The Economics of Adaptation to Climate Change*

An Integrated Assessment Framework

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Abstract

Current estimates of the cost of climate change in developing countries and of the needed adaptation measures are in very short supply. This is largely because the economics of adaptation to climate change is a new research area and no agreed methodology to assess adaptation costs has yet emerged. In addition, computations are made more complicated by data limitation in vulnerable countries. At the same time, an understanding of the full array of adaptation options is crucial to prioritize the most effective adaptation strategies. Better estimates of the overall budget implications of implementing "climate resilient development" are needed to both enable developing countries to implement their national strategies and plans and to inform discussions concerning possible international assistance.

The objective of this paper is therefore twofold. On the one hand, it develops technical knowledge and methodologies to assist developing countries cost, prioritize and sequence robust adaptation strategies into their development plans and budgets. On the other hand, it intends to estimate the global cost of adaptation to all developing countries in order to inform the international community's efforts on the additional resources needed to allow developing countries adapt to climate change.

As these twin objectives are somewhat at odds with each other, we adopt two different strategies in terms of methodology: a bottom-up approach at the country level and a top-down approach at the international level. The former is applied to six country case studies, in order to ground-truth on local databases and on work by national experts, as well as on discussions with local stakeholders. The latter relies on global datasets and combines inter-sectoral linkages within regions together with bilateral linkages among regions.

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1 Introduction

Climate change will have unequally adverse impacts on industrialized and developing countries. First suggested by Schelling (1992) and supported recently by Mendelsohn, Dinar, and Williams (2006), it is likely that countries in relatively cool regions of the world will benefit from global warming whereas countries in warm regions of the world will be harmed by global warming. Responses to climate change in terms of adaptation to the new climate will thus vary tremendously between industrialized and developing countries as well as across developing countries. Needless to say that this will be also true across sectors within each of these economies.

An understanding of the full array of adaptation options is crucial to prioritize the most effective adaptation strategies. Better estimates of the overall budget implications of implementing "climate resilient development" are needed to both enable developing countries to implement their national strategies and plans and to inform discussions concerning possible international assistance.

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As these twin objectives are somewhat at odds with each other, we adopt two different strategies in terms of methodology: a bottom-up approach at the country level and a top-down approach at the international level. The former is applied to six country case studies[1], in order to ground-truth on local databases and on work by national experts, as well as on discussions with local stakeholders. The latter relies on global datasets and combines inter-sectoral linkages within regions together with bilateral linkages among regions.

The proposed bottom-up methodology begins with a consistent downscaling of projected climatic changes from a multiplicity of General Circulation Models (GCM) to local levels. Subsets of the suite of downscaled climatic factors are then to be used to estimate the vector of impacts on key economic sectors of each country, using sector-specific impact assessment models. Based on this information, alternative government adaptation projects will be specified and optimally chosen subject to a government budget constraint. Thereafter, direct impacts of climate change will serve as inputs into a macroeconomic framework to examine the indirect intersectoral impacts of climate change as well as adaption strategies.

The proposed top-down methodology starts also with climate projections to derive regional sector-specific damage functions. However, this information is used to calibrate a global dynamic multi-sectoral CGE model to a baseline

[1]Country case studies include Bolivia, Ghana, Ethiopia, Mozambique, Bangladesh, and Vietnam. Selection of countries were based on overall vulnerability to major climate change impacts, differing environmental, social, and economic conditions, and adequate data at the national level.

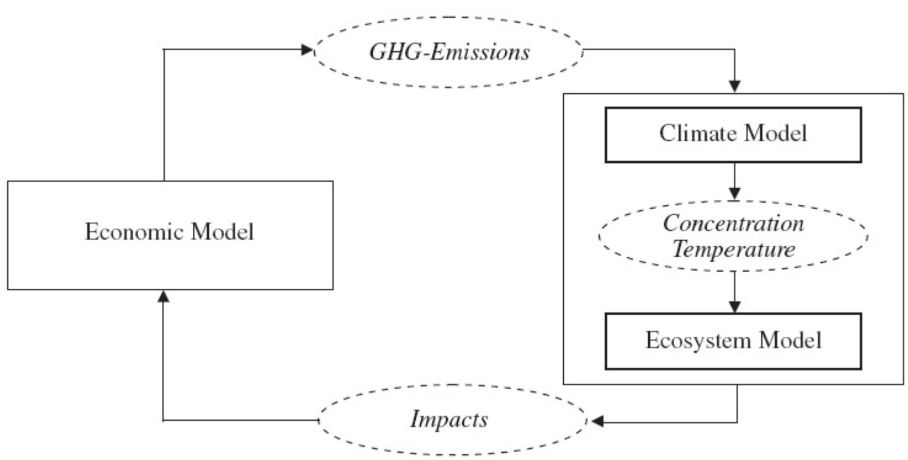
which different scenarios are applied to as counterfactual situations to estimate the cost of adaptation. We consider two approaches for estimating the cost of adaptation for all developing countries. The first approach is the simulation of additional investment needed to restore hypothetical welfare without climate change in all developing countries. The second scenario is the simulation of additional investment needed to equal marginal cost of adaptation to marginal avoided damages.

Climate projections are common to both approaches and are therefore the focus of the following section of the paper. The core theme of the study is the economics of adaptation to climate change and is discussed in details in sections 3 and 4 for the bottom-up and top-down approach, respectively. Drawing on adaptation strategies identified in the second part for six country case studies, the third part is concerned with extrapolating the cost of adaptation to all developing countries. Section 5 concludes with further developments.

2 Climate Projections

Integrated Assessment Models (IAM) are particularly well-suited for policy analysis as they link both environmental and economic models into a single system and capture therefore cause-effect chains as well as feedback. An illustration of the basic structure of these models employed for climate policy analysis is taken from Böhringer, Löschel, and Rutherford (2007) and reported in figure 1. "These models aim to represent the causal chain through which (i) economic activities trigger anthropogenic greenhouse gas emissions, (ii) emissions of greenhouse gases translate into atmospheric concentration, temperature shift, and climate change, and (iii) climate change feeds back via the ecosystem to the economy."

Figure 1: Schematic structure of IAM for climate change



IAMs represents then both adaptation to and mitigation of climate change. However, in our study future emission pathway is exogenous and thus, there is no link between the economic model and the climate model so we can start our analysis with the climate model.

Uncertainty is endemic to the problem of climate change and in particular to climate projections. It is present mainly in emission scenario and in climate models. In our study, however, we focus only on one emission scenario — the A2 SRES emission scenario[2] — for the following reason. The focus at the UNFCCC 15 COP in Copenhagen 2009 will be the near term which is between 2030 and 2050. As future emission profile is relatively robust across all IPCC scenarios for this time horizon, it is not affected by future mitigation strategies. Therefore future emission pathway is not subject to large uncertainty which supports the assumption of considering only one emission scenario. The emission scenario A2 is chosen as we see today increasing evidence around the world for moving into this direction.

On the other hand, uncertainty in the response of a climate model arises from both the effects of internal variability and alternatives structural choices[3]. Ensemble approaches are then commonly used to cope with the effects of uncertainties arising from variations in model structure and parameter settings[4]. However, as we are concerned with the transient climate response in our study, single GCM outputs are used in order to preserve temporal and spatial correlation within each particular climate model. Therefore uncertainty is explored by taking two different GCMs producing the driest and wettest outcome in terms of a climate moisture index. This analysis is conducted both at the country level and at the world level.

The above characterization of uncertainty in climate projections results in the specification of only two climate scenarios. As we assume that the current climate is the year 2000 constant concentrations projections (i.e. no climate change scenario), the two climate scenarios represent thus two climate change scenarios.

In terms of output, GCMs simulate a wide variety of atmospheric variables, but not all with the same degree of confidence. Temperature is generally considered to be the most reliable output whereas precipitation is more questionable. This may reflect that temperature fields tend to be relatively consistent over large areas whereas precipitation patterns are strongly influenced by topographic features (e.g. mountains and lakes) which are not accurately represented in the modes. Other variables such as humidity, wind speed and direction, atmospheric pressure, and runoff are usually considered much less

[2]From IPCC (2007b), the A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

[3]Examples for the former include climate sensitivity (temperature rise that would occur for a doubling of carbon dioxide concentration) and half life of global warming (time it takes for carbon dioxide concentration to fall to half its initial value) while examples for the latter are choices of resolution and basic physical assumptions on which parametrizations are based.

[4]Model structure is addressed with multi-model ensemble which is generated by collecting results from a range of models from different modelling centres and parameter settings with perturbed physics ensemble which is produced by generating multiple model versions within a particular model structure, by varying internal model parameters within plausible ranges.

reliable than temperature and precipitation.

All these atmospheric variables are simulated on a spatial and temporal scale. Reliability of GCM projection usually decreases with higher resolution of spatial and/or temporal dimension. Depending on the need of the case study, we may use in addition to temperature other GCM variables at different level of spatial and temporal resolution.

3 A Bottom-Up Approach at the Country Level

The first objective of this study requires full buy-in from local governments. This is not achieved only politically, but is also through developing local capacity on climate change issues and strengthening links between governments, donors, and international institutions in this area. A bottom-up approach is thus well suited as it builds directly on local databases, on work by national experts, as well as on discussions with local stakeholders. This section describes the proposed methodology and applied it to the Bolivia country case study.

3.1 Climate change impacts

Climate impacts (e.g. temperature or precipitation) on natural resources are quantified in the ecosystem model (e.g. crop model). For each sector under consideration, the ecosystem model converts GCM projected output into sectoral bio-physical impacts. To increase the reliability of these impacts in terms of both spatial and temporal resolution, local climate projections are used and obtained by applying an empirical/statistical downscaling method[5].

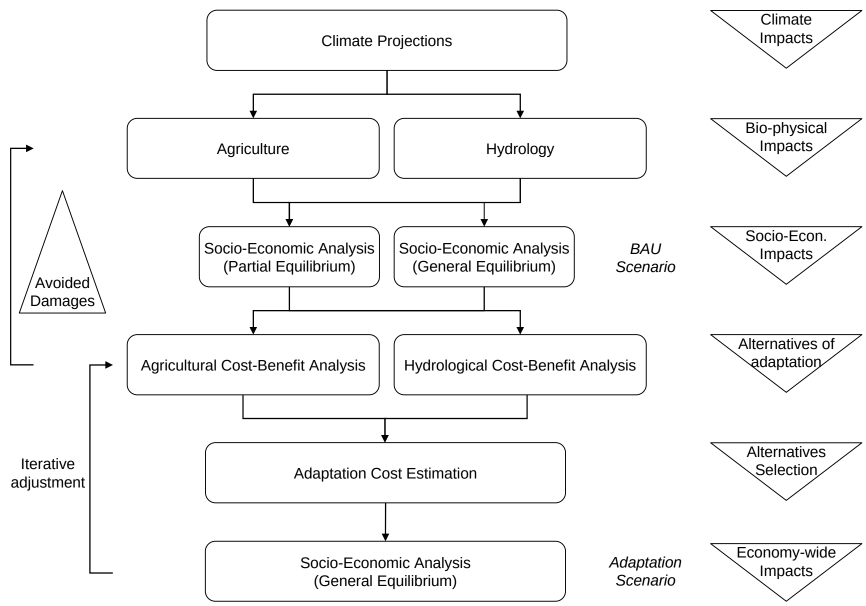
The economic model allows deriving bio-physical impacts into economic impacts. At the country level, these impacts are first valued at the sectoral level using a partial equilibrium model and then at the economy-wide level using a computable general equilibrium model.

Ongoing discussions with the Government of Bolivia have led to the identification of agriculture and hydrology as the two major sectors that will be focused on. An illustration of the overall bottom-up methodology with the two sectors identified in Bolivia is given in figure 2.

In the case of Bolivia, the lack of regional climate simulations or downscaling experiments implies that local climate projections are obtained by applying a very simple downscaling method (to be explained). Local projections of changes in temperature, precipitation and run-off are then used to derive physical impacts on agriculture (e.g. changes in attainable crop yields) and hydrology (e.g. changes in irrigation, hydropower and treated water supply), which are valued in a simple partial equilibrium analysis.

[5]Empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables (Bates, Kundzewicz, Wu, and Palutikof, 2008).

Figure 2: Schematic integration of the different components in the study



3.2 Climate change adaptation policies

The study is about helping people adapt to climate change. However multiple stakeholders face major challenges as they have to answer how and how much to adapt as well as where and when to adapt. In order to answer these questions in a consistent framework, we suggest the following 5-step algorithm:

1. Definition of alternative adaptation strategies;
2. Cost-benefit analysis of adaptation and development projects;
3. Estimation of adaptation cost;
4. Economy-wide assessment of adaptation measures; and
5. Iterative adjustment in the alternatives selection.

In the absence of any policy action, climate change will generate damages to the economy relative to the baseline without climate change. Therefore policy makers are ultimately interested in the impacts of adaptation policy measures relative to a situation where climate change is impending and agents are efficiently making autonomous adaptations. This situation is the *laisser faire* scenario in the presence of climate change and is considered as the business-as-usual (BAU) scenario. It is represented on the third row of boxes in figure 2.

According to the discussion on climate projections in section 2, uncertainty relative to climate models is explored by taking two different GCMs producing the driest and wettest outcome in terms of a climate moisture index for each of the region containing the country case studies. In the case of bolivia, the driest GCM for Latin America is UKMO-HadGEM1 whereas the wettest is MRI-CGCM2.

In addition to climate scenarios we assume an annual rate of interest of 5% and produce a simple sensitivity analysis around this central case by lowering the interest rate to 3% on the one hand and increasing it to 7% on the other hand. Adding thus these three different rates of interest results in the specification of 6 BAU scenarios. As a consequence, the 5-steps algorithm need to be repeated for each of the six BAU scenarios in addition to the no climate change scenario.

3.2.1 Definition of alternative adaptation strategies

The first step of the algorithm is to define potential adaptation strategies. Based on livelihood profiles, key vulnerabilities to climate change are identified. Engaging both local people (e.g. 14 municipalities in the case of Bolivia) and national experts (e.g. inter-ministry technical group), plausible alternative adaptation pathways are then developed and analyzed socially[6]. Ultimately these adaptation pathways are the base for deriving stylized adaptation alternatives for each relevant sector at the national level.

3.2.2 Cost-benefit analysis of adaptation and development projects

The second step is to conduct a cost-benefit analysis for the entire set of both adaptation alternatives and development activities[7] (fourth row of boxes in figure 2). For each of these stylized projects[8], costs and benefits are inferred yearly over the entire lifetime of the project. These estimations are based on existing and future potential adaptation and development projects as well as on expert judgements.

Adaptation measures consist of both costs and anticipated avoided damages or benefits in each year over their entire lifetime. The former are estimated by first itemizing the physical, engineering and/or biological components of each adaptation option. Each item is then quantified in both physical units and market value. The latter are estimated by first identifying all possible outcomes from the implementation of each adaptation option. Each outcome is then quantified in physical units and valued in monetary terms.

In the following step of the analysis projects are optimally selected and introduced at any year up to 2050 by maximizing benefits of all projects under a

[6]Note that in the case of the no-climate-change scenario this amounts to compile an inventory of adaptation measures already adopted under the current climate.

[7]Development activities are all development projects in a given country financed by domestic budget and official development assistance (ODA).

[8]These stylized adaptation alternatives are defined either at the local level or at the country level. If they are developed at the local level, they are translated into adaptation measures at the level of the country.

given budget constraint for each time period. This requires that critical project assumptions with regard to costs and benefits be consistent with a range of possible dates of implementation of the projects. For this reason each project is designed to be implemented in either 2010, 2030 or 2050 in addition to the six BAU scenarios.

3.2.3 Estimation of the adaptation cost

The focus of the third step is to estimate the cost of adaptation in each of the six case study countries (fifth row of boxes in figure 2). The cost of adaptation is defined as the additional costs imposed by climate change on the baseline without climate change. These additional costs comprise the cost of adaptation of projects which would not be implemented, had climate not changed as well as the incremental cost of development projects which are in any case implemented but with a higher cost than in the case of no climate change.

In the case of Bolivia for example, El Alto and its sister city of La Paz, the world's highest capital, depend on glaciers for at least a third of their water. And because of global warming those glaciers are melting at a faster pace. These glaciers serve as natural shock absorbers for rain, accumulating it in the wet season and releasing it in the dry season. An adaptation option to capture precipitations during the wet season could be the building of dams. This could also have been the case had climate not changed but maybe in fifty or one hundred years from now. It results that instead of investing in projects more oriented towards development, the government will invest in the project of dams earlier than it would have been otherwise which then constitutes a cost of adaptation to climate change.

The optimal combination and timing of projects for a given BAU scenario is selected by maximizing benefits of all projects under the government budget constraint for each time period and is the focus of the following subsection. Robustness of each optimal solution with respect to climate scenarios is tested by calculating the benefits of all selected projects under alternative BAU scenarios and is examined in the subsequent subsection.

Selection of adaptation alternatives

The problem of project selection can be formulated and solved as an integer programming problem. The goal is to select projects to invest in, such that benefits are maximized. Let project l need a flow of expenditure $c_{l,t}$ over its lifetime. Benefits of investing in this project are also realized over its lifetime and are denoted by $b_{l,t}$. The present value of these future benefits is given by $B_l = \sum_t \frac{b_{l,t}}{(1+r)^t}$ where r is the appropriate discount rate. Assuming a total budget of G_t for each time period over the model horizon, the problem may be stated as follow:

$$\begin{aligned} \max_x \; & W = \sum_l B_l x_l \\ \text{s.t.} \; & \sum_l c_{l,t} x_l \leq G_t \qquad \forall t \\ & x_l \in \{0, 1\} \qquad \forall l \end{aligned} \tag{1}$$

where x_l is a binary variable indicating whether project l is selected or not.

Extending the framework originally presented by Fankhauser (1997) and then modified by Callaway (2004), let S_0 be a scenario without climate change and A_0 the optimal portfolio of projects under this scenario (i.e. $\{x_l = 1, \forall l\}$), then welfare under current climate may be expressed as

$$W_0 = W_0(S_0, A_0) \tag{2}$$

which shows that welfare depends on climate conditions and on the selected projects in the portfolio. The cost of the optimal portfolio in every given year is given by the sum in that year of individual cost of selected projects and is denoted by $C_0(A_0)$.

Similarly, let S_1 be a scenario with climate change and A_1 the optimal portfolio of projects under this scenario, then welfare under climate change without adaptation is

$$W_1^D = W_1^D(S_1, A_0) \tag{3}$$

whereas welfare under climate change with adaptation is

$$W_1^A = W_1^A(S_1, A_1) \tag{4}$$

so that gross damages of climate change are $W_0 - W_1^D$ and avoided damages or gross benefits of adaptation are $W_1^A - W_1^D$. The cost of the optimal portfolio under climate change is then $C_1(A_1)$.

In the context of a bottom-up approach to adaptation, a formal definition for the cost of adaptation to climate change may be now stated as the following:

Definition The cost of adaptation is defined as the cost of projects which would not be implemented, had climate not changed in addition to the incremental cost of projects which are in any case implemented, that is $AC = C_0(A_0) - C_1(A_1)$.

It follows that net benefits of adaptation are gross benefits minus adaptation costs, that is $W_1^A - W_1^D - AC$, which means that net benefits may be equal to zero if all selected projects have unitary benefit-cost ratios.

Definition The residual impact is defined as the difference in welfare following the change in climate assuming optimal adaptation, that is $RD = W_0 - W_1^A$.

Robustness across climate scenarios

Robustness of each optimal solution with respect to climate scenarios is tested by calculating net benefits of all selected projects under alternative BAU scenarios. In other words, the idea is to analyze the consequence of optimizing for a given climate scenario, and have a different climate outcome occur. Net benefits of all selected projects in the optimal portfolio under a given climate scenario are thus re-computed for all other climate scenarios. Repeating this experiment using each climate scenario to determine the optimal portfolio allows most robust projects to be chosen.

3.2.4 Economy-wide assessment of adaptation measures

Based on CGE modelling, the fourth step provides an economy-wide assessment of all selected adaptation projects (last row of boxes in figure 2) and thus allows testing for robustness of the project selection with respect to indirect effects. This top-down analysis is linked to the bottom-up approach in terms of representing the different sectors needed to introduce climate change damages and adaptation measures, as well as in terms of including distributional impacts[9].

Calibrating to a situation where there is no climate change, the model is first used to project the different BAU scenarios against which potential adaptation policies are then applied to as counterfactual scenarios.

Assessment of adaptation policies requires the simulation of both costs and benefits of planned adaptation measures. Benefits are avoided damages and are introduced in the CGE model by reducing the negative impacts of climate change in the appropriate structural parameters. Costs on the other hand are incorporated through appropriate additional demand for inputs. Note that these input categories correspond to the ones defined and used in the cost-benefit analysis (e.g. skilled and unskilled labour).

Within individual countries people do not react uniformly to the threat of climate change. Based on household surveys, information on both consumption and income of different household categories are introduced into the CGE model. Consequences of adaptation policies to climate change is thus analyzed in terms of income distribution across these different household groups.

3.2.5 Iterative adjustment in the alternatives selection

The final step of our algorithm is the iterative adjustment in the selection of adaptation alternatives. When indirect effects are substantial, prices of simulated adaptation policies need to be adjusted in the second step according to changes in prices resulting from the fourth step.

As long as indirect effects are not substantial, one would expect to find that the estimate for consumer welfare accounting for planned adaptation is higher than the consumer welfare without planned adaptation. Implicitly this implies that adaptation costs, even accounting for changes in prices due to indirect effects, are lower than benefits of adaptation. On the other hand, if

[9] A more complete discussion on CGE modelling in this context is given in section 4.

the estimate for consumer welfare accounting for planned adaptation is lower than that without planned adaptation then this would suggest that the indirect effects add substantial additional costs to the adaptation costs estimated in the third step and cause adaptation benefits to be lower than adaptation costs. In this case one needs to re-select the set of adaptation measures chosen in that step, and possibly select measures that will not increase the demand for factors whose prices are found to increase substantially in the CGE model. Robustness is ultimately tested by simulating these adaptation measures under the different BAU scenarios.

An example of indirect effect for Bolivia is an increase in the wage rate for skilled labour if the government decides to build several dams at the same time. As the set of adaptation measures is skilled-labour intensive and its share significant relatively to the overall labour supply, wage rate of skilled labour may increase leading to higher project costs than the ones originally estimated.

4 A Top-Down Approach at the International Level

A widely used top-down model for performing quantitative analysis of global economic issues within an economy-wide framework is the computable general equilibrium (CGE) model. Although CGE models remain at a very aggregated level, they are particularly well-suited for policy analysis as they link markets into a single system and capture therefore feedback and flow-through effects induced by policy changes. As the world is divided into regions, the global CGE model combines then inter-sectoral linkages within regions together with bilateral linkages among regions. In addition, a dynamic CGE model incorporates the disincentive to invest associated with increases in the cost of investment as well as the idea that an increase in the return to capital causes an increase in investment.

A global dynamic multi-sectoral CGE model is therefore appropriate to analyze adaptation across all dimensions, i.e. regions, sectors and time. In particular, autonomous adaptation is a feature of the model structure while planned adaptation is a characteristic of the model counterfactual.

Calibrating the top-down model with country- and sector-specific damage functions to available empirical evidence will provide a baseline which different scenarios are applied to as counterfactual situations to estimate the cost of adaptation. We consider two approaches for estimating the cost of adaptation for all developing countries. The first approach is the simulation of additional investment needed to restore hypothetical welfare without climate change in all developing countries. The second scenario is the simulation of additional investment needed to equal marginal cost of adaptation to marginal avoided damages.

4.1 Climate change impacts

Climate impacts (e.g. temperature or precipitation) on natural resources are quantified in the ecosystem model (e.g. crop model). For each sector under consideration, the ecosystem model converts GCM projected output into sectoral bio-physical impacts. As we are dealing with world models, local climate projections are obtained by applying only a very simple downscaling method (to be explained).

Climate-response functions are based on empirical studies that have been carefully designed to include autonomous adaptation to climate change. They are either reduced-form functions derived from the detailed modelling approach of scientific bottom-up models or statistical functions from cross-sectional analysis. The first issue in representing damage functions in a CGE model is to relate physical impacts of climate change to variations of economic variables or parameters in the model. The second issue is to calibrate country- and sector-specific damage functions to available empirical evidence. Recent studies on introducing country- and sector-specific climate change impacts in a CGE model are reported in Bosello and Roson (2006).

Mapping physical impacts into model variables

The basic structure of any CGE model is based on household utility functions and firm production functions. Structural parameters are thus embedded in household preferences and industry technologies. Related to the former are for example shifts in consumer preferences (e.g. changes in energy demand for cooling and changes in expenditure on medical services) or variations in endowments of primary resources (e.g. changes in land endowment and changes in capital stock). Examples for the latter are related to technical changes (e.g. variations in sectoral productivity and changes in labour productivity).

Climate-response functions are reported in different ways. In some cases impacts are measured as the fraction of annual market output and in other cases impacts simply estimated in monetary values. The difficulty resides then in translating these impact estimates into exogenous changes in structural parameters of the CGE model. This implies first mapping sectors embedded in damage functions with sectors defined in the model and then converting impact values into consistent exogenous variations of model parameters.

Introduction of damages functions in our study is related only to sectors that are likely to be affected by climate change. The following list enumerates sectors considered and describes the modelling of each of these impacts.

Infrastructure Infrastructure is present in almost each sector of the economy — infrastructure for transportation (ground, water and air), energy system, telecommunication, water supply, flood control, hydropower, and coastal development and defences, health and education, and for residential and commercial purposes — which implies impacts from climate change across all sectors. Consequences are likely to be related to the integrity, performance, lifetime and design criteria for much of the infrastructure. These impacts results in an diminution of the capital stock (related to changes in extremes) and an increase in the depreciation rate (related to changes in means) of the corresponding sector.

Agriculture The agricultural sector is probably the most carefully studied of all sectors as it is critical for human survival. Changes in agricultural yields are represented in the model as changes in the productivity of land associated with the agricultural sector.

Water resources Water is one of human basic resources. Climate change is likely to lead to increased drought which implies reductions in irrigation, hydropower and treated water supply. A simple approach to introduce these impacts into the model is through a change in the productivity of each of these associated sector.

Forestry Ecological models predict shifts in the geographic distribution of tree species as well as changes in forest productivity. These impacts are translated in the economic model as changes in the productivity of land associated with the forest sector.

Health Impacts on human health come from climate-related diseases among which are included vector-borne diseases (malaria, schistosomiasis and dengue fever), cardiovascular and respiratory disorders, and diarrhoea. The two main drivers considered in the economic model are labour productivity responding to changes in morbidity and mortality, and variation in private and public expenditure for health care services.

Coasts Sea-level rise has a wide range of impacts on coastal resources. Included in this study are erosion and inundation whereas flooding, salt water intrusion, and wetland loss are omitted. Resulting potential losses of land are simulated in the model by reducing the endowment of land devoted to agriculture.

Damage functions in our study are expressed as a function of temperature and income. Income acts as a measure of adaptive capacity and thus mitigates the impacts when income increases.

Country- and sector-specific damage functions

In the literature three main sources of climate-response functions are available at the regional and sectoral level. Mendelsohn, Dinar, and Williams (2006) quantify market impacts of climate change on every country of the world for each of the five major economic sectors that are expected to be affected by climate (agriculture, water for hydropower and irrigation, coastal resource, energy consumption, and forestry). In the FUND model, Toll (2008) studies impacts of climate change distinguishing 16 major world regions and sectoral damage functions (agriculture, forestry, water resources, energy consumption, sea-level rise, ecosystems, human health and extreme weather in the form of tropical storms). Finally the global damage function in the DICE model (Nordhaus, 2008) is based on 13 regions and seven damage categories (agriculture, sea-level rise, other market sectors(forestry, energy systems, water systems, construction, fisheries, and outdoor recreation), health, non-market amenity impacts, human settlements and ecosystems, and catastrophic).

Damages functions are based on the literature when it is appropriate and if available substituted or complemented by internal estimations. We exclude the use of response functions from Mendelsohn, Dinar, and Williams (2006) as they are all calibrated to the United States and then extrapolated to other countries using strong assumptions which result in crude approximations for developing countries. Damage functions in Toll (2008) are reduced-form functions whereas (Nordhaus, 2008) derives statistical functions. We start with damages functions from the latter as they are readily available in Nordhaus and Boyer (2000) and then implementable in our model.

4.2 The global cost of adaptation

The economic model allows deriving bio-physical impacts embedded in damage functions into economic impacts. At the global level, these impacts are quantified worldwide using a computable general equilibrium model. Damages of climate change are reduced when agents adapt which and divert thus resources which constitute the cost of adaptation. Attempts of quantification of adaptation costs based on optimizing IAM are found in Bruin, Dellink, and Agrawala (2009) and Bruin, Dellink, and Tol (2007).

4.2.1 Empirical implementation

The top-down model used in this study is drawn from the SwissGEN model (Cretegny, 2008). It is a global dynamic multi-sectoral CGE model which represents the flows of commodities between agents in the global economy. As the world is divided into regions, the model combines inter-sectoral linkages within regions together with bilateral linkages among regions. Bilateral trade flows assemble regional exports of trade with associated transport costs. Imports are differentiated commodities by their country of origin.

The model assumes optimizing behaviour from agents. Consumers demand is determined by budget-constraint intertemporal optimization and producers combine intermediate inputs, and primary factors at least cost subject to given technology. In all production activities of the global economy, agents are assumed to produce under constant returns to scale. They face markets that are perfectly competitive with free entry and exit.

The length of the time interval is critical in this type of analysis. On the one hand, a long time-step (10 years) allows integrating into the model policy-relevant details such as regional or sectoral disaggregation. On the other hand, a short time-step (1 year) makes the model more realistic. We assume a time-step of five years in order to match closely the budget period of the Kyoto Protocol (the current period is from 2008 to 2012).

The model's algebraic structure is formulated in a complementarity format, in which the general equilibrium of the economy is posed as a vector of market clearance, zero-profit and income balance equations (Mathiesen, 1985). It is numerically calibrated using the MPSGE subsystem (Rutherford, 1999) for GAMS (Brooke et al., 1998), and solved using the PATH solver (Dirkse and Ferris, 1995).

Level of aggregation

The core input-output tables are provided by the GTAP 7 database which is based on the year 2004. The GTAP database combines detailed bilateral trade, transport and protection data characterizing economic linkages among regions, together with individual country input-output databases which account for inter-sectoral linkages within regions.

While the GTAP 7 database features 113 regions and 57 sectors, we aggregate the data set to distinguish 10 regions and eight sectors/commodities (agriculture, forestry, manufacturing, energy, services). Regions are either industrialized or developing regions. Within the former, countries are grouped by continent (NAM — North America, EU — Europe, AS — Asia, and OC — Oceania) and within the latter, countries are aggregated according to the World Bank developing country groups (LAC — Latin America and the Caribbean, AFR — Sub-Saharan Africa, MENA — Middle East and North Africa, ECA — Europe and Central Asia, SAR — South Asia Region, and EAP — East Asia and Pacific).

The choice of sectoral aggregation level is based on the need to represent the main discriminatory features involved in the policy issues on adaptation and on considerations of data availability. The central issue here is to ensure a consistent mapping of sectors defined in damage functions with sectors represented in the model. The agriculture sector is a useful illustration as the agricultural damage function already accounts for autonomous adaptation between different crops and livestock which means that the agriculture sector as a whole should be represented in the model. It follows that when intra-sectoral autonomous adaptation is already accounted in bottom-up models that are used to derive sectoral damage functions, the CGE model need to incorporate only inter-sectoral autonomous adaptation. The eight sectors considered here are agriculture, fishing, forestry, energy, processed food, manufacturing, water and services.

In addition, we consider three main factors of production — labour, capital and land. However in order to have a realistic competition of land between agriculture and forestry, we distinguished between six types of agro-ecological zones defined by length of growing period. These roughly divide the world along humidity gradients, which are calculated as the number of days with sufficient temperature and precipitation/soil moisture for growing crops at 0.5 degree grid cell size (Monfreda, Ramankutty, and Hertel, 2009).

Calibration of the model

The calibration of a dynamic model involves constructing a growth path for the world economy assuming there is no climate change. It corresponds approximately to the current climate defined by the year 2000 constant concentrations projections. It includes therefore future development that would have happened in the absence of climate change and assumes implicitly stabilization of emissions at the rate of natural removal.

The cleanest approach is to set up the model along a steady-state growth path. In the steady state all quantities grow at the exogenous growth rate of the economy and all prices expressed as present values decline at a given exogenous interest rate (reflecting the pure rate of social time preference). The economy growth rate is assumed to be equal to the world population growth rate[10] which means that per capita quantities do not grow in the steady state (which reflects that technological change in the A2 storyline is slower than in other storylines). This approach avoids capturing adaptation deficit in the calculation of adaptation costs as it assumes that the economy is precisely in a long-term equilibrium. With regards to capital stock, we assume it depreciates at a constant geometric rate.

The central case assumes an annual rate of interest of 5%. A simple sensitivity analysis around the central case assumes a lower interest rate at 3% and a higher interest rate at 7%[11].

4.2.2 Scenario simulation

Business-as-usual

Even in the presence of a policy action that would stabilize emissions at current level, climate change will generate damages to the economy relative to the case without climate change. Therefore policy makers are ultimately interested in the impacts of adaptation policy measures relative to a situation where climate change is impending and agents are efficiently making autonomous adaptations.

Economic impacts of planned adaptation are not independent of the development path that the economy would have followed without adaptation policy. As discussed in section 2, uncertainty relative to climate models is explored by taking two different GCMs producing the driest and wettest outcome for the world in terms of a climate moisture index. The former is UKMO-HadGEM1 which is 14% drier on average over the 67'420 land cells of the globe whereas the latter is MRI-CGCM2 which is 6% wetter on average over the 67'420 land cells of the globe. Adding the three different rates of interest results in the specification of 6 BAU scenarios.

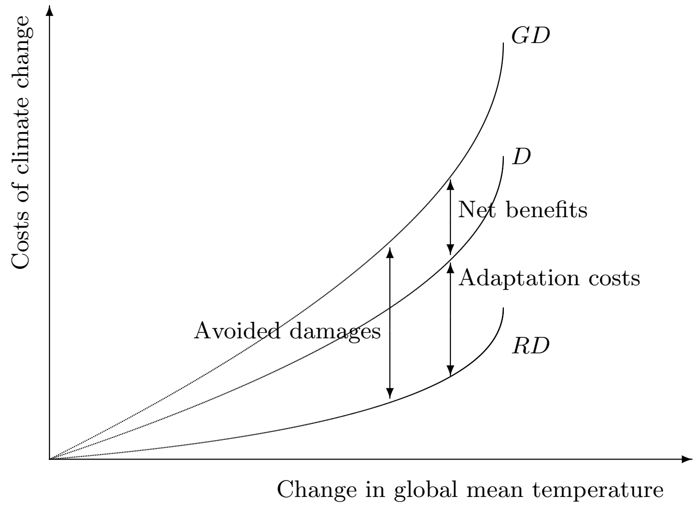
Adaptation policy

Adaptation is the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC, 2007a). Considering that climate change affects

[10] As future emission pathway is assumed to be exogenously given, there is no inconsistency in decoupling population growth from emissions.

[11] Nordhaus (2008) uses a rate of 5.5% in the DICE model, which implies a pure rate of social time preference of 1.5% for a 2% growth rate in the world economy and an elasticity of marginal utility of consumption equal to 2.

Figure 3: Role of adaptation in the costs of climate change



negatively the economy as shown in figure 3, investing in adaptation allows reducing gross damages of climate change GD to residual damages RD. Assuming positive return on investment results in positive net benefits of adaptation from the difference between avoided damages (gross benefits of adaptation) and adaptation costs. Net damages D are adaptation costs in addition to residual damages.

In the case of an uneven impact of climate change around the world, adaptation may either reduce negative impacts or increase positive impacts of climate change. In addition our study distinguishes between autonomous or spontaneous adaptation and planned adaptation. The former constitute a conscious response to climate change whereas the latter results of a deliberate policy decision.

Let PA_N and AA_N^* be the level of, respectively, planned adaptation and optimal autonomous adaptation under negative climate change impacts, where $0 \leq PA_N \leq 1$ and $0 \leq AA_N^* \leq 1$, and PA_P and AA_P^* be the level of, respectively, planned adaptation and optimal autonomous adaptation under positive climate change impacts, where $PA_P \geq 0$ and $AA_P^* \geq 0$, then net damages are the sum of residual damages RD and adaptation costs AC as follows,

$$D = RD\left(GD, PA_N, PA_P, AA_N^*, AA_P^*\right) + AC\left(PA_N, PA_P\right) \tag{5}$$

where $RD = (1 - PA_N)\, GD\left(AA_N^*, AA_P^*\right) + PA_P GD\left(AA_N^*, AA_P^*\right)$ and either PA_N or PA_P equal to 0. Gross damages GD are climate-response functions with optimal autonomous adaptation. When impacts of climate change are negative, $PA_N = 0$ means no adaptation while $PA_N = 1$ represents full adaptation reducing gross damages to zero. For positive climate change impacts, GD and RD are negative so that $PA_P > 0$ makes positive impacts of climate change even larger.

Our study focuses on planned adaptation. Two approaches are considered to estimate the cost of planned adaptation. The first scenario looks at the additional investment needed to restore hypothetical welfare that would have occurred in the absence of climate change in all developing countries. The second scenario examines the additional investment needed to equal marginal cost of adaptation to marginal avoided damages, which means that

$$\frac{\partial D}{\partial PA_N} = \frac{\partial RD}{\partial PA_N} + \frac{\partial AC}{\partial PA_N} = 0 \qquad \text{for} \quad PA_N > 0, PA_P = 0 \tag{6}$$

$$\frac{\partial D}{\partial PA_P} = \frac{\partial RD}{\partial PA_P} + \frac{\partial AC}{\partial PA_P} = 0 \qquad \text{for} \quad PA_P > 0, PA_N = 0 \tag{7}$$

for all regions.

With regard to financing adaptation to climate change in developing countries, we assume as a starting point that a distortion-free lump sum transfer mechanism is available for raising funds in industrialized countries.

5 Further Developments

Climate module Emissions of anthropogenic greenhouse gases are triggered by economic activities so a natural extension of the model is to introduce a climate module that would explicitly link socio-economic projections with future emissions.

Carbon tax The UNFCCC's Adaptation Fund financed by a two per cent share of the proceeds from the trade of carbon credits generated under the Clean Development Mechanism (CDM), is expected to raise at most $5 billion per year by 2030. Introducing a tax on carbon in the model, it could be used then to determine the per cent share of the proceeds from the trade of carbon credits generated under the CDM necessary to cover the cost of adaptation in developing countries.

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