelope? This can be determined by defining additional criteria not explicitly included in the original problem formulation. The additional criteria or constraints can be easily added to the existing model structure and a new model run can show their implications for the emission corridor. Another possibility is to use the inverse IAM as a "post-processor" to check whether a selected path inside the corridor is really a permitted one.

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